The dynamics of technological discontinuities: a patent citation network analysis of telecommunication switches

Arianna Martinelli

The Dynamics of Technological Discontinuities: a Patent Citation Network Analysis of Telecommunication Switches

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Pai Mei: [punches through a block of wood from three inches away] Since your arm now belongs to me, I want it strong. Can you do that?

The Bride: I can, but not that close.

Pai Mei: Then you can't do it. What if your enemy is three inches in front of you, what do you do then? Curl into a ball? Or do you put your fist through him?

(Quentin Tarantino, "Kill Bill Vol. 2")

Acknowledgement

Writing this (last) bite of the thesis makes me realize I survived my “Omaha beach”, with all respect for those who were really there in 1944. This comparison started in autumn 2007, when, after my holiday in Normandy, my supervisor Alessandro Nuvolari suggested the similarity between the PhD and D-day. Retrospectively, I think it was one of the most clumsy attempts to cheer me up during one of my periods of PhD blues. However, he indeed succeeded. I am still wondering why this argument worked but I suspect it did because it spelled out what I refused to accept for a great part of this experience: the loneliness of research. This might sound a bit dramatic considering the amount of conferences, workshops, and seminars we attend in order to make everybody else aware of our ideas and doubts. But at the end of the day, research is a lonely path.

In any case, the Ph-D-day metaphor brought up some questions: what is the role of encouraging colleagues? And of other Phd students? I am still wondering about the role of supervisors: are they the ones encouraging you from behind the firing line, or just the “family picture” to keep in the pocket and look at during the inevitable panic? I haven’t figured it out yet, and I am perfectly happy to keep my doubts.

As regards supervision, I feel very lucky; not only did I have active supervisors, but I could also count on the help of many colleagues.

I am truly indebted to Alessandro Nuvolari for his help and support, but also for his pushy attitude (Pai Mei docet). He was inspirational and a great source of encouragement. He patiently addressed my questions and doubts, and very generously shared his knowledge, from W. Churchill’s quotations to bad steam engine design. His thesis *The making of the steam power technology* was of great inspiration as a successful example of combining qualitative and quantitative research about artifacts and their technological development. Finally, not being a historian myself, discussion with Alessandro allowed me to enlarge, if not my research interests, my general perspectives on long-term economic development.

The support I received by Bart Verspagen was less continuous but no less important and useful. I really appreciate Bart's challenges, research rigor, and directness in addressing the "bad and the good" of my thesis. Furthermore, he seemed to know exactly when I needed to be reassured about "being on the right track". I cannot imagine what a PhD student could ask more of his promoter.

Finally, I would like to thank Bert Sadowski and the members of the "Small Committee" for providing useful insights and comments.

Even if they were not officially involved in my PhD, a special mention goes to some other people working at the (former) T&B group. First of all, I would like to thank Rudi Bekkers for sharing not only his immense knowledge on telecommunication switches but also his (probably even larger) music library. It is not the time for blame, but it is Rudi's fault if I felt in love with telecommunication switches, and after opening the Pandora's box he was very good in keeping up the "engineering mentoring". He got me a soldering iron and his help was fundamental for catching up on the engineering background. Finally, he read and reviewed several drafts of the chapters providing very useful comments.

It was also a great pleasure to share several breaks with Önder Nomaler who sometimes scared me with extremely odd ideas... some of which are now incorporated in the thesis after recognizing they were indeed very good ones (I still remember the first time we discussed "the genetic approach to patents"). Önder was also extremely helpful in selecting the title of this thesis. If you do not like it, that is my responsibility, as his actual suggestion was: *Networked Learning of Technology for Make Benefit Glorious Notion of Cumulativeness.*

In the years at Tu/e I have shared the office with very patient Dutch colleagues; they did not seem too bothered by my Mum's frequent phone calls. Both Bas and Sjoerd helped me with the daily troubles of being a foreigner and my Dutch integration process. In particular, observing Sjoerd I learnt how to prepare a good sandwich with brown bread, Becel, and chocolate hagelslag.

Finally, I would like to thank Letty Calame for her help in sorting out some bureaucracy during the PhD, for the cutest iPhone sleeve I have ever had, and for being such nice company at Scala.

Over time, many more people made T&B a pleasant place to work. I am sure I am forgetting someone, but I would like to thank: Isabel, Alberto, Irene, Effie, Michiel, Andrew, Jojo, Lili, Ted, Ies, Marianne, Saskia, Saurabh, and Wim. I have lost count of the lunches and beers we had together, but each of them was a great pleasure.

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Since more than one year ago, I moved from Tu/e to Friedrich Schiller University in Jena. I feel very lucky to work in such a dynamic and enthusiastic place. It is difficult to express how much I feel indebted to Marco Guerzoni for the good care he took of me in the last part of the PhD. It is great fun, after years, to be able to share the house with such a good old friend. I found his scientific attitude and painstaking theorizing about everything very inspiring. Finally, I am not totally sure our "regression towards the mean" is working, however I am trying hard to be more optimistic (and to forget about Arianna-type problems) and to overcome my annoyance for his good mood in the morning.

A special mention goes to Dave Hugh-Jones. I hope he did not regret too much his volunteering to edit the whole manuscript. I know it was a great effort not only to correct my "atrocious prose" but also not complain (too much) because "equilibrium" is not in any page. Our discussions were fraught but necessary to push the research rigor as much as I could; I promise: I will work on external validation! Finally, I would like to thank him for his company, his caring attitude, his wit and sense of humor, and his capacity to understand when I need a proper tea.

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I am not sure I should thank the people in Scala, who made me sort of addicted to tango. Now that I cannot dance as much as before I understand how lucky I was to find so many tango-crazy people.

Infine, vorrei ringraziare i miei genitori per il loro amore e supporto. Lo so che a volte é difficile essere cosí lontani e condividere alcune delle mie scelte, ma spero comunque di rendervi orgogliosi. Questo libro dedicato a voi con tutto il mio amore.

Milan - Jena, 10th May 2010

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List of Acronyms

ATM Asynchronous Transfer Mode

BHCA Busy Hour Call Attempt

BOC Bell Operating Company

ECO Electronic Central Office

EWL Electronic Wired Logic

CCITT International Telegraph and Telephone Consultative Committee

IC Integrated Circuit

IEV International Electrotechnical Vocabulary

IEEE Institute of Electrical and Electronics Engineers

ISDN Integrated Service Digital Network

IP Internet Protocol

LSI Large Scale Integration

NGN Next Generation Network

PCM Pulse Code Modulation

PSTN Public Switches Telephone Network

PTT Post, Telegraph, and Telephone

QoS Quality of Service

SPC Storage Program Control

SMD Space Division Multiplexing

TDM Time Division Multiplexing

TCP Transmission Control Protocol

VLSI Very Large Scale Integration

Part I

Introduction

Chapter 1

Introduction

Although all economists recognize the primary role of technical change in explaining long-term economic growth, they differ in the choice of the theoretical framework for studying it. In particular, neoclassical economists reduce innovation and technical change to a simple problem of maximization under constraint carried out by a representative agent. Entrepreneurs maximize their production function under the constraint of factor prices, they can access nearly infinite combinations of inputs in order to produce the output, and the choice of a particular input combination is driven by changes of their relative prices.

On the basis of the work of economic historians (and historians of technology) (Rosenberg, 1963; Rosenberg, 1982; Rosenberg, 1994; Abbate, 1999), evolutionary economists find this simplified description, that singles out market as the main driver of technological change, inadequate. In fact, technological change should be considered as a complex phenomenon involving the co-existence and interaction of both technical and socioeconomic factors (Sahal, 1981*b*). The understanding of technological change is related to the understanding of its artifact characteristics (e.g. technical and service characteristics, complexity of the systems, measures of performance, etc.), the agents involved in the innovative process (e.g. inventors, firms, universities, etc.), and the general economic context.

This perspective implies a very ambitious research program covering all the features listed above; in fact, departing from the neoclassical (i.e. market driven) approach means enlarging the spectrum of relevant aspects for the study of technological change. From a methodological perspective, this entails dealing with qualitative research and appreciative theorizing defined as a rigorous *storytelling* (Nelson, 1989). Furthermore, appreciative and formal theorizing are not exclusive but complementary: the former provides the empirical observations, regularities, and puzzles, ultimately, the research questions that can be explored by the latter.

The holistic approach to technological change described in the previous paragraphs puts forward a broad and interdisciplinary research agenda. However, in order to build a consistent and comparable *corpus* of literature some guidelines and boundaries are required. For instance, appreciative theorizing addresses mainly the industry level, often dubbed "mesolevel" in order to position it between the most known (and used) micro and macro levels. Interest in this intermediate level strongly characterizes evolutionary (economic) studies and respond to the scientific need to identify both representative units of analysis and common patterns. The choice of such level stems from the work of Joseph Alois Schumpeter, recently reappraised by the "technological regimes" literature and the neo-Schumpeterian tradition.

Joseph Alois Schumpeter was a pioneer in the study of innovation and in his work he distinguished two patterns of technological change. In the *creative destruction* pattern, innovation emerges from firms that did not innovate before. In this case, the figure of the entrepreneur is central, a person able not only "to think new", but also to successfully promote its ideas. By contrast, in the second pattern, the *creative accumulation*, innovation emerges from firms that did innovate before. In this case, the promoter of innovation is not an individual but the R&D facilities of (generally large) firms. Furthermore, these patterns not only differ in the source of innovation, but also in the way the exploration of the technological space takes place. The first case is characterized by the "widening" of the available knowledge, whereas the second one by its "deepening".

An important result of the recent literature is to unfold the link between technological regimes and Schumpeterian pattern of innovation. Technologies differ along several dimensions such as: conditions of opportunity and appropriability, degree of cumulativeness, and knowledge base characteristics. The combination of those elements defines the technological regime, which plays a relevant role in determining the (Schumpeterian) pattern of innovation. The *creative accumulation* pattern (also dubbed Schumpeter Mark II) is associated with an increase in the appropriability of innovations, an increase in cumulativeness, and the importance of less targeted and generic (referred as basic) knowledge. By contrast, *creative destruction* (Schumpeter Mark I) displays opposite associations (Breschi, Malerba and Orsenigo, 2000). As sectors can be uniquely assigned to one of the Schumpeterian pattern, from a technological and cognitive perspective firms tend to differ more across than within industries (Malerba and Orsenigo, 1996*b*; Malerba and Orsenigo, 1996*a*; Malerba and Orsenigo, 1997). Therefore, when the main interest is technological change, the industry level is the appropriate one. In this respect, also the Pavitt taxonomy (and its extensions) represents an attempt to find commonalities among firms related to their innovative characteristics and behaviors (Pavitt, 1984; Castellacci, 2008). The following chapter further discusses the rationale behind this analytical choice and the differences to alternative theoretical approaches.

It is interesting to notice that even when the industry level is chosen as the relevant one, several questions still remain open. In fact, it is still at stake how an industry is defined, who is part of it, how actors are linked and interact, and which institutions are present. In this respect, the sectoral system of innovation approach (SSI) provides a rigorous framework for the storytelling of technological change (Malerba, 2004). In fact, on the one hand the SSI approach emphasize the need of a *"... multidimensional, integrated and dynamic view of sectors..."* (Malerba, 2002, page 248), on the other hand it provides a *"... workable definition* *[of it]. . .* " (Malerba, 2002, page 250). According to the SSI the relevant aspects to consider and examine are: (i) knowledge base and learning processes, (ii) demand, and (iii) market and non-market interactions among the actors.

The first contribution this work tries to make is in the field of appreciative theorizing. This thesis provides a detailed account of telecommunication switching industry structural change from its origin to recent years[1]. A telecommunication switch is a component of the telecommunication infrastructure; in particular, it allows the establishment of a phone call, by realizing a connection from a selected inlet to a selected outlet, for the duration of the call. From the artifact perspective, a telecommunication switch is a complex device integrated in a large network system. In this early part of the work it is also necessary to point out why such a piece of research should be of any interest: *Why should economists be interested in the telecommunication switching industry? What type of appreciative theorizing can emerge from the analysis of this industry?* This industry went through several waves of radical and competence destroying technological change that would not produce any opportunities for new entrants. In fact, this industry was characterized (until very recently) by slow industrial dynamics with few players, all related to four pioneering firms[2]. Therefore, this industry represents an interesting case for studying the dynamics and interaction of technological and institutional barriers to entry, and the link between technological change and industrial dynamics in an oligopolistic market.

The need to understand the engineering characteristics of an artifact calls for *technology storytelling*. This thesis adopts what in the historiography of technology has been called internalistic approach. This means to focus exclusively on the artifact, its characteristics and design, and its evolution over time (Staudenmaier, 1985). In this perspective, the evolution of an artifact is explained solely by the technological challenges (i.e. technical bottlenecks) engineers encounter and solve. Therefore, this approach examines how engineers search for technical solutions, that is, how they explore the technological space. The persistence over time of those engineering heuristics implies a selective search of the available technological space and the existence of technology *inner dynamics*[3] that might hamper (or even prevent) prompt responses to market changes. The recognition that not all the possibilities in the technological space are available and equally searched constitutes a further difference between the evolutionary and the neoclassical framework.

A meaningful and realistic approach to the economics of technical change should consider

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[1] It is possible to claim that this thesis covers the history of the industry from its origin (end of the 19th century) to the end. In fact, with the advent of packet switching, a technology developed in a different industry, telecommunication switching industry was incorporated into data networking.

[2] These companies are: International Automatic Electric Corporation, AT&T (Western Electric), Ericsson, and Siemens. They were all founded by the 1910s and more details about their genealogy are displayed in chapter 4.

[3] It is interesting to note that from the perspective of the technology-society relation, technology *inner dynamics* might correspond to the *technology determinism* phase in the technology momentum theory put forward by Hughes (1969).

all the above features and complement technical aspects with economic considerations. In particular, if the market is not the only driving force it becomes less obvious: (i) "how and where" technological change originates and takes place, (ii) its rate of occurrence, and (iii) its direction (Mowery and Rosenberg, 1979). The concepts of technological paradigms and trajectories put forward by Dosi (1982) go in this direction, broadening the research agenda on technological change. Following the philosophical concept of a scientific paradigm introduced by Thomas Kuhn, a technological paradigm is defined as *"...[a] 'model' and a 'pattern' of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies..."* (Dosi, 1982, page 152). Therefore, the technological paradigm cognitively defines and bounds the search for technical solutions in the technological space. Furthermore, within the available technological space, only a limited number of solutions is actually undertaken. This subset constitutes the technological trajectories. The attempt to include these engineering aspects in the economic analysis corresponds to developing what Devendra Sahal calls a "microview of innovative activities" (Sahal, 1981*b*).

In this thesis, this microview on innovation is applied as the study of the patent citation network for a specific technology. The availability and accessibility of several patents databases made patents (for better or worse) very popular in innovation studies. In fact, in the recent years they have been extensively employed for computing indicators of innovative performance, country performance, knowledge relatedness, or to provide information about network of firms or inventors. In this work we follow the recent stream of literature that proposes a network approach, where citations provide the links between the patents. We adopt a stylized (but realistic) view on patents, considering them a collection of "technical problems and newly proposed solutions". Therefore, patents represent the building blocks of a technology and citations provide information about the relations between them. Furthermore, this work moves forward from a "Pythagorean" view (Sahal, 1981*b*) on patents where they are used exclusively for computational purposes. In fact, in this work we reconstruct the evolution of engineering search strategies (i.e. the engineering heuristics) using the qualitative information discloses in the patent.

The second contribution of this thesis is an in depth analysis of technology dynamics by means of patent citation network. Furthermore, a new conceptualization of knowledge flows (within a network) is proposed and used for empirically studying knowledge persistence. In fact, given the novelty of the network approach to patents there is a compelling need for indicators, algorithms, and methods for their systematic analysis. The necessity for such empirical tools is even more stringent given some structural characteristics of patent citation networks, such as directionality and acyclicity, which make the use of standard social network analysis tools difficult (or even meaningless). The few existing studies analyzing patent citation networks uses bibliometics tools, in fact, publication networks share some of the above mentioned features.

A further challenge posed by the development of new empirical methods is their link to innovation studies. In fact, if we contend that a patent citation network represents a portion of the industry knowledge-base, the study of the structure and evolution of such network should be meaningful in term of knowledge (and technology) dynamics. In particular, given the nature of patent citation networks (i.e. they represent connections among technical solutions), their structural characteristics can be insightful on the extent of cumulativeness of a specific technology. This thesis explores this aspect and, based on the genetic idea of "inheritance of genes", we propose an indicator to assess knowledge cumulativeness and persistence in a patent citation network.

Following the introduction of the previous pages, it looks appropriate to give to the reader a road map of the whole book.

Part I (chapter 2) will introduce the reader to some theoretical issues covered in the thesis. It is important to point out that it is a general theoretical introduction, providing the underpinning of what we could call the "general assumptions" of the thesis. These, already hinted in the previous paragraphs, are: the theoretical support of an industry level study, the link between technology and industrial dynamics, and a cognitive approach to technical change. Finally, this chapter will end (section 2.4) with the explicit statement of the research questions.

Part II (chapter 3 and 4) represents a piece of qualitative research that focuses on technological development and industry *structural evolution.* In particular, chapter 3 provides a detailed account of technology evolution in the telecommunication switching industry. The aim of this chapter is to highlight the technical characteristics along which telecommunication switches developed and which technological bottlenecks materialized. From this chapter it emerges that technological progress in the industry follows a "challenge-and-response" (Rosenberg, 1974) pattern where the main driver appears to be the solution of technical bottlenecks. Furthermore, this chapter tackles the issue of performance measurement (i.e. service characteristics) stressing the "not-off-the-shelf" nature of a telecommunication switches and the interoperability to other network infrastructures. Chapter 4 is an account of the *structural evolution* of the telecommunication switching industry from its infancy until recent years. This means considering several aspects, such as the emergence of new technologies, changes in firm competences and skills, firm diversification and integration strategies, and the role of public authorities and institutions. As this can result in a very complex task the chapter is divided in two parts. In the first part the industry is considered as a whole, and for each period five dimensions are systematically discussed. These are: (i) market structure, (ii) barriers to entry, (iii) demand, (iv) relevant actors and their relations, and (v) source of knowledge and technology. In the second part switches manufacturers are individually considered with special attention to their (common) genealogy, their national context, their technological competences, and their patterns of diversification and specialization (Granstrand, Patel and Pavitt, 1997). This account will be fundamental for discussing the empirical results from the firm perspective.

Part III (chapter 5 and 6) centers on the analysis of technology dynamics through the use of patent citation networks. In particular, the analysis proposed tries to couple qualitative and quantitative research, moving beyond considering patents as a “count unit”, and considering also their descriptive contents. The analysis focuses on two aspects: (i) mapping the main flow of knowledge within a directed network using the established method proposed by Hummon and Doreian (1989) and (ii) the analysis of the newly introduced concept of knowledge persistence. We could consider these two chapters as an empirical counterpart of chapter 3, as they provide an empirical representation of the technological evolution and of the exploration of the available technological space. The first step of this type of analysis is the re-framing of the history of technology (chapter 3) in the technological paradigms and trajectories framework. This means to examine the technological advance through the lenses of the engineering heuristics and to pinpoint what search strategies engineers used over time. In this setting, paradigms can be distinguished by looking at the stability of such heuristics, the need for new technological competences, and the emergence of new technical bottlenecks. Finally, the co-evolution of technology and industrial structure is examined by looking at the results obtained from the patent citation analysis from the assignee (i.e. firm) perspective and interpreted using the detailed account of the firms history presented in section 4.3.

The second aspect of technology dynamics is knowledge persistence and the long term knowledge flows in the network. A patent citation network represents a system of knowledge generation and transmission (through citations), therefore, it is possible to identify the patents which were most successful in spreading their knowledge to later patens. This corresponds to study each patent citation structure from a global perspective. In chapter 6 this is operationalized by using genetic concepts such as the Mendelian law of inheritance of genes.

Finally, in Part V, chapter 7 provides a summary of the main finding of this thesis, discusses their implication, and suggests future lines of research.

Chapter 2

Technological change and industrial dynamics: Theoretical review

2.1 Introduction

The aim of this chapter is to provide the general theoretical background of the thesis. The first issue we tackle is the level of the analysis and the rationale behind choosing the industry level. This naturally follows from one of the contributions this thesis tries to make, that is an in depth case study of the evolution of the telecommunication switching industry. Therefore this work will enrich the already existing literature on industry appreciative theorizing central in evolutionary economics.

A consistent case study needs a theoretical framework that provides a guideline for identifying relevant events and actors; in this thesis, we compare several theoretical approaches and the sectoral system of innovation (SSI) is chosen. The next section will discuss the alternatives, however we can anticipate that SSI was chosen because its complex view on technical change, departing from a cost-function one. This links with section 2.3 where the theoretical and empirical literature about technological paradigms and trajectories framework is discussed. These concepts suggest the existence of a technology *inner dynamics* that needs to be investigated because of its link with the industry (and economic) level. This relates to the second contribution of this thesis and the analysis carried out in part III.

From a completely different perspective we can contend that we are here not only discussing a different type of microfoundation but also taking a step further towards it. In fact, neoclassical economists tend to focus on agents (either individual or firms), whereas we look at technologies, which are related to "technological regimes" and patterns of innovation carried out by firms.

The chapter is structured as follows: section 2.2 covers the literature about technological change and industrial dynamics and section 2.3 discuss the theoretical and empirical literature about technological paradigms and trajectories. The research questions and the structure of the thesis (ultimately, where their answers can be found) are explicitly stated in the conclusion.

2.2 Technological change and industrial dynamics

The traditional approach to economics recognizes two levels of analysis: the micro and the macro. Those levels are linked throughout the principle of microfoundation, which means the possibility to explain macro events from the aggregation of micro behaviors (of consumers, producers, etc.). In this perspective, what in the evolutionary tradition is called mesolevel and indicates the industry level[1] is neglected. To contend that firms differ along several dimensions (among the others: size, R&D intensity, and strategies) undermines a cornerstone of the economic theory, that is, the representative agent. In fact, these representative consumers, firms, etc. represent the building blocks of the aggregation process and of the microfoundations of macrophenomena.

The evolutionary approach to technological change departs from this perspective, neglecting the existence of such a representative agent (and questioning its utility for research purposes) and showing evidence on firms' heterogeneity (Nelson and Winter, 1982; Dosi, 2005). This approach contends that firms differ in term of their competences, capabilities, and routines; therefore in the way they behave and take decisions. The SSI builds on this tradition and on the observation that firms heterogeneity within a sector is lower than between sectors. This means that firms active in the same industry should undertake similar innovative and learning processes than firms from different sectors (Breschi et al., 2000)[2].

In this section we are going to briefly present alternative economic approaches to the mesolevel analysis and to discuss existing studies related to telecommunication manufacturing. Subsequently, we are going to discuss in depth the SSI approach and to put forward five analytical dimensions for the study of industry evolution. These dimensions will be used in chapter 4 for describing the *structural evolution* of the telecommunication switching industry.

2.2.1 Meso-level analysis: Different approaches

From a conceptual (but also historical) perspective, we can distinguish four different approaches to the mesolevel analysis that are summarized in table 2.1. It is interesting to notice that three columns refer to what we could call "schools of thought" (or even scientific paradigms), and one to the work of a single scholar that is John Sutton. We decided to include

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[1] In this review we are going to consider industry and sector synonymous.

[2] In this respect it is interesting to point out that this appears not to be the case when the aggregation by industry refers to products (Srholec and Verspagen, 2008). Later we will further discuss this point making more explicit what "being in the same industry" in the SSI perspective means.

his work because he examined the telecommunication switching industry in his *Technology and Market Structure* (1998), and his approach could hardly be classified in one of the other columns. In this section we are going to focus on the first three columns, whereas in section 2.2.2 we are going to focus on the last one.

Table 2.1: Comparison among different approaches to industrial organization

	SCP	**IO**	**J. Sutton**	**SSI**
Technology	Cost Function		α	Knowledge (e.g. paradigms and trajectories, probability to innovate, etc.)
Actors	Firms	Individuals and firms	Firms	Firms, individuals, organizations etc.
Nature of the firm	Not relevant	Principal agent model		Competences and capabilities
Relations among actors	Strategic interaction	Competition	Strategic interaction	Competition and cooperation
Institutions	Market	Incentive structure (Rule of the game)		Formal and informal (e.g. patents)

Industry level analysis is rooted in the structure-conduct-performance (SCP), sometimes referred to also as the "Harvard tradition". As the name suggests, according to this approach, firm's performance (in broad sense, including, profit, innovation, productivity, etc.) is determined by firm's conduct (in term of R&D strategies or investments), which is ultimately dependent upon market structure. The first column in table 2.1 shows that studies belonging to SCP framework focus on firms, which are the only actors considered. Furthermore, these firms interact only through competition and all the aspects related to technological change (i.e. knowledge creation, learning) are incorporated in the firms' cost function. The last row refers to the role of institutions, here defined as the *"set of common habits, routines, established practices, rules or laws that regulate the relations and the interactions between individuals and groups..."* (Edquist, 1997, page 46). SCP conceives only one relevant institution, which is the market: in fact, firms interaction takes place only in the form of market competition[3].

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[3] For more details about the SCP paradigm, see the causality flow chart at page 5 in Scherer and Ross's

This approach has several limitations, for instance, it has a "simplifying" attitude towards technological change, denying its complex and non-linear nature. This is reflected in the narrow view upon the actors involved, the type of relations among them, and the role of institutions. We could contend that this simplification is a consequence of the research method used, which is econometric analysis. In fact, most of SCP studies use large firm level dataset in order to estimate "industry effects" (McGahan, 1999; McGahan and Porter, 1997). An exception to this is the famous Porter's five forces[4] model that pertains to the SCP tradition. This model, popular in the business strategy domain, provides a standard way to discuss the attractiveness of an industry highlighting the characteristics of the competitive pressure experienced by companies in a specific industry (Porter, 1980; Porter, 1985). To our best knowledge, there are not pieces of research conducted within the SCP framework focusing on the telecommunication manufacturing industry.

Problems related to the strong empirical orientation of SCP (for instance, the endogeneity of the independent variables) brought about the need for a more rigorous theoretical analysis. This is here labeled Industrial Organization (IO), which is sometimes referred as the "Chicago tradition"[5]. Column 2 in table 2.1 shows that also in IO all the relevant aspects of technology are represented through a cost function. In this case, the actors involved are individuals, which embed the instances of organized groups. For instance, firm's behavior is deconstructed into a set of contracts undertaken by individuals such as managers or owners. These individuals differ in their incentive structure, which drives their behaviors and their strategic interaction (an example of this is the popular principle-agent model). Within this framework, several scholars studied the telecommunication industry, in fact, this complex industry offered different research topics at different stages. For instance, in its early time researchers focuses on the desirability of a regulated monopoly (the so-called natural monopoly) or on the monopolist's incentive to efficiency and innovation under different regulatory schemes. In more recent time, both service and infrastructure liberalization and de-regulation provided new steam for research. Among several topics, there are: new entrants' buy-or-rent dilemma[6] (de Bijl and Pietz, 2002; Cave and Prosperetti, 2001), the efficiency of different deregulation schemes (Laffont and Tirole, 2000), or to standardization problems in a network industry[7]

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book (1990).

[4] These are: determinants of rivalry, entry barriers, determinants of supplier power, determinants of substitution threat and determinants of buyer power (Porter, 1985, page 6).

[5] Some scholars could (rightly) argue that also SCP is part of IO and that we could refer to both as the "New Industrial Organization". This issue is merely about labels and later development of SCP, in fact, the differences between the two schools in the early phases are rather clear . Here it was decided not to use the adjective "new" (and use IO) because some books of history of economic thought do not already use it (Zamagni and Screpanti, 2004).

[6] New entrants in telecommunication service face the decision to build their own infrastructure (eventually investing in new network technologies such as optical fiber in order to provide "advanced" services) or to rent the former monopolist's network infrastructure at regulated price.

[7] Please notice that these listed topics and bibliography represent just the "tip of the iceberg" in a huge field.

(Shy, 2001).

Looking specifically at telecommunication switches it is interesting to notice that John Sutton, in his book *Technology and Market Structure* (1998) uses this industry as a natural experiment for corroborating his theoretical model. Sutton's work is hardly classifiable among SCP, IO, and SSI approaches; in fact, his work is characterized by both a strong sectoral and technological focus, combined with IO analytical tools (namely game theory). In this respect, his "bounded approach" is a way to accommodate empirically observed industry differences with generality of theoretical modeling. In his view, industries are characterized by an escalation parameter, α. This basically measures how much a firm can gain in the market, overspending its competitors in R&D. According to him α necessarily differentiates the way industries market structure responds to shocks of different nature. In particular, he contends that in "high α" industry, of which telecommunication switches is an example, an external shock will increase industry concentration. He recognizes that (radical) technological change might be a source of such a shock, however he uses telecommunication switches as an example of market shock, looking at the transition from isolated local industries to a global industry because of liberalization. Unfortunately, this period corresponds also to a period of radical technological change (the emergence of digital switches) and the author himself casts some doubts about the possibility of disentangling both effects on market structure. In particular, it is difficult to assess which of the two shocks would have a larger impact. In fact, on the one hand the development of digital switches was proved to be one of the longest and most expensive R&D programs, placing firms under financial pressure in order to sustain the investments[8] (Fransman, 1995). On the other hand it is somewhat of an overstatement to claim that the market was *in primis* local and *then* global. In fact most of the manufacturers had their own domestic market, however they were active in several other countries through joint ventures or local subsidiaries. In chapter 4 the long term process of domestic market globalization will be discussed, however, we can anticipate that data on digital switches show a rather slow and limited process involving few manufacturers.

Given the fact that the main topic of this thesis is the relation between technological change and industrial dynamics, we need to look at a theoretical framework that places emphasis on this aspect and that overcomes static analysis. A natural candidate is the Sectoral System Innovation approach (SSI), which specifically looks at the emergence of new technologies and at the understanding of the factors enhancing or reducing the probability of innovate (Malerba, 2002; Malerba, 2004).

2.2.2 The sectoral system approach

According to the literature there are three (nested) levels of analysis to study the evolution of an industry: *specific dimensions of industry dynamics*, *structural dynamics*, and *structural evolution* (Malerba and Orsenigo, 1996*a*).

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[8] See chapter 3 for further details.

The first level refers to the analysis of topics such as firm growth distribution, firm size distribution, and empirical regularities such as the persistence of heterogeneity both within and across industries (Dosi, 2005). The second level focuses on the dynamics of structural variables, such as entry, exit, firms' size, and product and process innovation. A typical example of this analysis is the industry life cycle model (inspired by the product life cycle model), according to which every industry goes through similar patterns of entry, exit, survival, and shift from product innovation to process innovation (Klepper, 1997; Klepper, 1996; Abernathy and Utterback, 1978). Finally, the highest level considers both the dimensions tackled at the lower levels and the industry as a whole: the emergence of new technologies, changes in firm's competences and skills, firm's diversification and integration strategies, and the role of public authorities and institutions.

The SSI approach is particularly suitable to the aim of this thesis because it considers technological change as a complex phenomenon (as it will appear from section 2.3) and provides a theoretical guideline for its systematic analysis.

In the SSI approach, presented in the last column of table 2.1, technological change is not simply a shift of the cost function, but attention is devoted to the way new technologies emerge, succeed, and finally diffuse. This means that the innovation process is decomposed and studied in all its phases (Rosenberg, 1982). For doing so concepts like technological paradigms and trajectories are used. As they will be the main topic of section 2.3, we postpone the discussion about their definition and rationale; here, we just observe that such concepts describe technical change as a composite phenomenon with its own dynamics (Dosi, 1997). This implies technologies are not homogeneous entities with the same technical and economic characteristics. They differ in the way they are developed, in the typology of actors involved, and ultimately they rely on different knowledge. This has consequences at the industry level, in fact specific knowledge features determine its level of transferability, both between firms and related industries. Knowledge characteristics such as tacitness, complexity and interdependence are directly related to the possibility of its articulation and transfer (Winter, 1987). Furthermore, the industry knowledge base represents a distinctive feature of technological regimes, and therefore, of the way firms innovate and learn (Breschi et al., 2000; Malerba and Orsenigo, 1997).

The SSI moves already away from considering firms the only relevant actors in the innovation process. Besides the recognition of the importance of firms in the innovation process, it becomes clear that in some industries the role of other organizations such as universities or private research centers is equally important (an example of this is the biotech industry). Furthermore, as technology evolves following its *inner dynamics* generated by the search activities of engineers, technicians, and inventors, they become central in the process of technology generation and selection. Again, the SSI proves to be more flexible in the selection of relevant actors and level of analysis.

Finally, given the conceptual links between the SSI approach and evolutionary economics, it is interesting to point out that, differently from the orthodox approach, the aggregation from individuals to firms is never additive. In fact, if on the one hand firms are a bundle of competences, capabilities, and routines, on the other not all of them are embedded in capital and workers (Nelson and Winter, 1982).

From the variety of actors considered it follows that the interactions among them are more complex. In particular, SSI recognizes the presence of both market and non-market relations; firms can collaborate creating networks for different purposes, and exploit their complementarities in endowments of competences. Clear examples of these are strategic alliances or joint ventures formed in order to benefit form firms heterogeneity.

Looking at the institutions, SSI, again, considers a larger number of both formal and informal institutions. Depending on the context, informal institutions, such as traditions and conventions, can bind individuals (and firms) as much as formal institution (e.g. the patent systems) (Edquist, 1997).

Following the definition, SSI provides a *"...multidimensional, integrated and dynamic view of sectors..."* (Malerba, 2002, page 248), and describing industry *structural evolution* means looking at how all the aspects reported in the last column of table 2.1 are changing over time. Ultimately, this means highlighting specific features of the industry dealing with different aspects of industrial dynamics, such as industry demography, heterogeneity of the actors involved in the industry and their behaviors, and the way innovation takes place (Nelson and Winter, 1982). In order to make the history consistent and comparable along time, chapter 4 will systematically focus on the five aspects listed below.

1. Market structure of the national and global industry
2. Barriers to entry
3. Market demand
4. Relation between relevant actors (manufacturers, operators, and governments)
5. Sources of knowledge

This list will be explained and further discussed in the introduction of chapter 4. However, we can already notice that some dimensions could pertain to the SCP or IO tradition (for instance, point 1 and 2). This is certainly true, in fact, we claim that what makes chapter 4 an account in the SSI tradition, is both the *joint* consideration of all these five dimensions, and the detailed analysis at firms level.

Finally, according to the evolutionary framework, technology and industry should co-evolve, reciprocally influencing each other. Given the multitude of aspects considered, all their possible links, and directions of causality, it becomes difficult to put forward testable hypothesis. Therefore, the rigorous and robust econometric analysis of co-evolutionary process represents a challenge for evolutionary economists. In this thesis, we are going to quantitively examine a specific aspect of co-evolution, focussing on firm's innovative behavior and performance. For this reason, the results obtained using the patent citation analysis will be also discussed from the assignee (i.e. firm) perspective and interpreted using the detailed account of firms' history presented in section 4.3.

Several studies have used the SSI framework for studying the telecommunication industry[9]. Furthermore, the article by Gaffard and Krafft (2001) explicitly put forward a comparison (stressing the divergence in expectations about the future of the industry) between a mainstream and an evolutionary approach to the study of the telecommunication industry.

As far as the author is aware, there are no studies concerning the *structural evolution* of the telecommunication switching industry from its infancy to recent years. However, some studies even if not explicitly pertaining to the SSI paradigm, emphasized some factors discussed in the previous pages within the SSI approach. These focus on: (i) firm's competences during the emergence of automatic switches (Lipartito, 1994), (ii) firm's diversification and integration as determinant of market success (Fransman, 1995), (iii) the relation to network operators and its importance for developing "transaction-specific assets" and the enhancement of manufacturers' technological competences (Sadowski, 2000), and (iv) the role of institutions, in particular public procurement, in steering the technological development of digital switching platforms (Llerena, Matt and Trenti, 2000). When relevant, the results of these studies will be incorporated in the account of the industry structural evolution between the late 1890s and 2000s (in chapter 4).

For concluding and introducing the next section, we would like to stress again the central role of technology (and knowledge). In particular, the link between technology and industry dynamics is twofold: on the one hand, the knowledge-base (and the technology) is what define the boundaries of an industry (Balconi, 1993); on the other hand, (Schumpeterian) patterns of innovation are endogenous and depend on technology characteristics such as technological opportunity, appropriability, cumulativeness, and characteristics of the knowledge base (Breschi et al., 2000). In this thesis we will make a micro analysis of a technological change focussing on cumulativeness.

2.3 Towards a micro view on technological change

The process of technological change and related issues have been studied in several scientific disciplines such as history, economics and sociology. These use different methodologies ranging from pure quantitative techniques (such as econometrics) to pure qualitative (such as narratives). Both extremes have some limitations; on the one hand an unsatisfactory representation of technological change and industrial dynamics, such as the one framed by the

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[9] For instance, in the book *Sectoral Systems of Innovation: Concepts, Issues and Analyses of Six Major Sectors in Europe* by Franco Malerba (2004), a chapter is devoted to late developments (fixed internet and mobil industry) of the telecommunication industry.

Structure-Conduct-Performance paradigm (see section 2.2), and on the other hand a lack of generalization of the results obtained. An authoritative historian of technology, Staudenmaier (1985) says:

> It is clear that both the designing and the maintenance of technological artifacts demand detailed attention to functional design constraints. [. . .] Technological activity does not occur outside this tension between design and ambiance (page 6)

This quote expresses the need to explore design characteristics of an artifact in order to understand its technological development and evolution. However, it is necessary to complement it with a description of the context, eventually the economic one. In this respect, the technological paradigms and trajectories approach includes both aspects (Dosi, 1982). This section is divided in two parts; the aim of subsection 6.2.3 is to introduce the theoretical framework used in this thesis and in particular to describe the conceptual departing from a neoclassical approach (and in particular from a cost-function view on technological change) and its advantages for our understanding of technological change. Given the empirical nature of this thesis, section 2.3.2 will review the empirical literature about technology evolution.

2.3.1 The theory

Neoclassical economics tends to reduce all socio-economical phenomena to a simple problem of maximization under constraint carried out by a representative agent. Innovation and technological change are not an exception; entrepreneurs maximize their production function[10] under the constraint of factor prices. The space of technology is represented as a nearly infinite combinations of inputs in order to produce the output. The choice of a particular combination is driven by changes in their relative prices.

Ultimately, this view on technological change makes it rather easy to answer the question *"What characterizes and drives the dynamics of technological change?"*, given the fundamental role of market as main driver. However, Devendra Sahal (1981*b*) observes:

> relevant patterns of technological innovation are primarily physical and only secondarily of a socio-economic nature. In particular, they remain unchanged over long periods of time despite changes in their environment (page 13)

This means that technologies (and artifacts) are not immediately responsive to changes in the economic conditions (and in particular to prices). Furthermore, Constant (1973) reappraises the economic motivations in the emergence of new (also radical) technologies, observing the

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[10] Production functions link inputs (generally two: capital and labor) with a homogeneous output. The common mathematical assumptions are continuity and continuous differentiability in all the variables. These allow for the exhaustion of the product and the use of isoquants.

independence of research[11] activities (and in particular the ultimate motivation of single inventors) from economic considerations.

Therefore, we need to depart from the *monolithic* market approach and, as the famous metaphor by Rosenberg suggests, we need to open and explore the *black box* of technological change. This means considering technological change as a complex phenomenon involving the co-existence and interaction of both technical and socioeconomic factors. The understanding of technological change is related to the understanding of its underlying technical details (e.g. degree of complexity of an artifact, measures of performance), the agents involved in the innovative process (e.g. inventors, firms, research centers), and the general economic context (Rosenberg, 1963; Rosenberg, 1982; Rosenberg, 1994; Abbate, 1999).

The focus on technical features implies the presence of an *inner dynamics* in technology, which might hamper (or even prevent) prompt responses to market changes. Furthermore, unraveling this *inner dynamics* of technology entails departing from a simple definition of technology as "applied science", and focusing on its cognitive dimension; as Vincenti (1990) suggests technology is "engineering design knowledge".

Focusing on the cognitive dimension and the design of technology allows broadening the research agenda on technological change, looking at (1) "how and where" technological change originates and takes place, (2) its rate of occurrence, and (3) its direction (Dosi, 1982; Mowery and Rosenberg, 1979). In order to understand these crucial issues there is the need to develop what Devendra Sahal calls a "microview of innovative activities[12]".

Again, departing from a "market driven approach" indicates the recognition of some limitations in technological advances. These boundaries have different natures, firstly, they can be cognitive if they are related to the personality and background of entrepreneurs and engineers[13]. Second, there are some limitations in the flexibility of production techniques[14], the way an artifact is designed, and possible technological bottlenecks.

A meaningful and realistic approach to technological change should consider all the above features and complement technical aspects with economic considerations. In this respect new theoretical concepts are needed and in this spirit, the concept of technological paradigm was elaborated from the concept of scientific paradigm. The philosopher Thomas Kuhn, who first introduced the scientific paradigm, defined[15] it as a: *"constellation of beliefs, values,*

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[11] Following Constant (1973), the word research always refers to search activities related to the new paradigm (see below for a definition).

[12] In this respect, section 1 of chapter 9 of its Patterns of Technological Innovation (1981*b*) is called "Toward a Microview of Innovative Activity".

[13] In this respect see all the literature about routines and cognitive bias.

[14] This implies, for instance, a limited degree of substitution between factors in a production function. This observation, coupled to aggregation problem and the heterogeneity of the capital stock, originated the Cambridge controversy in the 1960s.

[15] It is worth noticing that one of the early critiques of Thomas Kuhn's book was the "flexibility" of the concept of paradigms, which was used in 21 possible definitions. The philosopher addressed this criticism in the postscript to the second edition in 1967 (Lakatos and Musgrave, 1970).

techniques and so on shared by the members of a given [scientific] community" (Kuhn, 1962)

This concept was translated to technology by Constant (1973), who wrote:

> A technological paradigm [...], like a scientific paradigm, is also rationale, practice, procedure, method, instrumentation, and a particular shared way of perceiving a set of technology (page 554)

According to this definition, as the scientific paradigm cognitively limits the scientific community, the technological paradigm characterizes (and limit) the conceptual and research space of a specific technology.

This theoretical model of technical change was ignored for some time until the publication in 1982 of the paper *Technological paradigms and technological trajectories* by Giovanni Dosi (1982)[16]. In this seminal paper a new theoretical framework is proposed, where the concept of technological paradigm is coupled with that of technological trajectories. In particular, technological paradigm is defined as:

> [a] 'model' and a 'pattern' of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies' (Dosi, 1982)

Although the two definitions are formulated differently, they both stress the *shared* and *binding* nature of the paradigm. In fact, if we think about technological change as a series of "problem solving activities" carried out by engineers, (technical) solutions emerge from their technical (and cognitive) background. Therefore, this engineering search provides the motion and steer the process of technological change. It follows that the technological paradigms set the boundaries of all the possible solutions.

Given the set of all these technical solutions, only a small number is actually undertaken. These are represented by the concept of technological trajectories.

> A technological trajectory, i.e. to repeat, the "normal" problem solving activity determined by a paradigm, can be represented by the movement of multi-dimensional trade-offs among the technological variables which the paradigm defines as relevant (Dosi, 1982)

Again, given all the technical possibilities, technological trajectories indicate what is actually selected and implemented; it follows that their conceptual function is to indicate the direction of the technological change within the technological paradigm.

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[16] It is actually interesting to note the discrepancy in the citations received by the two articles. In a simple search in Google Scholar on the 28^th February 2009 Constant's paper received 10 citations, whereas Dosi's 1640.

Going back to Staudenmaier's quotation, the analysis of a trajectory (as above defined) highlights the selection mechanism and the features of the tension mentioned[17].

The concept of paradigm introduced above can be deconstructed and made explicit through *heuristics*. Following the philosophical parallel these heuristics represent the rules engineers apply (or do not apply) in their research. They are the "search strategy" followed in exploring the technological space defined by the paradigm. In Dosi's (1982) word:

> a technological paradigm embodies strong prescriptions on the directions of technological change to pursue and those to neglect (page 152)

Examples of these heuristics can be: "in order to increase the efficiency of a steam engine, increase the rate of expansion" or the famous "Moore's law"[18] which prescribes miniaturization in order to increase memory capacity. Given a specific technology the understanding of the underlying engineering heuristics (and by extension the understanding of an artifact's technical aspects and design) is crucial for explaining the emergence of trajectories and new paradigms.

Summarizing, the "paradigms and technological trajectories" framework accounts for three specific characteristics of technological change:

1. the *local* nature of technological change, meaning that firms explore a limited portion of the available technological space;
2. the inherent *cumulativeness* of the innovation process along specific trajectories;
3. the *irreversibility* of technological change, as it is driven by its *inner dynamics*.

The parallel between scientific and technological paradigm holds also in the "dynamics": just as scientific paradigms can shift, technological paradigms could also undergo major transitions that bring about technological discontinuities and the rise of opportunities (Constant, 1973; Dosi, 1988*a*). However Constant notices that the necessary conditions for a technological paradigm shift are different from the ones needed for a scientific paradigm shift; in fact the former can take place if and only if an alternative candidate paradigm is available (Constant, 1973).

From a different perspective, shifts of technological paradigms or trajectories are also related to the extent of a technological advance, where a paradigmatic change represents a radical change (as it affects also the cognitive domain of the actors), whereas the technological

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[17] It is worth noting that, although the concept of technological trajectory was firstly presented in the paper by Dosi (Dosi, 1982), similar concepts have been present in earlier works. The two most notable examples are natural trajectories (Nelson and Winter, 1977) and technological guideposts and innovation avenues (Sahal, 1985).

[18] According to Moore's law, the number of transistors that can be placed inexpensively on an integrated circuit has increased exponentially, doubling approximately every two years

trajectories represent an incremental and gradual refinement within the existing paradigm. In this view, a paradigmatic change brings about the reshaping of the technological space, as well as of the heuristics. In a new search environment, what engineers search for and the way they reach for it will mutate (Vincenti, 1990). It is worth pointing out that linking paradigmatic shift to radical change and technological trajectories to incremental change does not undermine the relevance of the latter. On the contrary, the literature has often stressed the importance of incremental advances and adjustments after a radical innovation for the success of a technology or an innovation (Silverberg and Verspagen, 2005; Verspagen, 2007).

2.3.2 The empirics

The theoretical articulation of the concepts of technological paradigms and trajectories has been followed by some attempts to investigating them empirically. This type of analysis implies the re-conceptualisation and operationalization of the those concepts in something measurable. Besides this, a second difficulty emerges from the availability and systematic collection of the required data.

Before looking at these works, originated by the seminal paper by Metcalfe and Saviotti (1984) it is worth discussing a related research topic; the early literature about technology output measures. This digression is necessary in order to both place the "paradigm and trajectories view" in the right epistemic context and to understand the roots of the empirical literature about technological evolution (pre-Metcalfe and Saviotti's approach).

A way to tackle the problem of how technologies emerge, evolve and diffuse is looking at its "measurable" dimensions. In this tradition we can find attempts to typify technological evolution (Van Wyk, 1979) or to find "invariant" patterns of technological change, such as learning-by-scaling (Sahal, 1985). Furthermore, the need to assess the efficiency of R&D programs (looking at their productivity comparing input and output) fostered research about the elaboration of performance measures for new technologies. If on the one hand the focus on performance of a new artifact or technology is straightforward, practically only very simple devices have an unique indicator of performance. Given the problem related to the comparison of multiple indicators, the report *Research Into Technology Output Measure* (Gordon and Munson, 1981) prepared for the National Science Foundation represents an attempt to deal with the issue and the construction of an unique measure for the state of the art of a technology. Beyond the indicators obtained for two case studies (computers and antibiotics), this report constitutes a good review of the contemporary literature on the topic[19] and it reveals

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[19] The literature on the topic was rather scarce, however Appendix A reviews the existing literature and denote the use of several statistical techniques for aggregating indicators and different starting assumptions. The articles reviewed in detail are:

1. Sahal D. (1976) "The Generalized Distance Measures of Technology", in *Technological Forecasting and Social Change*, 9(2) 289-300
2. Dodson E. N. (1970) "A General Approach to Measurement of the State of the Art and Technological

the presence of rather scattered empirical efforts with no attempt to elaborate a theoretical framework around them[20]. Furthermore, it is interesting to notice, at the beginning of section 1.3, the authors' frustration in realizing not only the presence of multiple indicators but also the impossibility of compiling a comprehensive and exhaustive list. In fact, interviews with several experts in the field were not effective in agreeing on a unique list. However, given the numerous indicators, the authors suggest a taxonomy and they aggregate them into three groups:

1. Physical measures which "...describe [technology] in the way that a blueprint might..." (Gordon and Munson, 1981, page 22);

2. Performance measures which "deal with the use of the technology" (Gordon and Munson, 1981, page 22);

3. Production measures which capture the improvement in production processes (Gordon and Munson, 1981, page 23).

From these groups, the aim of the report is to compound all these measures in a unique indicator of *the state of the art* technology and, therefore, they go beyond pure indicators of performance and look at a broader spectrum, for instance evaluating also efficiency in production. However, in this early literature there is still no interest in looking at the eventual relations among these class of indicators, which was to be precisely Metcalfe's and Saviotti's contribution (1984).

In this fragmented and empirically oriented literature, the concepts of technological paradigms and trajectories provided a new theoretical framework. In fact, performance indicators look like a meaningful way to look at technological trajectories and detect technological ruptures (Christensen, 1993; Christensen and Bower, 1996). In this perspective, Dosi's seminal paper has two functions: on the one hand to provide a new theoretical framework for studying technological change accounting for its *inner dynamics* (which was discussed in subsection 6.2.3), and on the other hand to frame in a theory the fragmented (empirical) literature about technological output and evolution.

Advance", in |emphTechnological Forecasting, 1 391-408

3. Alexander, Arthur J. and Nelson, R. J. (1973) "Measuring Technological Change: Aircraft Turbine Engines", in *Technological Forecasting and Social Change*, 2(5) 189-203

4. Denver Research Institute (1978) "Methodologies for characterizing technologies", EPRI-EA320 (Palo Alto, CA Electric Power Research Institute

5. Lienhard J.H. (1979) "The Rate of Technological Improvement Before and After the 1830s", *Technology and Culture*, 20(3) 515-530

[20] An exception is the article by A. J. Alexander and J. R. Nelson (Alexander and Nelson, 1973) where an analytical model based on technology production function and R&D expenditures is presented.

In this dual perspective, the seminal paper by Saviotti and Metcalfe (1984) bridges these two functions by proposing to focus on two set of indicators, one accounting for the technological performance and the second for technical design, and on the relation between them. The evolution of these indicators and the evolution of their relations gives a representation of technological change and therefore, by extension, of technological trajectories. In particular, this approach, partially departing from the list of measures presented above, focuses on two sets of relevant characteristics: technical characteristics and service characteristics. The former refers to specific technical specific features of a product, for instance, looking at cars (the example presented in the original article), technical characteristics could be the number of cylinder of the engine, the type of transmission, different braking systems, etc. These features are under the control of producers, therefore they pertain to the domain of supply. Service characteristics refer to the way a product fulfill consumer needs; again, in the case of the car, these might be the speed, the comfort, the number of passengers, etc. Clearly, these pertain to the domain of the users, hence to patterns of demand.

The description of these characteristics highlights the similarity with the classification proposed by Gordon and Munson (1981), reported in the previous pages. However within this framework it becomes clear that these different characteristics cannot simply be compounded as the former affects the latter in a way that depend on the nature of the technology and on the design. Furthermore, these relations can be mapped as sketched in Figure 2.1.

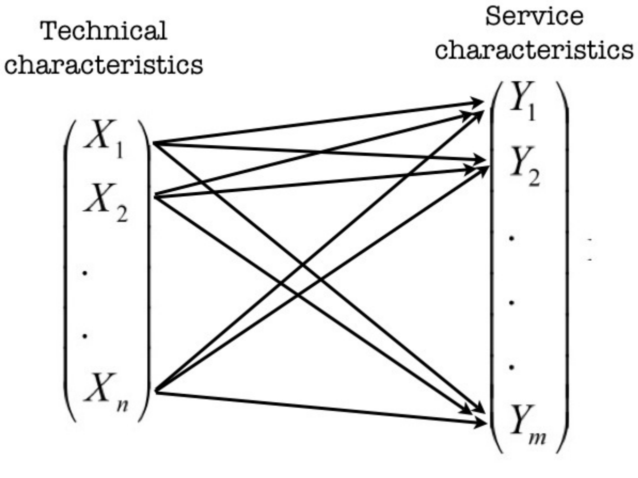

Figure 2.1: Representation of a product as two sets of characteristics, technical and service, and a pattern of mapping. Source: Metcalfe and Saviotti, (1984)

In this framework, technological advance can take place not only through advances in the two sets of characteristics (changes in the element of the vector in the figure) but also in the way they are connected (the arrows of the figure). Therefore, technological trajectories can be defined as the pattern of improvements of technical characteristics that determines an overall improvement in service characteristics, and therefore in the overall performance. It is interesting to notice that if on the one hand this approach deals with the issue of providing an operative definition of technological trajectory, still, the choice of the data source and of the way these characteristic can be aggregated in an unique indicator remains open. In fact, the need to reduce the n and m characteristics (see figure 2.1) to a single indicator puts forward two problems: first how to determine the weights of each individual characteristics and secondly how to relate and map the two sets of characteristics. The authors tackle the first issue suggesting two strategies: the contribution of each characteristic should depend either on its relative contribution to the pattern of use of a technology[21] or on the relative changes in the various dimensions of the technology itself (following Sahal (1976)).

This framework stresses the role of the interdependencies between technical and service characteristics, and it focuses on the functional and design aspects of an artifact. However, the concept of *inner dynamics* introduced before is rather overlooked although it might be assimilated to the map of characteristics relation and its stability over time.

This approach has been applied to study the evolution of some technologies through the analysis of characteristics' evolution; for instance, Saviotti and Trickett (1993) study the evolution of the helicopter. The analysis is carried out using empirical data about technical and service characteristics for 152 helicopter models introduced between 1940 and 1986. The "pattern of correspondence/imaging between technical and service characteristics", that means the identification of the arrows in figure 2.1 is identified calculating correlation among the variables and regressing service characteristics on technical characteristics. The analysis of links between the set of technical and service characteristics can highlight the presence of technical trade-offs. These are common in artifacts where a change in a technical characteristics can have either a positive or negative effect on single service characteristics, eventually determining an overall negative effect. Finally principal component analysis is used to reduce the numerous characteristics considered and to highlight some trade-offs mentioned before. In the three periods considered, two components were extracted: the first one could be interpreted as the size of the helicopter and the second one as the range. This suggests that any improvement regarding the size of the helicopter is at the expense of the range. Moreover, the plotting of the evolution of the helicopter models in the principal components space allows one to point out at what characteristics become more important in each period. This means that the plots depict the evolution of engineering heuristics in the technology.

A similar methodology (differing in the cluster analysis techniques) is applied by Castaldi et at. (2009) to tanks. The technical literature suggests the presence of two important service characteristics: mobility and battlefield capability. The presence of a design trade-off becomes clear as for a long time it was impossible to increase the performance in one of the characteristics without reducing the other; more battlefield capabilities was related

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[21] As noticed by the authors this approach is not new as it can be assimilated to the early work on product characteristics (Lancaster, 1966) and hedonic price method (Griliches, 1971).

to an increase in armour thickness and therefore weight. This emerges also from the data and through cluster analysis it is possible to see the evolution of the technology and in particular it is possible to appreciate over time the change of priority between these two service characteristics.

Still in the conceptual line proposed by Metcalfe and Saviotti, an attempt to tackle the issue about the mapping of the relations between technical characteristics and service characteristics is provided by the $N-K$ model (Frenken and Nuvolari, 2004). This model was developed in biology for studying complex systems such as the dynamics of population evolution[22]. However, as pointed out by Frenken (2000), this model is content-free and can be used to generally study "...the implication of the interdependencies..." (Frenken, 2000, page 257). Therefore, as the $N-K$ model was applied to mapping the relations between genotype and phenotype, it can be used to map the interdependencies between technical characteristics and service characteristics.

For explanatory purposes we can re-interpret figure 2.1 from a $N-K$ perspective. That system has n design dimensions performing m functions and the number of interdependencies is n as all the functions are affected by all the design dimensions. The set of all the possible combinations of design dimension (in biological term, the alleles), determines all the possible designs and therefore the design space[23]. Each design is evaluated according to its "fitness", which is function of all the individual fitnesses (indicated with Y_i in figure 2.1). It is worth noting that figure 2.1 represents an extreme case of $N-K$ model where $N=K=n$ meaning that all the functions depend on all the design dimensions. For example, in the case of a car this would correspond to a design where speed, comfort, number of passenger, etc. are all simultaneously dependent on all the set of technical characteristics. This is generally unwanted as designers try to optimize/reduce the number of interdependencies in order to have a more flexible design (see for instance the structure matrix approach (Murmann and Frenken, 2006).

The generalized version of the $N-K$ model relaxes the assumption about K, which is

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[22] The original model was presented by Kauffman in the book *The origin of Order. Self-Organization and Selection in Evolution* (1993)

[23] For instance, in the empirical application of the $N-K$ model to the steam engine by Frenken and Nuvolari (2004), N is equal to seven. These are:

1. Low or high pressure;
2. With or without separate condenser;
3. Single or double acting;
4. Not compounding or compounding;
5. Reciprocating or rotary or water returning;
6. Open or close top;
7. Single or double cylinder.

Given this setting, where six designs dimensions have two alleles and one three, the number of possible designs is 2^6 x 3=192.

not the same for all the design dimensions. In this case the pleiotropy of a design dimension is the number of functions that are affected by a change in that design dimension (the number of outgoing arrows in figure 2.1), whereas the polygeny of a function is the number of design dimensions affecting it (the number of incoming arrows in the same figure). It is worth noticing that recent literature about complex system re-conceptualized the idea of dominant design in term of pleiotropy; in fact if the cost of changing a design is proportional to its complexity (and in particular to the pleiotropy of its functions) and we re-conceptualize the "dominant design" as a design "highly-costly-to-change" an established set of design dimension with high pleiotropy will constitute the core of an artifact and it will be therefore part of the dominant design. This definition is particularly useful in the case of complex artifacts, where the dominant design can emerge also at "lower" level (i.e. the components ore subsystems) (Murmann and Frenken, 2006).

Given all this, the $N - K$ model posits a multidimensional design space and a fitness landscape, where actors search for local optima, from which it is not possible to reach another design with higher fitness. These search paths towards a local optimum can be interpreted as a technological trajectory.

Frenken and Nuvolari (2004) applied the $N - K$ model to the case of the steam engine. They noticed that only 13 out of the possible 192 [24] were actually produced. Again this proves a limited and therefore selected exploration of the technological space. Beside their results[25] it is interesting to look at their use of the $N - K$ model and their variables in order to assess to what extent their search path is actually a representation of a technological trajectory. The first characteristic considered relates on the possibility to have a "low pressure" or "high pressure" steam engine. The latter was invented in the second part of 1790s by R. Trevithick and its main advantage (in respect to previous designs) was the reduced size that made this model appealing for specific uses such as transportation. This mutation looks like a simple change in design characteristics, however, as the engineering communities working on this specific feature of the design were not communicating, it represents a paradigmatic change (as they were not sharing a cognitive background (Dosi, 1982)).

All the methodologies presented in the previous pages rely on the seminal paper by Metcalfe and Saviotti (1984) and their concepts of technical and service characteristics. Recently, a new research line based on completely different conceptual assumptions (and data) has emerged. In particular, the new methodology looks at the identification of technological paradigms and technological trajectories from the industry knowledge base perspective. Following Dosi (1999), technological paradigms differentiate according to the knowledge and

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[24] See footnote 23

[25] Their results focuses on tracing the interdependencies (in broad sense, they calculate the K in the case of the steam engine), highlighting the presence of "design trade-offs". Furthermore, they analyze the sectoral distribution of designs in order to highlight the use of specific designs for specific (economic) activities. Their results show the presence of both inter and intra sector variety, in particular after the 1780 several designs were used in each sector.

heuristics they rely upon. Therefore the analysis of a technology knowledge base (and its evolution) sheds some light on the underlying paradigm and its eventual shifts. In this perspective, the empirical analysis is carried out by using patent data and patent citation networks using a set of relevant patents representing the knowledge base of a technology.

Patents are a set of exclusive rights granted by a state (national government) to an inventor or his assignee for a limited period of time in exchange for a public disclosure of an invention. This means that patents carry a lot of information about the innovative process, such as: who is the inventor, who is going to economically exploit the innovation (the assignee), the time (file and issue date), and the field of the innovation (technological classes). These information can be used to empirically study the innovative process, however, the patent provides also a description of the innovation. They therefore also provide qualitative data that can be used for tracing the engineering heuristics we mentioned before. The use of the qualitative data embedded in a patent represents a novelty both respect the empirical studies just reviewed before (in the field of empirical representation of technological change) and respect the established use of patents as innovative indicators. However, we have to point out the existence of trade-off affecting the disclosure function of patents: firms want to disclose just enough information to have the patent granted and retain sufficient advantages over their competitors. In this respect, patents rarely represent a full technical disclosure, however enough for the investigation of engineering heuristics. Another type of crucial information provided by patents regard citations to previous patents and therefore the patent's *prior art*. This constitutes all information that has been made available to the public in any form before a given date that might be relevant to a patent's claims of originality. Therefore, a citation establishes a knowledge flow between patents and therefore links two pieces of technology. For this reason, a patent citation network can be considered a network of knowledge flows connecting different pieces of technology. In chapter 5 more attention will be devoted to the use of patent and citation data.

The analysis presented in chapter 5 belongs to this strand of research, therefore section 5.3 will address the methodological and computational details. Here we just sketch the conceptual description in order to appreciate and discuss its differences with previous works. The analysis of the connectivity structure of the patent citation network allows one to identify a set of patents which constitutes the main flow of knowledge[26], which is consistent with the idea of a technological trajectory.

It is worth noting two things about this method: first, the identification of a technological trajectory as a series of patents and their citations stresses the incremental (and local) nature of technological advances. In fact, this approach uses the "problem-solving" information embedded in a patent and links it to previous technological developments in order to show an ordered path of local, cumulative, and irreversible technical change. In this sense, it satisfies the definition of technological trajectory put forward in the previous pages. Furthermore, the

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[26] See subsection 5.3 for what "main flow of knowledge" in this context exactly means.

linking through a series of subsequent “problem solving” activities seems the perfect way to describe a technological space, and the qualitative research of the most connected patents can unravel the heuristics followed by engineers.

The second observation regards the use of patents for studying a technology knowledge base and the understanding of what part of the knowledge base patents actually capture. From the literature, it emerges that technology knowledge base can be characterized in several ways such as looking at its complexity, degree of tacitness, and proprietary nature (Winter, 1987; Nelson, 1992). In particular, combining the last characteristics we can distinguish four types of knowledge bases displayed in figure 2.2.

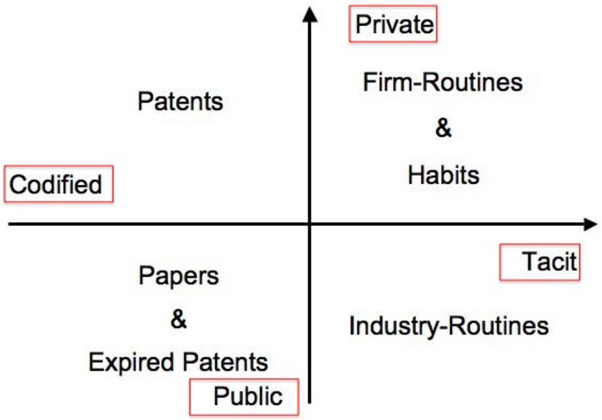

Figure 2.2: Representation of knowledge base

The first quadrant represents private and codified knowledge. Patents are an example of it, whose aim is to disclose information (therefore they are codified) but which represent proprietary knowledge. Continuing on the right side we can find firm routines and habits that are private and tacit; in fact they are firm specific and difficult to transmit. In the lowest quadrants there is the public knowledge base, both private and public. An example of the former are scientific papers and the expired patents; they both disclose novelty, however they are public and therefore they can be freely used. Finally, in the last quadrant industry routines and practices represent an example of public and tacit knowledge.

This figure shows that patents account only for a fraction of the whole knowledge base of an industry. The importance of this fraction is industry specific as it depends on the propensity of patenting of an industry.

This approach to the knowledge base establishes the link with industrial dynamics and section 2.2. In fact, as we can use patent citation networks for studying industry knowledge base dynamics, we can extend the analysis to the industry technological regime.

Recently some articles have used the connectivity measures and a search algorithm proposed by Hummon and Doreian (1989) in order to identify the main flow of knowledge within a patent network[27] for mapping knowledge evolution. These articles can be divided into two groups depending on which of the aspects just described they focus on.

For instance, Verspagen's recent paper (2007) applied this method to the case of fuel cells. His focus is primarily methodological, as it is the first attempt to use this algorithm in a patent citation network. However, in analyzing the series of important patents, he is interested in showing the engineering side by looking at the technical contents of the patents. This allows him to identify the emergence and decline of streams of research and technical solutions. Finally, he explicitly links these series of patents with the concept of technological trajectories defined by Dosi (1982). The work by Fontana, Nuvolari and Verspagen (2009) is nested in the same research line, studying LAN technologies. In particular, they look at the engineering dynamics in a large technical system such as a computer network and they look at the emergence of technological bottlenecks that can jeopardize or slow the innovation process. Furthermore, this article shows the advantage of using patent citation networks over simple citation counts[28].

Other contributions (Mina, Ramlogan, Tampubolon and Metcalfe, 2007; Mina, 2008) focus more on the aspect of knowledge dynamics and are interested in examining how scientific and technological knowledge co-evolve in the search for solutions of emerging problems, in medical innovations. It is interesting how these works, despite using the same search algorithm, the same methodology, do not very explicitly investigate technological trajectories evolution.

What both sides of the same method recognize is the need to couple quantitative research with in-depth qualitative research through the use of interviews and technical literature. In this respect, this methodology fulfils the methodological suggestion by Sahal (1981*b*; 1981*a*) of focusing on the investigation of the technology *inner dynamics* and departing from both a pure theoretical approach (characteristic of the neoclassical approach) and an empirical one (dubbed "Pythagorean").

2.4 Conclusions and research questions

The aim of this chapter was to provide the general theoretical background to the thesis. We use the word general because this review is not exhaustive of all the research topics covered,

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[27] As we will see, the original article studies the literature about the discovery DNA. However, as the conceptual assumptions hold, the same method can be applied to patent citation network. Furthermore, the differences with this original article will be highlighted in the next section.

[28] Further on this point in Chapter 5.

but it is meant to underpin the general assumptions recurring in the whole thesis. However, some chapters will have a more specific literature review.

The first general assumption is the choice of the level of analysis, which is the industry. As pointed out in section 2.2, this is not obvious for orthodox economists, but it becomes so for an evolutionary one. This follows from the empirical observation that industries differ because they deal with different technologies and knowledge. Therefore the mesolevel is meaningful for improving our understanding of the link between technological change and industrial dynamics.

The second general assumption follows from the previous point and regards the existence of a technology *inner dynamics*. It follows that technologies do not instantaneously adjust to market changes and engineers (through search heuristics) have a primary role in shaping them. In this respect section 2.3 covered the literature about technological paradigms and trajectories. Furthermore, in that section an other topic was discussed, which is the empirical representation of technological change. It deserved a place in this general review not only because of its links with the theory but also because much of this thesis deals with the empirical analysis of technology dynamics. It was therefore important to clearly state how the use of patent citation data differs from, and adds to, the existing literature.

To conclude this chapter we are to state the research questions which can be grouped in three.

1. HISTORY STORYTELLING (IN THE TELECOMMUNICATION SWITCHING INDUSTRY). At several points of this thesis we stressed the importance of the work done by technology historians in unfolding the drivers of technological change. In particular, this type of qualitative research shed some light on technology *inner dynamics* and engineers' research strategies to overcome technical bottlenecks. In this thesis we use secondary technical literature such as technical books, journals, and patents in order to reconstruct the way research and development took place in the telecommunication switching industry. In this respect the research questions can be formulated in this way:

    - *From a pure engineering perspective, how can we characterize technology dynamics in the telecommunication switching industry? What are the recurrent engineering heuristics?* In chapter 3 we present the long term history of technological development with the aim of identifying specific technical bottlenecks. In chapter 5 we will re-frame the technological history focusing on the evolution of engineering heuristics.
    - *From the study of technological change in the telecommunication switching industry, can we clearly map the relation between technical and service characteristics?* Answering this question will show to what extent we can focus on performance indicators for the study of technological advance in this industry (chapter 3).

2. Appreciative theorizing. If on the one hand appreciative theorizing is less rigorous than formal theorizing, they are complementary in nature. In fact, it is from appreciative theorizing that research questions emerge and then eventually tackled using formal modeling (Nelson, 1989). In this thesis the case of the telecommunication switching industry is examined. It represents an interesting case because it allows to shedding some light on the relation between technology and industry evolution in an oligopolistic and regulated sector.

    - *What are the consequences of the interplay of both technical and institutional barriers to entry? In this setting, to what extent does radical technological change provide an opportunity for newcomers?* This aspect is examined in chapter 4 and section 5.6. The first provides an account of the *structural evolution* of the telecommunication switching industry, and the second examines the patent citation network from firm's perspective.
    - *Given the low number of firms, their common ancestors, and tight links, to what extent do we observe firm heterogeneity?* The limited number of players in the industry allows for their qualitative and quantitative analysis. In particular, in the second part of chapter 4 companies are compared accordingly their national context, their degree of internationalization, their degree of specialization, and finally, market success in the digital switches.

3. Empirical analysis of technology evolution. The third field of contribution is the empirical representation of technological change using patent citation data. Patents represent a source of (systematically) available micro-data about technology, therefore their use looks like a natural choice for the analysis of technology micro-dynamics. As a patent citation network represents an industry knowledge base, network techniques can be used to study technology and industrial dynamics. However, patent citation networks are directed and acyclical, meaning that "classic" social network analysis is not suitable and new analytical tools should be developed. Given the nature of citation (i.e. a knowledge flow) network structural characteristics can be informative about knowledge characteristics and dynamics, and in particular about the extent of cumulativeness and persistence. Finally, the grace of the proposed methods is the possibility to integrate quantitative and qualitative research. In this respect, the explicit research questions are:

    - *Given the difficulty of evaluating (and comparing) telecommunication switches' performance, how can we evaluate the extent of technology dynamics?* In this thesis the notion of radicalness is related to the knowledge side (rather than the performance side). Therefore, patent and citation data are used for assessing the inventive step occurred. Chapter 5 and 6 show two methods for mapping and studying the emergence of new technologies.

- *Does the patent citation network provide a meaningful representation of the technological space? If yes, how can we link its structural characteristics to cumulativeness and radicalness of technological change?* The answer is provided in chapter 6 with the introduction and use of the persistence and thickness indexes.

Part II

Technology and Industry Evolution

Chapter 3

Technical Change in the Telecommunication Switching Industry

3.1 Introduction

The aim of this chapter is to examine technological change in the telecommunication public switches industry from its origin until the recent years. This account provides the (technical) background knowledge and the engineering narrative against which compare (and validate) the results obtained with the patent citations network analysis exposed in chapter 5.

History of technology can be approached from three main perspectives: internalist, nonhistorical, and contextualist (Staudenmaier, 1985). Each of these focuses on different aspects; for instance, in the internalist approach the focal point is the artifact and its design whereas the contextual approach creates *"...historical syntheses of technical design and historical context..."* (Staudenmaier, 1985, page 11). By contrast, the nonhistorical approach refers to the research in social science (for instance in sociology or economics) that recognizes technology as a central factor of analysis. However, it rarely focuses on a single technological area, being interested in the broad concept of technological change and its effects.

In this chapter, the technological evolution of telecommunication switches is described using the internalist approach. This choice is driven by the belief (supported by interviews with engineers) that technological progress in the industry follows by and large a "challenge-and-response" pattern (Rosenberg, 1974), where engineers' research is driven by the emerging technical bottlenecks. In fact, because of the specific characteristics of the artifact (i.e. a capital good integrated in a large technical system, the telephone network), of the technical field, and of the industry (i.e. oligopoly), a great part of the technological development took place in R&D laboratories with little concerns for social and cultural aspects. However, this does not mean that technological development took place in vacuum and therefore chapter 4 is devoted to the analysis of the context where innovation came about.

This chapter starts with a description of the sources used and the existing literature about the history of telecommunication switches. The second section provides some general knowledge about telephone network structure and functions, in order to define exactly the type of equipment this work studies. The third section represents the bulk of the chapter reviewing all the switching generations. Finally, a summary with conclusions will follow.

3.2 About the literature

Before reviewing the technological milestones in the industry, it is essential to examine previous studies and the sources used for the following sections. In particular, the choice of the sources is strictly related to the purpose of this chapter. As anticipated in the introduction, the aim of this chapter is to provide the technical background for understanding technological advances in the telecommunication switching industry, so secondary technical sources will be mainly used.

If we focus on the broad topic "the telephone", numerous books and articles have been published about its development, diffusion, and social and cultural impact. If, on the other hand, we focus on telecommunication network technologies, the situation is different. In his book, Staudenmaier (1985) classified *Technology and Culture*'s articles and it emerges that by 1985 only 3 articles were published about telegraph and telephone respectively. For an invention considered one of the most important technological achievements, those numbers are very low. Repeating the exercise considering more recent publications numbers increase but still remain very low[1]; moreover, only one publication is about switching and it focuses only on the very early development of the so called switchboard (Mueller, 1989). From this exercise it seems that historians of technology so far have not paid much attention to the development of telecommunication infrastructure. We can hypothesize that historians of technology have taken a more holistic approach, focusing on the telephone as representative of the whole "telephone system". Moreover, the telephone itself might seem more interesting as it is the interface between the technological system and users (and therefore the society). For this reason, technological developments at the network level are consider only if they significantly improve or change the functionalities (for instance, mobile telephony or new telephone services) of the interface, which is the telephone. Finally, comparing the amount of literature about telephone and telegraph we can notice that the latter is a well-studied subject. This might be because the telegraph was the very first technology (if we exclude optical telegraph) that allowed long distance communication. Despite its success, at the very

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[1] A search in Jstor for *Technology and Culture* retrieved 14 articles with the word "telephone" in the title and 6 with the word "telegraph" (Site accessed on the 18^{th} July 2008) .

early phase its introduction was rather controversial. Its potential use for trading military secrets and for speculation in stock exchange market made its early adoption very difficult.

Leaving the contribution of history of technology and looking at the technical literature about switches[2] we can find different types of publications, these includes:

1. IEEE transactions and journals (for instance, *Transactions on telecommunication*). They constitute the technical relevant literature and the usual means for dissemination of technical developments among telecommunication engineers and scientists.
2. Books and reports published by national Post, Telegraph and Telephone (PTT) companies. The company itself in order to explain and describe the national context quite often publishes this books. An example of this is the famous *A History of Engineering and Science in the Bell System*, a multi-volume history prepared by members of the Bell Laboratories technical staff and published between 1975 and 1982[3];
3. Publications released by telecommunication manufacturers in order to advertise and describe their own switching platforms;
4. Books (very few, indeed) meant to broaden engineers' historical and national focus.

The review of the next section will mainly use secondary sources and in particular the last one listed before. The few books that can be included in the last category have proved to be exhaustive and extension of the previous three.

In this perspective, this chapter can be seen as an attempt to summarize (for a non-technical audience) the technological milestones in the industry.

A final remark is devoted to a single engineer who was very active within several sources listed above (type 1, type 2, and type 4) and placed lot of effort in trying to diffuse technical knowledge about different switching platforms among engineers. Amos Edward Joel, Jr. (1918-2008) is an American electrical engineer, known for numerous publications and over seventy patents related to switching systems. He worked at Bell Laboratories between 1940 and 1983 being involved in a broad range of projects from the development of electronic switches to developing mechanisms for optical switching. Because of his appointment and responsibilities, he was a privileged observer of R&D on cutting edge technologies in the switching industry. For the IEEE Press he edited *Electronic Switching: Central Office Systems of the World* (Joel, 1976) and *Electronic Switching: Digital Central Office Systems of the World* (Joel, 1982). These volumes collect several scientific articles (mainly published

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[2] For data about telecommunication and network development at country level, ITU (International Telecommunication Union) and OECD publish yearly reports.

[3] Note that this work was published for celebrating the Bell Centennial in 1976. Each volume of the series was meant to describe the contribution of the Bell Laboratories to different technologies and in different periods. The most relevant for this thesis are: Volume 1 covering the early phase of telecommunication switches (Fagen, 1975) and volume 3 entirely dedicated to them (Joel and Swindler, 1982).

into IEEE journals) describing by manufacturers (and therefore by extension by country) all the electronic and digital switching platforms. Among his less technical (and therefore more interesting for this work) we can find a two volume book *100 Years of Telephone Switching (1878-1978)* (Chapuis, 1982; Chapuis and Joel, 1990) published in 1982 and 1990 in collaboration with R. J. Chapuis. Finally, in the same years, he edited (together with G. E. Swindler) the volume related to the development of telecommunication switches at the Bell Laboratories included in the multi-volume book *A History of Engineering and Science in the Bell System* (Joel and Swindler, 1982).

For concluding, the review of the next pages is based on comprehensive guides and aimed to understand the technical and services characteristics of a telecommunication switches as an artifact and to describe the conditions and circumstances of technological change in the switching industry. This (undoubtedly partial) account constitutes the building block of section 5.4, where specific engineering heuristics will be discussed and the account of the next pages will be reframed into technological paradigms and trajectories.

3.3 Telephony network and telecommunications switches.

However important, the invention of the telephone by Alexander Bell in 1876[4] merely provided the invention for what now is called a terminal equipment. Soon after, in order to overcome the simple point-to-point transmission (and avoid the need for expensive dedicated, direct lines between all customers) the concept of telephone network was developed.

The evolution of the telecommunication network infrastructure (but this can be true for all network infrastructures such as electricity, railways, etc.) has been mostly driven by mere expansion in order to connect a growing number of subscribers and upgrading; therefore technological change in telecommunication infrastructures takes place through the incorporation of new equipment and new components. However, beyond the upgrading of single parts of the network, the conceptual idea and functions of telephone network were rather stable. In fact, the so called Public Switched Telephone Network (PSTN) changed very little for 100 years, and it is only in recent time evident the transition to the Next Generation Network (NGN)[5] boosted by the advent of internet and the need of high speed connection. Generally speaking, this transition and the (conceptual and physical) differences between the two networks will be the subject of the final part of the fourth section. As explained before, the basic features were rather stable over time and therefore we have chosen to take its description as the starting point of our history.

If we look at the PSTN as a technical system, we can distinguish between four subsystems and functions (Antonelli, 1995):

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[4] US patent 174,465 “Improvements in Telegraphy” filed on 14 February 1876.

[5] Sometimes referred as the transition from “plain old telephone service” (POTS) to “pretty amazing new services” (PANS).

1. Distribution system;
2. Switching equipment;
3. Transmission system;
4. Signaling subsystem.

Figures 3.1 and 3.2 sketch a very simple structure of the PSTN where it is possible to distinguish the enumerated the four subsystems.

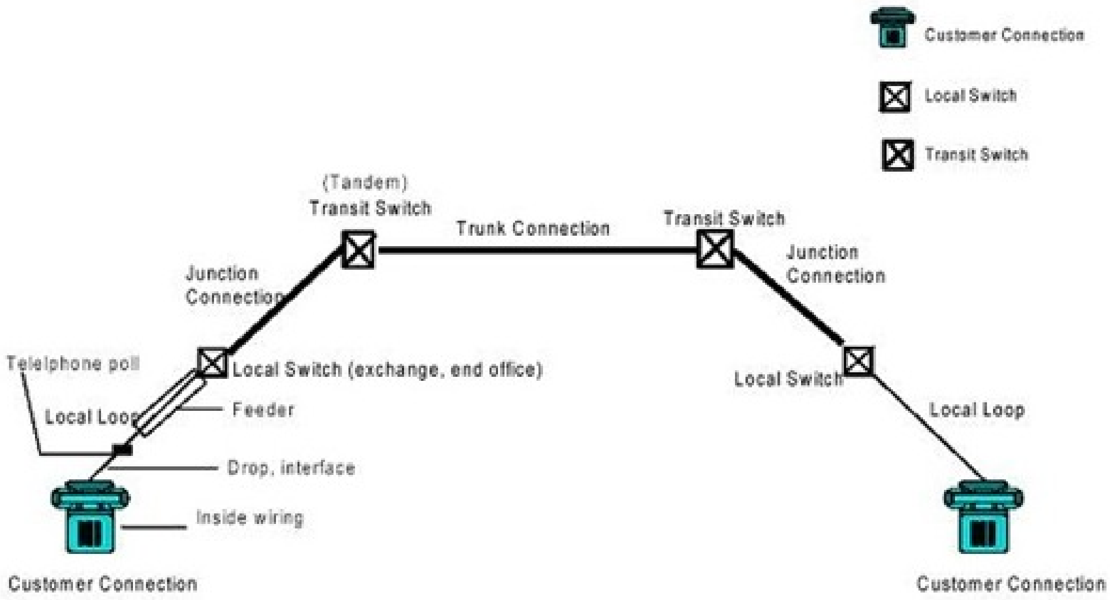

Figure 3.1: Representation of the PSTN

Source: http://www.ictregulationtoolkit.org/en/Section.2092.html

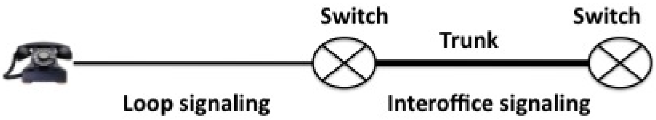

Figure 3.2: Signal function

The distribution system, often referred as the *last mile* (usually a twisted copper wire) is connecting terminal equipments (in this case, both telephones) to the local exchange, often called *local loop*. The switching system allows for terminating[6] phone calls without having direct connections among costumers. This subsystem includes both local exchanges, which directly connect to costumers' premises, and transit exchanges, which connect to other switches[7]. Furthermore, a tandem switch is a special type of transit switch used for long distance calls as it connects different parts of the network. The transmission system provides the connection between switches; in particular, a junction connects two switches in the same local network, whereas, a trunk refers to interurban connections[8]. Finally, figure 3.2 illustrates the role of signaling system. Using the word of a pioneer in the field, A. Jouty[9] a signaling system is: *"... a language which enables two switching equipments to converse for the purpose of setting up calls ...* (Chapuis, 1982, page. 306)" It is therefore the function that allows the exchange of information about the establishment and the control of a connection and the management of the network (in contrast to user information transfer). Depending on which part of the network signaling system is controlling you could find loop signaling (also called subscriber signaling) or interoffice (trunk) signaling (to which the above quote refers).

This brief description of a PSTN provides a starting point in order to understand what type of equipment is the subject of this chapter; it also provides the starting point in order to better appreciate what the transition to NGN implies.

To conclude, this chapter (and this thesis, by extension) is about technological development of wireline public switches, so mobile and Private Branch Exchange (PBX) are excluded.

3.3.1 Telecommunication switches

The *International Electrotechnical Vocabulary (IEV)* provides some official definitions that might be useful to report. For instance, it defines *Switching* as:

> The establishment, on demand, of an individual connection from a desired inlet to a desired outlet within a set of inlets and outlets for as long as is required (Chapuis, 1982, pag.17)[10]

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[6] In the telephony jargon, the word termination refers to the establishing of the connection between the caller and receiver.

[7] Switch, switching equipment and exchange equipment can be considered synonymous. They generically indicate a switch without qualifying its position in the network (as when words like local or transit are added).

[8] Please note that this terminology refers to the British and international context. In fact, outside the United States, the word "exchange" is considered to be a synonymous with "central office" or "office" (therefore a switch) whereas in United States it indicates a geographical territory served by one or more central offices where the same tariff (or fat rate) is applied (from here the name Local Exchange Company -LEC for indicating a local operator). In United States, "trunk" corresponds to "toll" (and "long distance" can be considered a synonymous for both). Again, "interoffice trunk" is the American corresponding of "junction"(Chapuis and Joel, 1990).

[9] Chairman of the CCITT (French acronym for International Telegraph and Telephone Consultative Committee) Study Group XI Telephone Signaling and Switching between 1968 and 1973.

[10] IEV code 714.11.01

The same source defines *Switching System*:

> A system for establishing connections from inlets to desired outlets and for supervising and releasing established connections (Chapuis, 1982, pag.17)[11]

An *Exchange (in telecommunication), switching office* is defined as:

> An aggregate of traffic-carrying devices, switching stages, signaling means and controlling means enabling incoming lines to be connected to outgoing lines as required by individual callers (Chapuis, 1982, pag.17)[12].

Finally, we can define *Switching stage* and *Switching network* respectively as:

> An aggregate of switches constituting a subset of the switching centre and designed to operate as a single unit from a traffic handling point of view (Chapuis, 1982, pag.17)[13]
>
> The switching stages of a telecommunication exchange taken collectively (Chapuis, 1982, pag.17)[14]

Figure 3.3 illustrates some of the above definitions. Each box represents an *exchange* or *switching office*[15]. The content of the boxes is rather stylized and the connection between the circles represents the *switching stage*. As it will be clear in the next section, the presence in each box of a single *switching stage* is an oversimplification of the figure. The collection of an exchange *switching stages* constitutes the *switching network*. Moreover, figure 3.3 is a simple schematic of one of the key PSTN switching principle: the circuit switching. The transition from PSTN to NGN can be seen as a transition from a circuit switched to a packet switching network (for an explanation see Technology box 4 below). Until the 1990s, virtually all switches were of the so-called circuit-switched type. The characteristic feature of these types is that the end-to-end connection is established at the start of the call, and remains in place until the end of the call. In addition, a fixed and exclusive capacity is allocated for the full length of the call. Circuit switching presents some advantages in term of routing computation[16] and Quality of Services (QoS). However, the circuits within the switch are not used in a very efficient manner as they are also occupied when there is no information to transmit (e.g. when one of the partners of the telephone conversation does not speak).

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[11] IEV code 714.11.03

[12] IEV code 714.11.04

[13] IEV code 714.12.01

[14] IEV code 714.12.04

[15] According to what explained before some are local exchange some are intermediate (local or transit) exchanges

[16] Routing algorithms calculate the most efficient path (e.g. the cheapest or the less loaded) through the network; circuit switching presents an advantages because the computation is performed only once when the phone call is initialized.

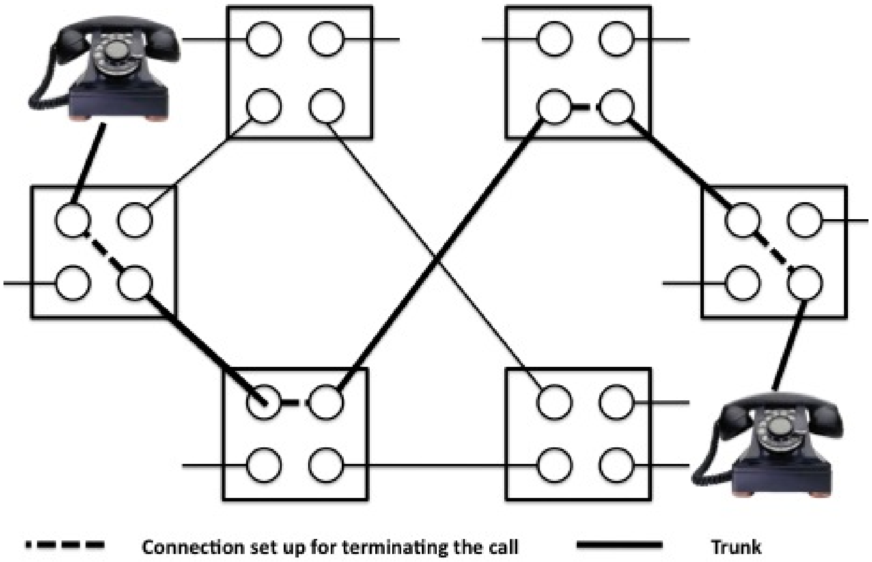

Figure 3.3: Representation of *Switching stages* and *Exchange*.

Despite its simplicity, figure 3.3 gives some hints about the complexity of telecommunication switches and about the fact that technological change did not take place only in the switching mode (i.e. from circuit switching to packet switching) but also at lower level, like the technology that established the actual connection in the switching stage (dashed lines). Following this point and switches being part of an infrastructure system, their evolution is strictly related on the one hand to component's evolution and on the other hand to other network subsystem evolution (in particular transmission).

Figure 3.4 illustrates this point showing the joint evolution of telecommunication switches, transmission, and semiconductors. Furthermore, the figure represents the convergences of these different trajectories, and in particular the recent convergence of telecommunications and computers. As transistors, integrated circuits (IC), large-scale integration (LSI), and very large scale integration (VLS) became available they would be incorporate in transmission and switching system. Moreover, as will be explained in the next sections, development in computer industry are fundamental for the development of the Storage Program Control (SPC), one of the landmark of the so-called electronic switches. Therefore, the long-term technological development in telecommunication switching industry is an interesting case of technological change driven by both internal and external forces. In particular, the availability of components and complementary technologies is fundamental for making a switch generation economically feasible. An example is the 30 years delay between the prove of feasibility and commercialization of digital switches because of the high costs of some electronic components (subsection 3.4.5 will elaborate more on this).

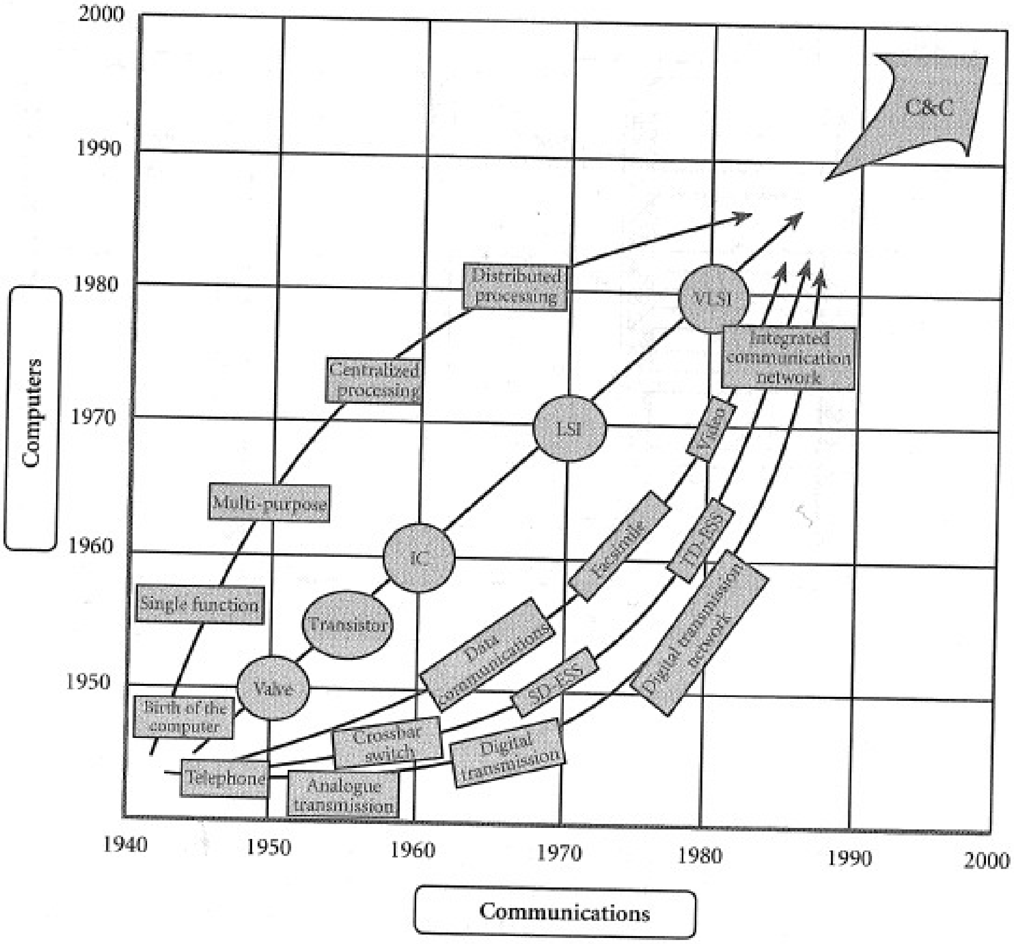

Figure 3.4: Evolution in telecommunication

Source: Mansell and Steinmueller (2000) citing Kobayashi (1980)

Finally, it is interesting to notice the evolution of the relation with one of these exogenous forces' originating industry, that is computer industry and in particular computer networking. The nature of this relation changed over time, it started as a co-evolution in term of component supply relation to finally become a real technological competition with the emergence of packet switching. In fact, the stable increasing demand for data transmission characteristics of the 1990s and the stable increase in bandwidth availability reinforced fierce competition between technologies offered by the two industries.

3.4 Technological change in telecommunication switches

This section reviews technological change in telecommunication switching industry between 1870s and early 2000s. The focus will be on the development of different switching platforms and, where necessary, the related technologies. Table 3.1 provides a summary of time development listing the type of technology used and the corresponding switching platforms.

Table 3.1: Technologies and switching platforms (time refers to their commercialization and diffusion)

Time Frame[1]	Technology	Model	Section
1870-1890	Manual switch	Switchboard	3.4.1
1889-1960	Electromechanical direct-control step-by-step system	Strowger, Lorimer, Rotary	3.4.2
1930-1965	Electromechanical indirect-control indirect-control or common control	Panel and Crossbar	3.4.2 and 3.4.3
1965-1975	Space-division SPC	Electronic switch	3.4.4
1970-1985	Time-division digital *centralized* SPC command	Digital switch	3.4.5
1980-1990	Time-division digital *decentralized* SPC command		3.4.6
1990-...	Packet Switching	ATM	3.4.7

Source: Adapted from Chapuis & Joel 1990.

[1] The time frame is just for reference, see the individual sections for more precise dates.

Before moving to the actually history of technology, we are going to discuss telecommunication switches' technical characteristics and some pitfalls related to their performance measures.

Telecommunication switches differ (both between and within generations) along several technological characteristics. In the books *Electronic Switching: Central Office Systems in the World* (Joel, 1976) and *Electronic Switching: Digital Central Office Systems of the World* (Joel, 1982), which collects several IEEE articles about specific switching models, we can actually see which ones company's engineers point out for each described model. From those books and other technical literature (related to previous generations) it emerges that the most referred characteristics are:

1. The **switching fabric**, which indicates the nature of the crosspoint, and the physical

mean throughout the connection within the switch is ultimately established;

2. The **traffic logic**, which regards the way the a call is planned, routed, and finally terminated. This aspect is related to the way the signaling function[17] is actually organized in the whole network and within the switching network;
3. The **multiplexing technology**, upon which depends the way in which this information is processed within the switch and how more than one circuit (and therefore more than one call) can actually be transmitted on a single cable;
4. The **nature of the traffic in the switch**, which relates to the characteristics of the information switched in the switching network;
5. The **nature of the service traffic**, which relates to the characteristics of the information switched in the telephone network;
6. **Technical components**, which refers to the components used in the switch and their characteristics and technology (e.g. analogue vs digital circuits);
7. Finally **signal to the end user**, which refers to the way a phone call is actually terminate.

These characteristics are rather general, despite they might not be relevant for all the switching platforms listed in table 3.1 (for instance, switchboards did not have “logic”). The history of technology presented in the next pages will focus on these dimensions.

The technical characteristics listed above bring about the possibility to determine several service characteristics, often assimilable to performance measures (Saviotti and Metcalfe, 1984). These become extremely relevant in the decision of adopting new switching platforms; for instance, new switches investments, beyond the direct equipment cost, are evaluated along several dimensions such as: (1) installation cost, (2) installation space (sometimes called floor space), (3) power consumption, (4) flexibility in adding capacity or extra features, (5) environmental conditions (e.g. needs of cooling system), and (6) maintenance cost (Danielson and Macurdy, 1982; Keister, Ketchledge and Vaughan, 1976). Each listed improvement could be measured using indicators, such as: number of circuits, number of lines (both local and trunk), space occupied or Busy Hour Call Attempt (BHCA[18]).

A collection of these indicators might give an idea of the general advance in performance, however, telecommunication switches were “tailored-made” products, not available “off the shelf”, and supplied through public tenders, in order to meet the specific needs of the network operators.

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[17] See chapter one for a definition.

[18] A unit to express the traffic capacity of an exchange when it is confronted by the heaviest traffic of high-traffic days.

Table 3.2: Digital local Switch: Max number of lines (thousands)

Company	Max Line
Alcatel (E10)	30
Northern (DMS 10)	7.5
ITT (System 12)	12
NEC (Neax 61)	100
Plessey (System X)	50
GTE (No. 5 EAX)	150
Average	58.25

Source: Joel (1982). Years are not reported but they refer to installation up to 1982.

Table 3.2 focuses on a specific service characteristic that is the maximum capacity of selected digital switching platforms; it shows a great variety of size and the coexistence of both small and large switches[19]. It is interesting to notice that the maximum number of lines for an AT&T No.5 Crossbar switch (a preceding generation) was 27,000-35,000 lines (Chapuis and Joel, 1990), smaller than the average digital platform, but still bigger than some digital switching models. Therefore, capacity alone does not seem to provide a good indicator to appreciate the extent of the improvements driving the technological change. It cannot be considered as a measure of performance because the statement "the higher is the capacity, the better is the switch" does not hold.

Following Frenken and Nuvolari (2004) the coexistence of different designs with a variety of service characteristics (and therefore product variety) depends on the level of uncertainty[20] and on the presence of diversified users. In the case of telecommunications switches coexistence is driven by both. For instance, the uncertainty about future development (and prices) of microprocessors delayed the introduction of digital switches, despite all the companies were already working on prototypes since years. The diversification of the users deserves some explanations; network operators (the users of the switch) might share some ideas about how demand was evolving or the new services customers wanted, however they relied on different legacy systems. This means that, overall, they were trying to achieve similar level of services however using different types equipments. In fact, each operator had its infrastructural legacy characterized by specific topology[21] extremely costly to change. For instance,

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[19] Note that all the switches in the table are local office, so comparable according to their level in the network.

[20] In particular, in the $N-K$ model uncertainty depends on the complexity of the technological landscape. The more complex is a technology, the more designs will emerge (Frenken and Nuvolari, 2004). See Chapter 2 for further details on the $N-K$ model.

[21] The topology of a telephone network depends on aspects such as the population to serve, its distribution on the territory, the trade off between switching and transmitting, and forecasts about network expansion.

once the local switch was placed and all the subscribers were connected through the twisted copper-wire (the already mentioned *last mile*), any relocation of the local switch is very expensive, unless a major network restructuring takes place. The lock in to different (network) topologies determines the demand for switches with different characteristics and fostering their co-existence.

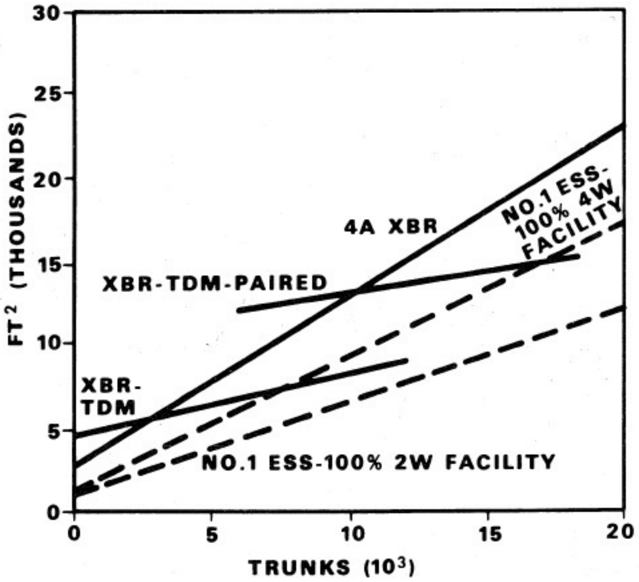

Figure 3.5: Tandem System Floor Space Comparison
Source: Joel (1976)

Going back to table 3.2, we can eventually explain the advantage of electronic switches looking at other dimensions; for instance, figure 3.5 gives a representation of the gain in floor-space moving from crossbar switches (indicated with XBR) to two different versions of electronic switches (the No. 1 ESS with 2 or 4 wires). For a wide range of size switch (x-axes), the use of electronic switches determined a gain in occupied floor-space.

3.4.1 The early phase: the manual switch

Switching techniques started in the 1870 for the telegraph network, with the purpose of connecting different national and international telegraph offices. In the earliest days of telephony, switching systems were manual: the caller (also: the originating party) used a ringer attached to the telephone set to attract the attention of the central office operator, to whom the caller gave the number of the desired user (also: terminating party). The operator, using a switchboard would first ring the receiver and then through-connect the two lines on the switchboard using patch cords with plugs at both ends. The first manual exchange developed from telegraph switching was installed at New Haven in 1878, serving 21 subscribers. With the increase in number of subscribers, diseconomies of scale emerged. Their source was the increasing complexity of the organization and control in the network[22]. In fact, each switchboard for reasons of space could only be connected to a limited number of subscribers and in order to connect subscribers from different switchboards a "transfer" connection was needed. In dense areas, with more subscribers, the use of these "transfer" connections and therefore the involvement of more than one operator was more likely. It was therefore noticed that the connection cost was increasing with the number of subscribers (Mueller, 1989). This problem was called the "switchboard problem" and the first solution put forward was the "multiple switchboard" developed in 1883. In this case, each operator was dealing with a limited number of originating users but in front of him/her there was an array of connecting jacks for every terminating subscriber. Therefore, one operator was enough for connecting all the subscribers in the same exchange. However, this solution implied technical developments in systems for testing the availability of receiver subscriber's line. At the beginning, messenger boys were used for sending "busy bulletins" or simply shouting the names of busy subscribers, lately subscribers' accessibility was tested by touching the sleeves of the jack with the plug tip of the operator's answering cord.

With the growing number of subscribers, switching functions (and therefore switching systems) became crucial for service operators and therefore several "switchboard conferences" were promoted. In 1892, exchange managers listed a series of recommendations, one of which stating that the making of a connection should be handled entirely by trained professionals and that "...any attempt to take the user into service and make him do a part of the work is a movement which is not in the right direction...."[23]. Retrospectively, this statement is very highlighting about AT&T mentality on costumers involvement and AT&T resistance in introducing automatic switches.

In the following years, switchboards diffused in the world and with the exception of Western Electric[24], they were mainly produced by artisans in small work-shops.

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[22] As noted in Mueller (1989) the number of circuits (N) needed to connect all the possible subscribers (S) does not grow in direct proportionally but at the more rapid rate of $N = S^2/2$. The presence of the switch avoids the deployment of all these physical connections but does not lower the number of all the possible combinations.

[23] Reported by Mueller (1989) as a transcript of the *Committee on Switchboards and Telephonic Apparatus* meeting held at the AT&T Co. office between 15-18 March 1892.

[24] Western Electric Company was an American electrical engineering company, the manufacturing arm of AT&T from 1881 to 1995 when AT&T changed the name of AT&T Technologies (in a very simple way what was left of Western Electric after the voluntary divestiture of the AT&T system) to Lucent Technologies,

3.4.2 The emergence of electromechanical switches

During the phase of improvement of manual switchboards, research on automatic switches blossomed; patents were granted and prototypes were built in the last decades of 19th century[25]. None of these attempts was successful, and, it was only in 1893 that the first automatic switch was presented at the International Exhibition in Chicago by its inventor Almon Brown Strowger (1839-1902). Strowger was an undertaker in Kansas City who, for enhancing the prestige of his business, was the first phone subscriber in his city. His major competitor not only became a subscriber as well, but had also a girlfriend working as telephone operator reverting all the business calls to him. Once the trick was discovered, Strowger tried to find a way to circumvent the "hello girl" (as the female operators were usually called) by designing a fully automatic telephone switch. The invention described in his patent [26] is about a selector that moves following electrical impulses sent by the caller, until it positions itself into the right contact. The contacts (in total 100) could be disposed in line or in a 10x10 matrix. Strowger and his nephew (Walter S. Strowger) produced their switching system in their new venture, the *Strowger Automatic Telephone Exchange Company*, and the very first Strowger switch was installed in La Porte (Indiana) in 1892. This switch implies changes in customer premises' batteries (one for calling and one for speaking) and two buttons for indicating the called number (one for the decades and the second for the units). Furthermore, it required six wires between the subscriber and the exchange (three for dialing, one for speaking, one for releasing the call, and one for the earth return).

The success of the Strowger system in the American market was determined by the massive adoption of this system by independent operators[27], outside the Bell Telephone Company and its subsidiaries[28]. The scarce interest displayed by AT&T seems to be rooted in the recommendation presented before and therefore in AT&T's uneasiness in involving customers in switching operations (Fagen, 1975).

Further developments in the Strowger exchange took places through the collaboration with Frank A. Lunquist, the two brothers John and Charles Erikson[29], and Alexander E. Keith. Starting in 1895, they refined the design that becomes what is now known as the Strowger system. They designed a two-motion (vertical and horizontal) selector presented in figure 3.6[30].

The image above shows the sequence of "dialing" the 2369. The caller sends the impulses and step-by-step a series of selectors are rotated according to the number dialed. Finally, this group of inventors also is responsible for an invention that will characterize telephone

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[25] For a detailed list see Huurdeman (2003) at pages 192-193.

[26] US patent 447,918 granted in 1889.

[27] In 1910, 131 Strowger systems were in place connecting 200 000 subscribers. All of them belonging to independent companies.

[28] Later indicated as Bell Operating Companies (BOCs).

[29] The resemblance of the name to Ericsson, the telecommunication manufacturer, is purely coincidental.

[30] US patent number 638,249.

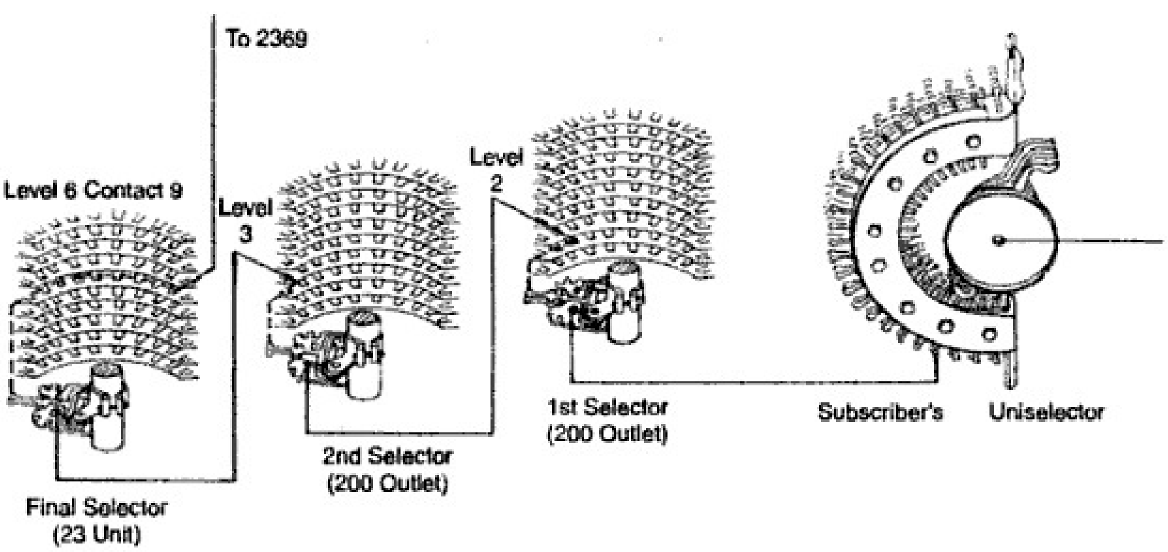

Figure 3.6: Strowger system, dialing the number 2369 (from right to left)

design for long time, in 1896 the calling buttons were substitute by a dialing disk[31]. The new designed selector went into operation again in La Porte in 1895.

After Strowger's retirement, upgrades to his system continued at *Autelco*[32] and they mainly relate to a sizable increase in the number of subscribers (up to 10,000 in a exchange place in operation in Chicago in 1903). Furthermore, since 1912 with the installation of a Strowger system in Epsom (England), it diffused in Europe where it was manufactured by several European companies and adopted in numerous networks.

The Strowger system made operators unnecessary, determining a dramatic decrease of operational cost in switching. As mentioned before, its success took place mainly through its adoption by the American independent operators, whereas Bell operators decided for an intermediate solution that was the semiautomatic exchanges[33]. In semi-automatic systems all the manual parts in the exchange were substituted by automatic equipment but controlled by the operator. This intermediate solution made unnecessary to involve the subscribers in dialing (and therefore reduce mistakes caused by subscribers' inability) and generally reduced the number of operators needed (Chapuis, 1982).

The three most popular semi-automatic systems were: the Automaual system, the Siemens

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[31] US patent number 596,062.

[32] The name of the company was changed in 1901.

[33] According to Huurdeman (2003) in 1902 1.1 million subscribers were using automatic switching with independent operators and 1.3 millions semiautomatic with Bell operators.

and Halske system and the Western Electric system[34]. During the events organized by *National Telephone Exchange Association of the United States* the debate about the two options (automatic vs. semi-automatic) was very lively and it also spread in Europe where Strowger type (therefore automatic switch) was adopted by the German empire, the Kingdom of Bavaria and Austria-Hungary. The main argument put forward by the supporters of the semiautomatic switch was its simplicity in usage and the avoidance of substituting the telephone for one with the dialing disk.

The discussion continued in the first decade of the century and was resolved after World War I: the increase in telephone traffic, the increase in labor cost, and the shortage of labor force steered the decision towards the adoption of a fully automatic switch. The first one installed in the Bell system was in 1922 at the Pennsylvania office in New York.

Once network operators achieved a consensus on on automatic switches, other designs than Strowger type started to be developed and commercialized. Some of them were adapted version of the semi-automatic system developed before the World War I (for instance, the LORIMER system in Canada, the PANEL system in the United States, the ROTARY system in Europe and United States, and LME-500 Points in Sweden[35]).

3.4.2.1 The LORIMER System

The review of the so-called *indirect control* systems starts with the LORIMER System as it was the most influential system for its contemporaries. It was developed by three Lorimer brothers (George William, James Hoyt, and Egbert) working at the American Machine Telephone Company (a former organ builder) and their patent was filled in 1900 (Huurdeman, 2003).

Figure 3.7 provides a diagram of the LORIMER exchange. The subscriber set had a disk-and-lever selection system for sending switching pulses to the exchange. At the front of the telephone, four levers (H, in the figure only one is represented) were placed and the called number was selected by pulling each lever to the correct digit of the phone number, corresponding to thousands, hundreds, tens, etc. After the setting of the number the circuit was closed using the switch P. In particular, a handle was cranked to wind a clockwork mechanism, and the clockwork rotated the disks at a constant speed sending the dialed pulses to the exchange. Through the relay G, electromagnet K was energized attracting the continuously rotating wheel R (driven by the motor M) towards wheel L and start the rotation of the selector shaft. The exchange switchgear was just about the reverse of the phones, the rotation of contact arms and their falling into the notches of the toothed disk J generated the "revertive pulse" to be sent back to the subscriber station (at the so called subscriber's number setting device). The electromagnet F, pawl and ratchet D, ensured the countdown of the pulses until position 1 is achieved. In that position contact E opened causing the de-energisation of relay

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[34] For a description see Chapuis (1982) chapter II-4.

[35] Huurdeman (2003) reports also some automanual systems that in this review are not considered.

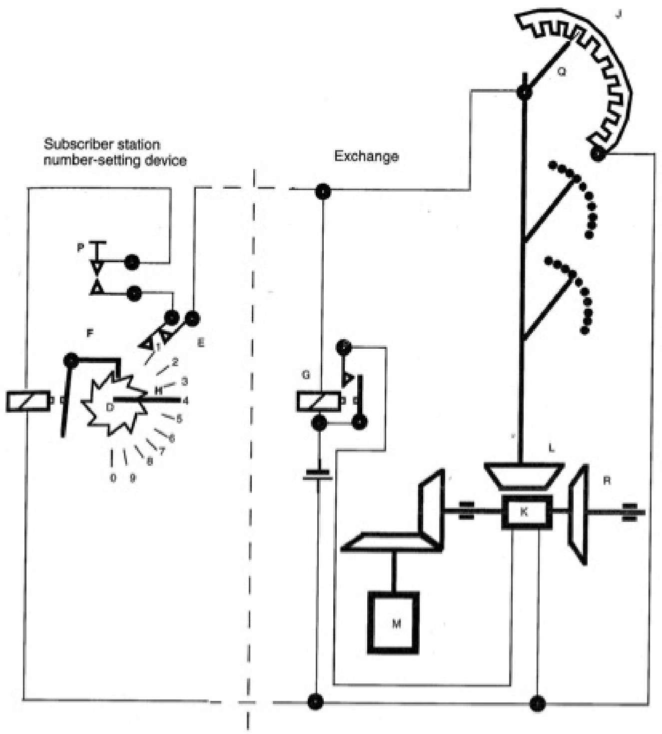

Figure 3.7: Principle of the LORIMER system
Source: Joel (1982)

G and electromagnet K; therefore, selector wipers were stop in the position corresponding to the digit set of the subscriber.

The main differences with the Strowger type were: (1) the selector had only one rotary movement, (2) the selector rotation was controlled by a magnet that was disengaging the driving shaft, and (3) the use of "revertive pulse".

Despite that the LORIMER system was a somewhat slower switching system than the Strowger, the advantages put forward were: the minimization of errors in dialing as the subscriber could check the number to dial from a small window before closing the circuit, the size (less floor space occupied) and noise reduction obtained by the use of a revolving switch rather than Strowger's bi-motion switch, and the power cost reduction. From the operating point of view, LORIMER switchgear cost was lower making it appealing to new customers[36].

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[36] The Edmonton system was quoted at $34 per line compared to Automatic Electric's $40 per line. Source: http://www.bobsoldphones.net/Pages/Lorimer/Lorimer%20Brothers.htm accessed on the 19th September 2008.

Unfortunately these advantages could not offset the fact that the LORIMER system was unrefined and unreliable. In fact, there were problems with the dialing speed generated by the clockwork in the telephones not matching the switching rotation speed at the telephone exchange hampering its use in very large exchange (Joel, 1982), and the exchange gear itself needed constant attention to the bearings and motors to keep the rotation speed constant.

Lorimer's brother company soon disappeared as very few prototypes were installed but in 1903 Western Electric that used Lorimer's idea for their PANEL and ROTARY system bought Lorimer's patent.

3.4.2.2 The ROTARY and PANEL system

These two systems can be considered as offspring of the above-mentioned LORIMER system. Western Electric starting from the acquisition of Lorimer's patent developed both systems, designed mainly for large capacity exchanges in order to meet the increasing demand in big cities.

With the increase in the size of the network and in order to cope with the diseconomies of scale before mentioned, AT&T settled a "Traffic Division" in 1899 with the specific purpose of studying traffic loads and calculating optima for the size of the equipment needed in order to maintain acceptable traffic handling capacity. Finally, it became clear that for increasing efficiency, bigger switches were more economical[37].

Following the example mentioned, high-access switches provided the best solution for engineers. However, in order to implement this an other invention was needed; this was the "number translator" (the ancestor of what later will become the "register") developed by Edward C. Molina at AT&T in 1906. This device translated the caller decimal basis dialed number in a new series of pulses on a larger basis. This allowed a faster access of the caller to a larger number of available lines.

From an external examination, a PANEL system resembles a manual switchboard where multiple jack are lined up at regular interval.

In picture 3.8 we can see a schematic representation of a PANEL connecting 100 subscribers (generally each exchange was made up of 5 PANELs) using 30 selector rods. As can be seen, the selector explores the PANEL in an upward movement, where the selector would

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[37] In an example reported by Chapuis (1982) at page 167 from Robertson (1947):

> In a group of 200 subscriber lines, the probable number of simultaneous conversations during a busy hour will be about 16 [...if there are] two groups of 100 lines, each, then the probable number [...] will be about 10. With 200-line switches (selectors), it will be necessary to employ 16 switches (giving 16 x 200 = 3200 bank-contacts multiplied over the 16 selectors). With the 100-line switches, 20 switches will be needed (giving 20 x 100=2000 bank-contacts). The saving of 4 switches by adopting the 200-line [...] more than counterbalances the cost of the bank-contacts and their multiple. This is still more evident if we consider maintenance cost [...]

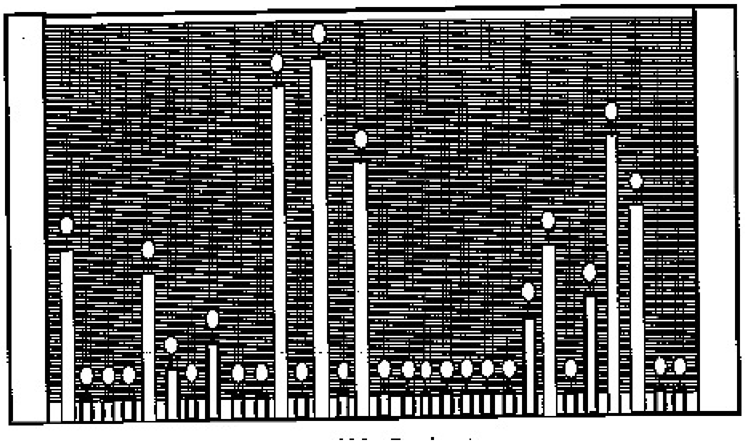

Figure 3.8: PANEL system
Source: Joel (1982)

rise up on a PANEL. The sender controls the upward movement in accordance of the revertive pulses received from the selector. Comparing PANEL functioning with a switchboard we can say that the brain of the operator is replaced by the “sender” performing the function of translator and number setting, and by sequence switches. The latter represents a primitive memory with programmed instructions, nowadays common. In this sense, PANEL switch was the first telephone switch using the “store and forward” concept; in fact, the “senders” could store a number and route the call the best way possible.

ROTARY system was developed together with the PANEL system at the AT&T; therefore, it shares some features with it and with its antecedent, the LORIMER system. Just like in the LORIMER, the selector was cylindrical (whereas PANEL has a flat contact bank), however it was an open cylinder making the maintenance operation easier than in the LORIMER. Furthermore, bank contacts were explored in a horizontal rotary movement rather than a vertical like in the PANEL. The 300 lines were situated at 10 levels with 30-lines contact per level. The translator, invented by Molina, was used also in the ROTARY system; the search of the level was still numerical (using decimal bases) whereas the automatic hunting for a free line (to a next stage or trunk) was carried out on 30 lines in a level. The wipers on each selector were controlled by an electromechanical operated clutch and the “revertive impulses” were generated by the notches on a wheel. Just like for the PANEL, the ROTARY also had sequence switches, mechanical memories programming successive operations required in setting up connections.

In 1912 AT&T conducted a study about the two system developed: the PANEL and the ROTARY and the former proved its superiority for systems serving a large bundle of trunks, required in very dense location (like big cities). From that point on AT&T will start focusing on the PANEL system and the first fully automatic PANEL system was installed in 1921 in Omaha[38]. Although, the ROTARY system was considered not suitable for the American market, it was improved and developed in Europe at Bell Telephone Manufacturing Company[39] in Antwerp. Between 1910 and 1975 several series of ROTARY switches were produced by BMT and other ITT[40] subsidiaries in the world. The first fully automatic ROTARY system was installed[41] in 1914 in Darlington (England) one day after the German occupation forces asked BTM to close their business. The prototypes, drawings and machines of BTM were saved by sending them to sister company STC (owned by Western Electric) in United Kingdom. After the end of World War I the production of ROTARY system started again at BTM.

3.4.2.3 LME 500-Point System

The LME 500-Point system produced by Ericsson is an indirect offspring of LORIMER, PANEL and ROTARY. In fact, the Swedish Telverkt (the Swedish PTT) sent two engineers (Axel Hultman and Herman Ollson) in the United States with the mission to study American switches. After this study trip, they designed a prototype system for automatic switches suitable for the Swedish context. The LME-500 Point System incorporate numerous features of its predecessors. The most significant were:

1. a continuously rotating shafts obtained by electro-magnetically controlled clutches;
2. the use of a register for translating the pulses transmitted by subscribers;
3. the "revertive pulses" setting the count down stopping the selector at the desired position;
4. the high capacity (in terms of number of selectors);
5. the use of "sequence switches" controlling the group selector and linefinder).

However, this system presents a very peculiar selector design characterized by a large exploration capacity made possible by the economical system of multiplying between selectors. In fact, the selector bank was explored, not using Cartesian coordinates (as it is in all the switches presented before and shown in figure 3.9 [left]) but use polar coordinate geometry (figure 3.9 [right]). The wiped arms in the selector moved in two way: first rotating and then

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[38] Some semi-automatic PANEL system were installed already in 1915 in New Jersey.

[39] This company was founded in 1882 and was part of the International Bell Telephone Company, a holding for the foreigner activities of Bell Telephone. This company (together with other subsidiaries) was object of a regulatory intervention in 1925. In this year, all Bell Telephone's foreigner activities were divested and acquired by ITT.

[40] The ITT International Telephone & Telegraph was founded in 1920 and will become one of the major player in telecommunication switches until its dropout in 1986.

[41] Two semiautomatic ROTARY switches were installed in Sweden in 1912 and France in 1913.

radially. As for the previous automatic system both movements are obtained by continuously rotating shafts.

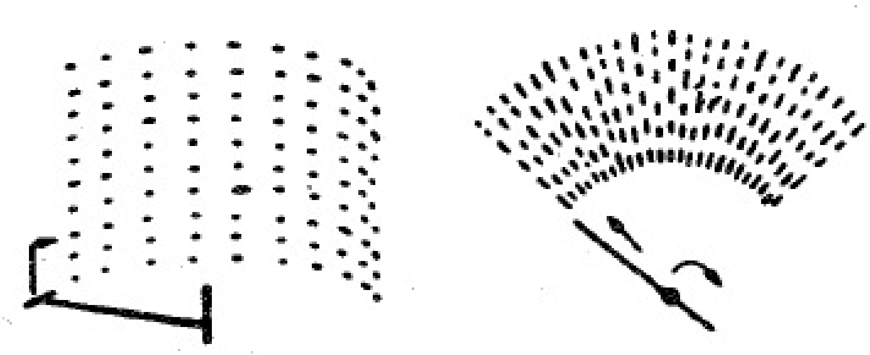

Figure 3.9: Selectors and their movement for a Strowger and for a LME-500 Point

Source: Chapuis (1982)

The fist LME-500 installed was installed in The Netherlands in 1923 with a capacity of 5000 lines. As by 1920 already numerous highly dense municipalities were already automatized, this system diffused in late adopter markets, such as: the Netherlands, Norway, Finland, China and South Africa. Remarkably, one of the point of strength of this system was the robustness and the low maintenance cost because of the robust mechanical structure and the easy of replacing units.

3.4.3 The emergence of common control switch: The Crossbar

According to Chapuis (1982), the development of Crossbar switch is an example of tenacity and persistence needed in implementing new ideas. In fact, the development of one of the most successful switching platform lasted more than 20 years and was the result of the integration of two streams of independent research carried out at the two sides of the Atlantic ocean; precisely by G. A. Betulander at Televerkt (in Sweden) and by J. N. Reynolds at Western Electric (in the United States). Since the end of 1890s Betulander worked at the development of an automatic switching. His main contribution was twofold, firstly to conceive an automatic system consisting entirely of relays, and secondly, the separation of the units in charge of the *selection circuit* and *connecting circuit*. The starting point of the all-relay system was to assemble connecting units as a matrix, where the relay is operated as “connecting point” at each intersection.

Figure 3.10[left] shows a simple matrix with three subscribers and nine points of connections; however only six relays are needed to connect each pair of the three subscribers (Figure 3.10[right]). Furthermore, engineers were aware the number of relays and the number of wires

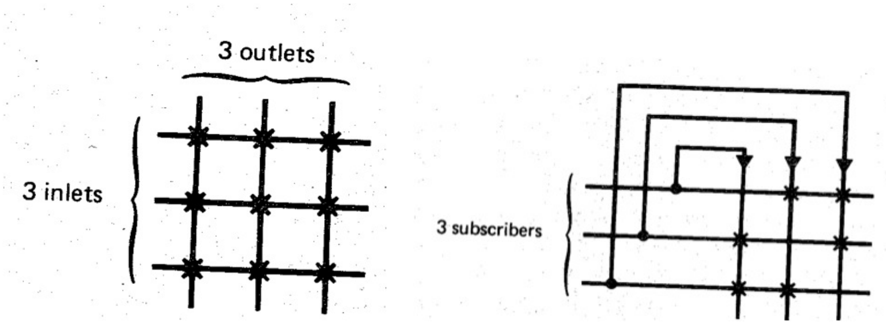

Figure 3.10: The relays operated are marked with *
Source: Chapuis (1982)

rapidly increased with the number of switched lines, and the solution proposed was to divide the exchange into *connecting units* forming a *switching network*. With this setting, either a non-blocking system could be built using a very large number of cross points or probabilistic models could be employed for deciding the number of relays to include given a certain probability of blocking.

In order to have the system working properly, two further inventions were necessary: the marker and the linking system. To understand their function, and to clarify the functioning of Betulander's system, let's use Chapuis' (1982) description:

> (i) the calling line is identified; (ii) "recorder" receives the numerical information concerning the called line; (iii) a common unit, the "marker", identifies the position of the called line from the instruction received from the recorder; and (iv) a path, or call connection, is selected by the marker between the two points: the caller's line and the called party's line. (page 363)

The linking system relates to the way different units are linked within the switching network.

This system was patented in 1912 but its major drawback was the price, which was uncompetitive for large density switches. Finally, it was in 1918 that Betulander heard about the crossbar switch developed at Western Electric by J. N. Reynolds and never implemented. As said above, this system allowed to substantially decrease the number of relays, making the system economically viable. In 1919 Betulander invented the crossbar switch in the way it would successfully diffuse in telephone networks.

Figure 3.11 presents a Reynolds' selection bar. The vertical bar performs the selection function, whereas the horizontal one is a holding bar. When the selecting magnet is energized a roller at the end of the hinged finger is disposed under the sets of contacts at the intersection of the vertical and horizontal bars. Afterwards, when the holding magnet is activated a cam is placed under the roller in order to close the contact. After this operation the vertical selecting bar returns to the starting position and the closure of the circuit is secured by the holding magnet.

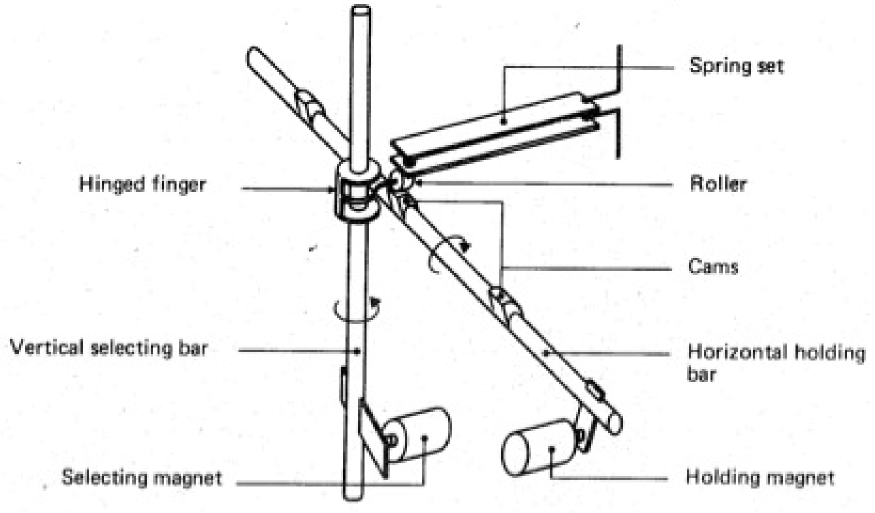

Figure 3.11: Reynolds' crossbar system
Source: Chapuis, (1982)

Betulander made two major changes to Reynolds' system inverting the function of vertical and horizontal bars, and changing the system of rollers and cams with flexible steel wire fingers. The integration of the modified Reynolds selecting bar in Betulander's system allowed overcoming the previous pointed drawbacks.

Despite the success the Crossbar later would achieve, it was defeated by the LME 500-point system in the tender promoted by Telverket in 1921 for selecting an automatic switch. What determined the Crossbar later success was its size versatility that permits this design to be used in a wide range of applications. This feature was possible because of the modular structure implemented by using the linking system. This implies the need to test the links between the different stages in order to find idle paths and terminate the call; this was one of the function of the marker. As example we can look at the first crossbar system developed, the Crossbar No.1 developed by AT&T. Figure 3.12 illustrates the switch between two subscribers located in different exchange.

On the left side there is the "outgoing block" switching the call from a subscriber to an other exchange and on the right side the "incoming block" routing calls from an other exchange to the called subscribers (the traffic between subscribers in the same exchange is handled by intra office trunks connecting outgoing and incoming blocks of the exchange.). Each block is divided in two set of frames (primary and secondary) involving a two-sage inter-linked system.

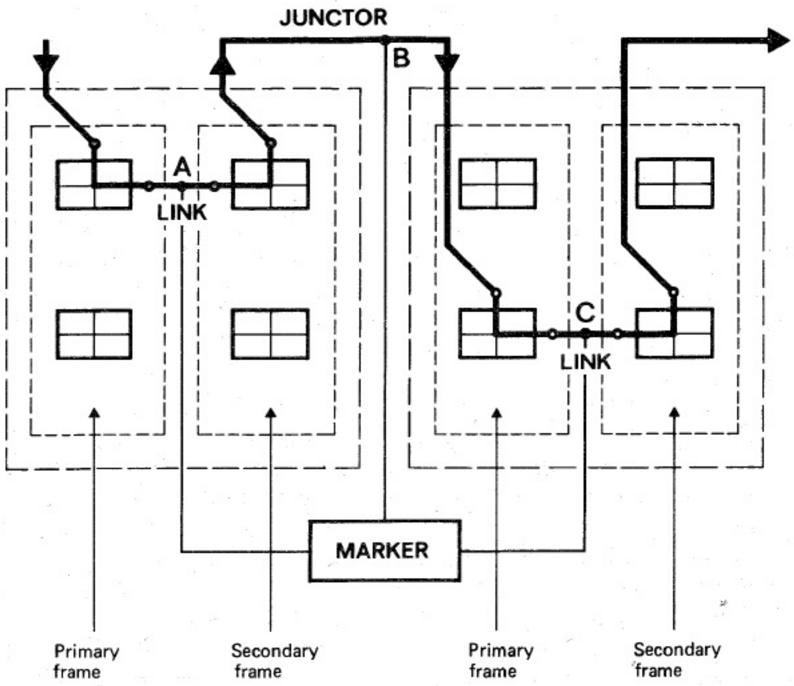

Figure 3.12: Scheme for a Crossbar switch
Source: Chapuis, 1982)

According to the picture the connection between outlet of the primary and secondary frames are called links whereas the connection between the two blocks is called junctor. The figure illustrates the presence of three links in tandem: A and C being a link and B being a junctor. As the marker knows the point of inlet and the desired outlet has to find between them an idle path; it has therefore to test all the three links in order to start the call. All these "idle or busy" tests and the rules for the testing of all the possible links (based on Booleran algebra) constitute the logic of a switch.

Starting in the early 1920s, AT&T was searching for a new system different from the already diffused PANEL with the following characteristics: less maintenance cost and more flexibility. After studying the Betulander system, AT&T engineers started to design a switch using the crossbar connecting unit and in this way the crossbar switch went back to the United States. The first Crossbar No.1, produced by AT&T, was introduced in 1938 in Manhattan.

After 10 years from this early research and deployment, AT&T was able to place in service a new crossbar platform, the No.5 crossbar. By 1979, this switching platform would become the most widely diffused system in the Bell System (Chapuis, 1982). The main difference with its predecessor was in the architecture, in the more generalized use of the common control, and in its "custom building" manufacturing. In terms of technological milestones, in the 1950s a consensus on the design of crossbar switch was achieved seeing other manufacturers starting the production of their own crossbar platform (in particular: LM Ericsson crossbar, Pentaconata crossbar by ITT and Japanese crossbars). These platforms shared (together with the AT&T system) some common features, which will determine the dominant design for this platform. Using Chapuis' words (1982), these were:

> a "switching network" composed of *selection units* operating according to the linking principle [. . .] and comprising a primary and secondary bank of crossbar units; markers to control the conditional selection; the selection process operated via the exchange [. . .] is generally performed by *two or three selection units in tandem*; different *markers* are used for each *selection unit* (generally with two markers per unit). (page 411)

Looking at this list it starts clearly to appear clear one of the switching principle common to all the switches designed from 1955 onwards: the separation between "switching network" and "control units" (the register). The former made of selection units setting up the path within the exchange and the latter constituted by a separate signaling network within the exchange.

3.4.4 Space-division Storage Program Control system (Electronic Switch)

Space-division storage program control (SPC) switch is the more precise technical name for what is commonly called electronic switch. As anticipated in the categorization used in table 3.1, different multiplexing technologies (see Technology Box 1) can identify different switches generations. In particular, if we combine the alternative multiplexing technologies with the different types of switched signals four different designs are possible. These are presented in the matrix in table 5.4.

Table 3.3: Possible combinations

		Switching Division	
		Space-division	Time-division
Nature of switched signal	Analogue	(1)	(2)
	Digital	(3)	(4)

Source: Chapuis, 1990

In the end, two designs became dominant: the analogue space-division type (1) and the digital time division type (4), commonly known as the electronic and digital switches respectively. However, as we will see later in the chapter also designs, (2) and (3), were explored[42].

After World War II scientific research on switches resumed and one of the technological milestones of these years was the development of the transistor at the Bell Laboratories[43] in 1947. Its antecedent, the vacuum tubes, were successfully implemented in transmission for amplification, modulation and oscillation. Whereas, their use in switches was constrained by the fact that a switch would have needed a large number of them[44] making the system expensive and plagued by serious heating problems.

The high technological uncertainty related to the use of electronics is well described by C. Jacobaeus, Executive Vice-President of LM Ericsson. He declared:

> During the end of the 1940's, the telephone industry began setting laboratories -albeit on a small scale - for studying in more detail the possibility of introducing electronic components as essential building bricks in switching engineering. Relatively few people really believed that electronics would come to play an important role in telephone exchanges. In industry at that time the electronic laboratory activities in switching were in the nature of an insurance against unpleasant surprises. (Chapuis and Joel, 1990, page 43)

One of these few optimistic place was the Bell Laboratories. There, during the 1950s some researchers unraveled the possibility of integrating electronic components (in particular, the just invented transistors) in the design of a telecommunication switch. A study group was appointed[45] to study the feasibility of a system requiring only "50 flip-flop" (i.e. transistors) to run an office of 500 000 lines. This vision was the starting point for the ECO (Electronic Central Office) project that culminated with the placing in operation (in Morris, Illinois) in 1960 of the first commercial central office using the Storage Program Control (SPC, see Technology Box 2) in 1960.

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[42] Research about (2) was widely undertaken at the beginning of time-division. In that case PAM (Pulse Amplitude Modulation) instead of PCM (Pulse Code Modulation) was used. A famous unsuccessful example is the Highgate Wood Exchange produced in 1956 by British manufacturers in the JERC program. It is remembered as the *monstre sacreé* because of the high number of electronic components (around 180,000, including valves, diodes, and transistors) compared to the number of lines covered (only 600).

[43] In 1925 Western Electric Research Laboratories and part of the engineering department of AT&T were consolidated to form Bell Telephone Laboratories, Inc. as a separate entity. Ownership of Bell Laboratories was evenly split between AT&T and Western Electric. Its principal work was to design and support the equipment Western Electric built for Bell System operating companies.

[44] In the Highgate Wood Exchange, 3000 tubes have been used for only 600 lines (Chapuis and Joel, 1990)

[45] Amos E. Joel was part of this group (Chapuis and Joel, 1990).

Technology Box 1: Switching division and multiplexing

In telecommunication networks (but this is valid also for computer networks) the **multiplexer** is the device that allows more than one signal to be sent simultaneously over one physical channel. Generally speaking, it combines inputs from more that one terminal and transmits the combined data stream over a single channel. Finally, the reverse process is processed by a demutiplexer. The integration of these devices in the network allows for economizing on expensive transmission resources.
The multiplexing can be done in different ways, the most commons are: *frequency-division multiplexing*, *space-division multiplexing* and *time-division multiplexing.*
In the *frequency-division multiplexing* multiple signals are modulated on different frequency carrier waves and added together to create a composite signal.
Space-division multiplexing systems are those in which speech paths are continuous through the exchange, and therefore each path is spatially separated from all the others.
Finally, in the *time division switching* systems speech paths are separated in time. This means information is sliced into a sequence of time intervals (the timeslots) corresponding to a speech sample.

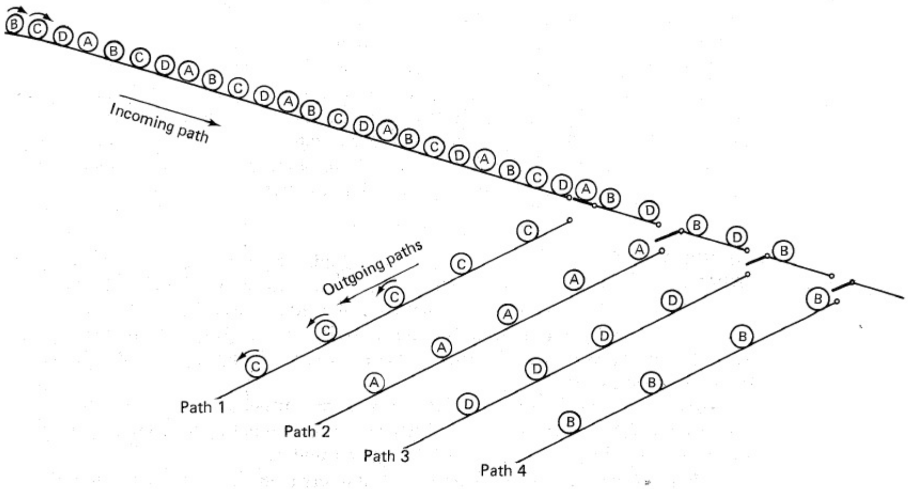

Fig. 3.4.4 Scheme of time-division switching of a time-multiplexed stream.
Source: Martin, 1977

Technology Box 1: Switching division and multiplexing - Continued

Figure 3.4.4 provides a scheme of the functioning a time-division switching of a time-multiplexed stream. Time slots are represented by the circles and different letters indicate they belong to different speech paths, and they have to be switched to the right outgoing path. This happens through the opening of gates at the exact right moment. In this system the physical path is not continuously closed but only for 125 μ- seconds each time.

The advantage of *time-division systems* was the reduced number of physical switch point needed. Martin (1977) gives an example of the size of the saving. In fact, if you want to physically connect N lines, than N^2 switch point are needed. This number can be reduced by using a multi-stage switching with a limited number of simultaneous interconnections. If no more than one tenth of lines can be simultaneously interconnected than $0.21N^2$ switch points can be used. It follows that for interconnecting 100 lines, time-division switch needs 100 switch points whereas space-division switch is likely to need at least 2100. As it will be shown in the next section the *time-division* principle was already known (as proof of concept) since the 1930s but it is only when fast logic circuitry became cheaper that it became economical (and therefore used).

Technology Box 2: Storage Program Control (SPC)

SPC was a control method pioneered at AT&T. It places most of the control logic in a permanent memory and each call is processed by the sequence of orders retrieved from that memory. The main advantage of the SPC is to make the control function independent and modular in its components. This means that higher capacity microprocessors could be easily integrated. The use of SPC is an invention that will persist in all the future switching designs. This will bring about:

1. the possibility of separating the speech and signaling paths;
2. the possibility of dividing a switching system in two: the hardware (the switching system) and the software (the switching control).

Therefore, SPC common control means that a computer runs a program that controls the switching system adding flexibility in the routing path and making the implementation of new services easier. The consequences from the organizational point of view are that manufacturers needed to acquire new competences, in particular programming skills.

Looking at the previous pages we saw that one way in which subsequent technological platforms differ is the way the control function is implemented and organized. We move from the very early systems where the subscriber has direct control (as a step-by-step switch) to the common control situation (as the crossbar switch) where the marker performs the controlling function (i.e. finding the path through the switching network). More specifically, in electromechanical systems, a plurality of common controls were used (and therefore more markers) in order to meet the plurality of controls needed for the efficiency of the switching system.

The use of electronic components made possible to use one single common control unit, moreover it added a new design dimension related to the *logic* of the system. As we will later see, some manufacturers preferred to use wired logic in order to mimic the function of the relay, however, SPC would become the standard common form of electronic common control.

The experiment at Morris was simply the prove of feasibility of a fully electronic switch. Unfortunately, from the economic perspective, it was not a simple plug-in replacement of the Crossbar switch for several reasons:

1. The necessity to change all customers' premises for a low current telephone set because of the impossibility of sending ringing tone through the gas-tubes used as crosspoint;
2. The difficulties in achieving an economic balance over different switch size because of the use of a single high-speed central processor that is basically the same both for big and small exchange;
3. Following the previous point, the dependability and the reliability of the switch is guaranteed by duplication of expensive electronic components. Furthermore, in an electronic switch, the failure of the processor can cause a complete failure of the network whereas in a multi-markers Crossbar switch the failure of one components could determine just a reduction of the capacity of the system.

Before the commercialization of the first AT&T electronic switch (the No. 1 ESS) these technical problems had to be tackled. First of all, the invention in 1959 of the "ferreed relay" solved the problem of substituting the customer premises as they provide a valid (and cheap) alternative to the gas-valve. The other issues were solved by the optimization of the design aimed to the reduction of the number of components and by the rigorous planning of the manufacturing process. These brought about a significant cut in the manufacturing cost; for instance, reducing the number of interconnections between frames and therefore reducing the wiring jobs during the installation process. Finally, the automatization of the troubleshooting function increased switch reliability.

AT&T developed its first electronic switch, the No.1 ESS, in 1963 and commercialized it in 1965. For its development, AT&T disposed $25 millions for 5 years, however, it actually took 7 years and $42 millions[46]. Looking at the overall development process, it becomes clear that No.1 ESS economic viability was achieved both through technological and manufacturing improvements. AT&T employed the Morris switch as an exploratory study, but Western Electric was involved and contributed in production planning. The close collaboration between the two parties (actually, being Western Electric the manufacturing branch of AT&T) since

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[46] This figures do not include manufacturing development and the development on the Morris switch. All inclusive, AT&T spent over $100 millions for its No. 1 ESS (Chapuis, 1982).

the very early stages allowed lowering design and production cost. This, coupled with space and capacity gains, made the No.1 ESS becomes rapidly economically viable. AT&T licensed all the needed technologies, so no "reverse engineering" was needed; eventually, the No. 1 ESS left a mark in term of system design, establishing the use of SPC (Joel and Swindler, 1982).

No.1 ESS quickly replaced the PANEL switching system introduced in 1921. Along all the development process, BOCs were kept informed in order to facilitate the installation process, and by the 1967 all the 24 BOCs had at least one of it. However, the process of adoption was not smooth; despite the re-training of numerous operators' human mistakes causes some outages to the system (Chapuis and Joel, 1990; Clark, McLoughlin, Rose and King, 1988).

In the same years two phenomena emerged in the switches engineering community:

1. the "professionalization" of the discipline throughout the increase in the number of publications (and therefore the degree of codification) and the teaching of specific courses at university. As noted by Chapuis (1990), transmission with its early adoption of electronics was considered the "noble" field, whereas switching was simply "wiring" left to practical technicians. With the adoption of electronic components, switching rose also its status among the electronic engineers.
2. the establishment of the ISS (*International Switching Symposium*). It started as an AT&T's licensees' meeting, it become institutionalized and enlarged at the beginning of the 1960s. It became an occasion to discuss technical problems, to see the state of the art and, because of the high cost of research related to electronic switching, to try to avoid too much duplication (Chapuis and Joel, 1990; Huurdeman, 2003).

Undoubtedly, AT&T and Bell Laboratories were pioneers in electronic switching and the No.1 ESS set the standard for the industry. Nevertheless, the other manufacturers undertook also research projects for the development of their own electronic platform, and by 1972, all the major manufactures had commercialized it. The design of an electronic switch represented a big challenge for manufacturers. First, fast technological change in electronic components made prototypes obsolete quickly, secondly, the use of SPC, contrasted the sequential relay operation modes, implied a completely different approach, and finally programming skills where not very diffused.

The introduction of other electronic platforms took place at different paces: Britain and France soon followed AT&T, whereas, Sweden and Germany were latecomers.

Table 3.5 is taken from the book *Electronic Switching: Central Office Systems of the World* (Joel, 1976) published by IEEE in 1976. This book is a collection of technical articles describing 29 electronic central offices. The table shows clearly a convergence towards what we could call the No.1 ESS model (meaning ML Reed and SPC) but also some variety in the choice regarding switching network techniques and control.

As explained before SPC was only one way to conceive the *logic* of the switch and *electronic wired logic* (EWL) was a viable alternative. The discussion was very lively in United Kingdom

Table 3.4: Production of Central Office Electronic Switching

Date of First Service	System Code	Country	Initial Manufacturer	Switching Network	Control
1965	No. 1 ESS	U.S.A.	Western Electric	ML - Reed	SPC
1966	TXE 2	United Kingdom	Plessey	EH - Reed	EWL
1967	10C	Belgium	Bell Tele. Mfg	EH - Reed	SPC
1968	No. 1 ESS - SP	U.S.A.	Western Electric	ML - Reed	SFC
1968	No. 1 ESS - Tandem	U.S.A.	Western Electric	ML - Reed	SPC
1967	ESK 10,000E	Austria	L. M. Ericsson	ESK Relay	EWL
1970	ESK 10,000E	Hong Kong	L. M. Ericsson	ESK Relay	SPC - MP
1970	ESC 1	U.S.A.	Stromberg-Carlson	EH - Reed	EWL
1970	E10	France	CGE	Digital TDM	EWL
1970	C1 - EAX	Canada	GTE - AE Canada	Crosspoint Switch	SPC
1970	No. 2 ESS	U.S.A.	Western Electric	ML - Reed	SPC
1970	NX - IE	U.S.A.	North Electric	Crossbar	SPC
1971	SP 1	Canada	Northern Electric	Minibar	SPC
1971	AKE - 13	The Netherlands	L. M. Ericsson	Codebar	SPC - MP
1972	Metaconta L	France	CGCT	Metabar, ML - Reed	SPC
1972	No. 1 EAX	U.S.A.	GTE - AE	EH - Reed	SPC
1972	D10 Local	Japan	(1)	Mini-Crossbar	SPC

Source: Chapuis, 1976

(1) Oki, Hitachi, Nippon Elec., Fujitsu, NTT-ECL (2) Siemens, T&N, SEL, De Te We

EWL= Electronic Wired Logic

MP= Multiprocessor

NA= Not Available

SPC= Storage Program Control

Table 3.5: Production of Central Office Electronic Switching - Continued

Date of First Service	**System Code**	**Country**	**Initial Manufacturer**	**Switching Network**	**Control**
1972	D10 Toll	Japan	(1)	Mini-Crossbar	SPC
1972	PRX 205	The Netherlands	Philips	EH - Reed	SPC
1973	ARE	Denmark	L. M. Ericsson	Crossbar	SPC
1973	EWS 01	West Germany	(2)	ML - Reed	SPC
1974	10C Toll	Australia	LCT	EH - Reed	SPC - MP
1974	SP1 - Toll	Canada	Northern Electric	Minibar	SPC
1975	ETS - 4	U.S.A.	North Electric	Codebar	SPC - MP
1976	No. 4 ESS	U.S.A.	Western Electric	Digital TDM	SPC
1976	TXE 4	United Kingdom	STC	EH - Reed	SPC
1976	No. 2B ESS	U.S.A.	Western Electric	ML - Reed	SPC
1976	E11	France	LCT	ML - Reed	SPC
1976	E10 - Tandem	France	CGE	Digital - TDM	EWL
1976	D20	Japan	(1)	Minibar	SPC
1976	No. 3 ESS	U.S.A.	Western Electric	ML - Reed	SPC
1976	TCS 5	U.S.A.	ITT	PnPn	SPC
1976	AXE 10	Sweden	L. M. Ericsson	EH - Reed	SPC-MP

Source: Chapuis, 1976

(1) Oki, Hitachi, Nippon Elec., Fujitsu, NTT-ECL

(2) Siemens, T&N, SEL, De Te We

EWL= Electronic Wired Logic

MP= Multiprocessor

NA= Not Available

SPC= Storage Program Control

where manufacturers were rather reluctant to use SPC because of the high investments required, both for R&D and manufacturing (especially in terms of new skills and competences). SPC seemed inappropriate for the English context where medium and small capacity offices were required. In fact, the high duplication costs for an SPC system and the programming costs appeared preparing the programs seemed excessive.

3.4.5 Time-division digital *centralized* SPC command

The development of digital switch can be considered as one of the longest research projects undertaken in the telecommunication industry: it took more that 30 years to go from the proof of concept to the commercialization. As already stressed in the previous pages, switches are complex systems therefore their development takes place along also the development of complementary technologies. Similarly to the electronic switch, digital switch emerges from the integration of two different technologies: the Pulse Code Modulation (PCM, see Technology box 3) and the *time division multiplexing* (as indicated in figure 5.4).

E. M. Deloraine (a French engineer working for the ITT's subsidiaries Standard Telephone and Cable) filed a patent in 1945 titled "Pulse Delay Communication System"[47] about what is now called *time slot interchange.* This explains how, for switching, the time slot of one channel within a group of time-division channels can be displaced to the time slot of a other channel. The implementation was the provision of a delay line adjustable to the code of the called line.

This *time slot interchange* constitutes one of the basic element of digital switch that is the T stage. The second basic element is the S stage, a device for the functioning of the switching matrix.

Figure 3.13 shows the principle of digital switch and the T and S stages are displayed. The former consists in an incoming speech memory needed to change the time slots allocation (and eventually covering the delay) between caller and called subscriber. In fact, we can see that caller x is associated to time slot 28 whereas the called subscriber b is associated to time slot 2, therefore, in order to terminate the call the timeslot has to be changed and some delay has to be applied. The latter consist in a cross point matrix made by electronic gates. For each time slots it works as a normal space-division matrix between inlets and outlets and being controlled by a memory. The addition of the T stage increase the utilization of the crosspoints and therefore it makes a more efficient use of the existing resource.

The presence of these T and S stages is one of the basic characteristic of digital switching platforms (see table 3.6 for different settings by manufacturer) that can be denoted by the order of these stages, like: T, TST or STS. The increase of the number of these stages increases switch capacity. The development of PCM was rather long as it took around 30

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[47] US patents 2,584,987 and 2,492,344 granted in 1952.

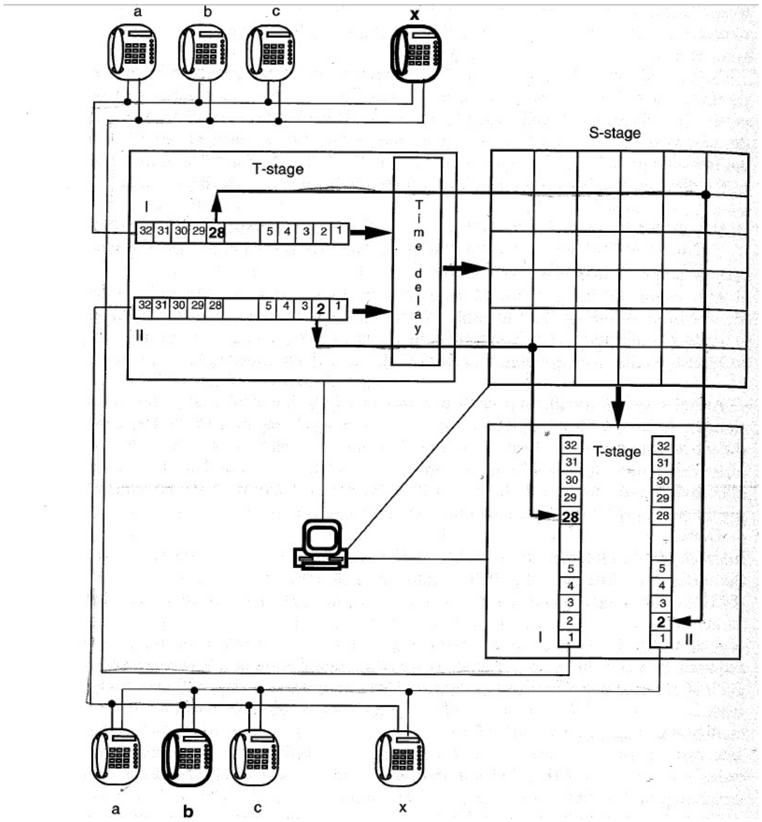

Figure 3.13: Principle of a digital switch

Source: Huurdeman, 2003

years, and even more if we consider similar applications already in use in telegraph network[48]. In the context of telephone switches, PCM was developed by Alex A. Reeves in 1938 at LCT (Laboratoire Central de Télécommunications, an ITT research facilities in France) but it passed almost unnoticed at the time. It was reconsidered during World War II, when the Bell Laboratories undertook a research project for the American Army. Later, in the early 1960s, with the appearance of the first efficient solid-state components and memories, PCM was successfully implemented in transmission.

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[48] In 1874 Emilie Baudot devised one of the first applications of time-division multiplexing in telegraphy. Using synchronized clockwork-powered switches at the transmitting and receiving ends, he was able to transmit five messages simultaneously.

Technology Box 3: Pulse Code Modulation (PCM)

The development of digital switches is related to the emergence of Pulse Code Modulation (PCM). PCM (opposed to PAM, Pulse Amplitude Modulation) is a method for providing a digital representation of an analogue signal where the magnitude of the signal is sampled regularly at uniform intervals, and then quantized to binary code.

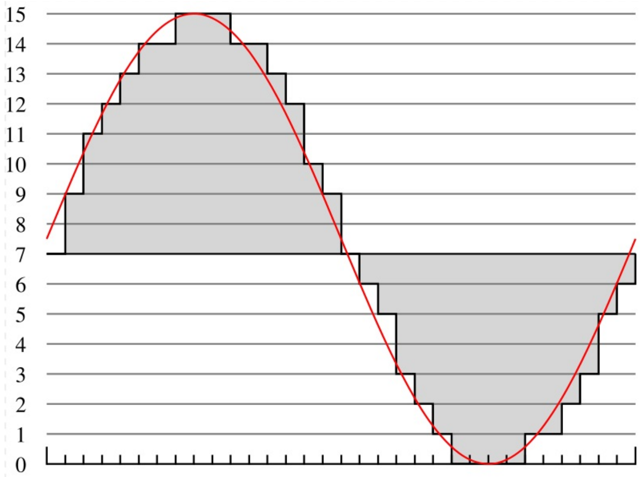

Fig. 3.4.5 Example of Pulse Code Modulation

Source: www.wikipedia.com

Just as an example, figure 3.4.5 shows a sine wave sampled and quantized for PCM (black line). For each regular interval indicated on the x-axis a specific algorithm chooses a value on the y-axis. In this way, the shaded area is determined and the values on the y-axis can be easily transformed in binary code and therefore encoded as digital data for storage or further manipulation (for instance multiplexing). Finally, the Nyquist theorem defines the minimum sampling rate necessary to obtain a complete reconstruction of a signal waveform from extracted sample. In order to maintain a minimum quality of the signal, the sampling rate should be the double of the highest frequency to be carried, For a toll rate with voice signal up to approximately 4kHz the sampling rate is fixed at 8 000 samples per second.

The development of the T1 PCM digital transmission for interoffice trunk started the process of digitalization of the telephone network. As it was efficient for distance up to 40 km and compatible over existing cables, it quickly diffused in the BOCs' network.

Furthermore, when PCM started to be used in international routes it became clear the need of standardizing it. This work, involving the agreement on a number of basic parameters (such as the number of coding bits, non linear quantization characteristics, etc.) was carried out at CCITT. Two major standards emerges: the so-called North American system (also used in Japan) characterized by a primary multiplex of 24 telephone channels and the so-called European system characterized by 32 channels (providing 30 telephone channels). This setting will have repercussion on the compatibility of switching platforms produced in different countries and it will therefore constitute a barrier to entrance for foreign companies (especially for Western Electric in Europe).

The digitalization of transmission in the early 1960s determined a technological separation between transmission and switching; switching would need further research (and components) before becoming fully digital. As the signal deteriorate through analogue and digital conversion, this technological separation brought about some signal quality and efficiency concerns that boosted research about digital switching.

The first attempt to integrate digital switch was the ESSEX (Experimental Solid State Exchange) project started in 1956 at Bell Laboratories whose aim was to prove the feasibility of a PCM time-division exchange. Notably, this was well before the commercialization of the space-division SPC No.1 ESS. In fact, despite the ongoing research about time-division and PCM, the high cost of components made very difficult its economic viability in the short run. Nevertheless, engineers were aware of the potential synergies deriving from the use of digital techniques in all network functions, in particular seeing the high cost of analogue/digital conversion.

Figure 3.14 shows the steps that brought about the transition from an "integrated analogue" network to a network almost fully digitalized (apart the *last mile* connecting the customer to the local office that will be digitalized with ISDN). This figure points out that:

1. As said above, network digitalization started from transmission, and in particular from trunk connection;

2. In switching, the digitalization started at the core of the network (transit and tandem switches) and then slowly spread to the edge, where the local offices are. In fact, the first digital switches designed and produced were intermediate offices. These were going to be connected to already digitalized trunks, reducing the number of expensive analogue-digital interfaces (visible also in the transition from phase b to c, where the number of analogue-digital interfaces goes from 4 to 2).

Further on this, figure 3.15 helps to understand the trade offs emerging with the adoption of time-division switches in presence of analogue and digital transmission. The left scheme represents a local switch provided with analogue and digital trunks (T_a and T_d, respectively) and loops[49] (L_a and L_d respectively); whereas the right graph reports qualitative cost curves, corresponding to different switching technologies and level of digitalization. Considering the space-division (SD) switch with no digital loops and trunks as a starting point, the deployment

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[49] Here considered as synonymous for *last mile*.

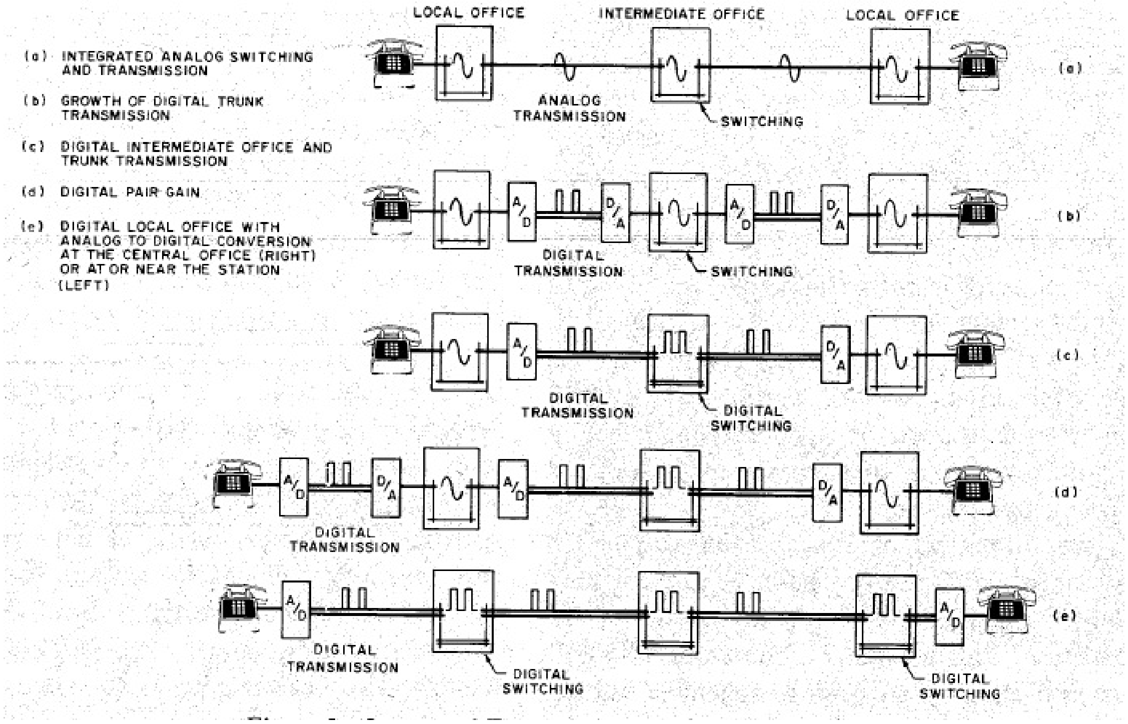

Figure 3.14: Integrated Transmission and Switching

Source: Joel, 1982

of digital transmission (both L$_d$ and T$_d$) simultaneously decreases the costs of interfacing with time-division (TD) switches and increases the costs of interfacing with SD switches. In its simplicity this graph illustrates the cost dynamic of the co-existence of different technologies (analogue and digital, and SD and TD).

To conclude, the diffusion of digital switches was slowed by the presence of two main technical bottlenecks. Numerous technical books agree on the identification of these analogue/digital interfaces as the major technical bottleneck for digital switches. In particular, they refer to the BORSCHT circuit[50]. The development of BORSCHT circuit started in 1972 but because of the continuous changes in the technology its development was rather slow. Finally, digital memories were fundamental in the function of delay signals. These were fundamentals for the T-stage as they solved the problem arising from imperfect clock synchronization between various exchanges (generally called frame alignments) and for intro-

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[50] The name Borscht is an acronym of the preformed functions: Battery feed, Overvoltage, Ringing, Supervision, Codec for analogue-digital coding and decoding, Hybrid to split the two-wire analogue speech circuit into two separate two-wire circuits for sending and receiving the coded digital signals and Testing.

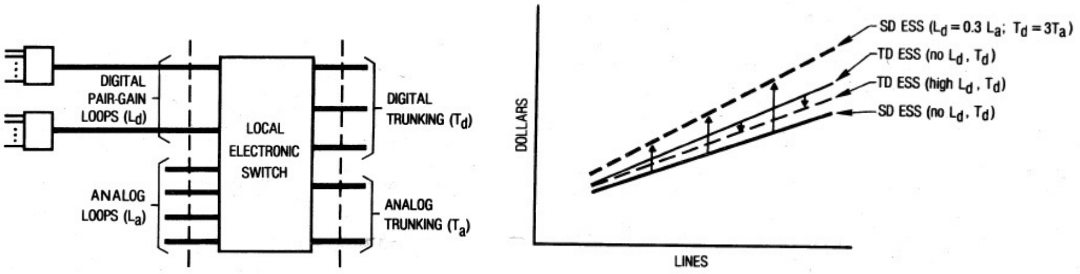

Figure 3.15: Qualitative SD/TD Cost Trade-Offs

Source: Chapuis (1982)

ducing the delay between the time arrival and the treatment in the switch of the incoming voice channel.

3.4.5.1 The other manufacturers

Until now Bell Laboratories and their manufacturing branch (the Western Electric) have emerged as a leading research institution for telecommunication switches. Nevertheless, with the emergence of a dominant design in digital switches also all the other manufacturers started to commercialize their own switching platforms. Technological uncertainty about digital switches dropped with the International Switching Symposium held in Paris in 1979. At that moment consensus about the general design of a digital switches was achieved. In Chapuis and Joel's (1990) words:

> The heyday of digital SPC switching had arrived and from now on all the new systems had to have stored-program control and digital switching networks. There was also a consensus as to the type of exchange architecture: it had to be modular as regards both hardware and software and decentralized in that microprocessors were used throughout. (page. 563)

Tables 3.6 and 3.7 are taken from a book called *Electronic Switching: Digital Central Office Systems of the World* published by Amos E. Joel. This book mimics the source of table 3.5 in the previous subsection as it is a collection of technical papers aimed to describe digital switching systems developed by the major manufacturers.

These tables provide a summary of the systems developed as intermediate (toll or tandem systems) and local switches. The fact that manufacturers largely focused on intermediate switches is again because of the synergies with digital trunk. This explains why they are more numerous. In particular, table 3.6 reports also early designs showing some heterogeneity in terms of the type of control (SPC vs. Wired logic) and the type of networks. However, only few of them were actually in service, the majority being just laboratory or field experiments.

3.4.6 Time-division digital *decentralized* SPC command

The 1980s were the years in which the second generation of digital switches emerged, the time-division digital *distributed* control opposed to the *centralized* one. This distinction is made by Chapuis (1990), who points out that the terms *distributed* do not refer only to the geographical distribution of the telephone network but to the *distributed control* and the *distributed switching.* These are the two features that distinguish the second generation of digital time-division switches.

Distributed control pertains to the architecture of a switching system itself. Equipment modules were designed to serve groups of system terminations (e.g. lines, trunks, data links etc.). The use of VLSI technology in these modules made their control autonomous. This means that they could complete calls within their module (or within certain modules) independently of the controls elsewhere in the system. In this system the call processing (namely the call distribution and system information processing) could be performed by controls decentralized in different modules or by the central control. The balance between these two controls depended on the design of the switch, and, at the extreme, central control is absent in a *fully decentralized* systems. Normally speaking, the more the control is distributed the more is the capacity of the switch.

Finally, a second feature of this time-division digital switch generation is the *distributed switching.* This is the inclusion of "switching network" capability in the network: calls between terminations on the same module could be completed without passing through any other system elements. Also in this case, the extent of distributed switching depended on the switch design.

The presence in the network of these autonomous modules affected the trade-off between transmission and switching cost, and therefore network topology. Decentralization also permitted small companies to enjoy some new services allowed by digital switches and brought digital connectivity closer the customers' premises enhancing the realization of ISDN (Integrated Service Digital Network).

ISDN completed the digitalization of the network allowing digital transmission over ordinary telephone copper wires. This refers to the distribution subsystem mentioned in section 3.3 and in figure 3.14 to the small connection between the telephone and the Analogue-Digital converter. The use of ISDN improved not only the quality signal but also made possible the provision of new services (like video-conference) and broadband connection.

The development of this new generation was pushed by the rapid changes in costs and capability of digital technology and pull by the huge increase in new services offered and in the software to implement them (Chapuis and Joel, 1990).

Table 3.6: TDM Digital Switches Intermediate Office

Country	System	Manufacturer		Network	Size	Control	Status	Year
ITALY	SINTEL 1	TELETTRA	S(R)-S	(8p)	250	WL	LAB EXP.	1966
JAPAN	DEX-TI	NTT	S(R)-S	(8p)	192	WL	LAB EXP.	1967
UK	EMPRESS	BPO	STS	(8p)	192	WL	FIELD EXP	1968
AUSTRALIA	1ST	APO	TSTST	(8p)	192	SPC	FIELD EXP	1971
U.K.	MOORGATE	STC	SSTSS	(8p)	384	WL	FIELD EXP.	1971
NETHERLANDS	DTX 500	NETH.PTT	TS	(8p)	1.1 K	SPC	LAB EXP.	1972
FRANCE	E10	CIT	TT	(8p)	7.2 K	AT	SERVICE	1975
U.S.	No. 4ESS	WE	TSSSST	(10s)	107 K	SPC	SERVICE	1976
U.S.	IMA 2	VIDAR	TT	(9P)	1.4 K	SPC	SERVICE	1976
ITALY	SINTEL 3	TELETTRA	SSTSS	(8p)	14.4 K	SPC	FIELD EXP	1976
ITALY	PROTEO	SIT-SIEMENS	TST	(8s)	16 .3 K	SPC	FIELD EXR	1976
NETHERLANDS	PDX	PHILIPS	TST	(8p)	23 K	SPC	FIELD EXP	1976
W.GERMANY	EWS-D	SIEMENS	TSST	(8p)	63 K	SPC	LAB EXP	1976
SWEDEN	AXE	LME*	TST	(8p)	32 K	SPC	FIELD EXR	1976
U.S.	No. 3 EAX	GTE-AE	SSTSS	(3s/3p)	60 K	SPC	SERVICE	1978
U.S	DTT 200	COLLINS	TST	(8p)	1.5 K	SPC	LAB EXP	1977
U.S.	DMS200	NORTHERN	TSSSST	(8s)	60 K	SPC	FIELD EXP.	1977
UK	SYSTEM-X	4 COS.	?		32 K	SPC	LAB EXP	1978
U.S.	DTM	STROMBERG-CARLSON	TST	(8p)	4 K	SPC	?	
JAPAN	NEAX81A	NEC	TSST	(8s)	13.4 K	SPC	LAB EXR	1977
FRANCE	MT 20	THOMPSON -CSF	TSST	(8p)	65 K	SPC	SERVICE	1979
JAPAN	FETEX 100TOLL	FUJITSU	TSSSST		60 K	SPC	LAB EXR	1979
JAPAN	HTX-TOLL	HITACHI	SSTSS	(8p)	60 K	SPC	LABEXR	1978
JAPAN	NEAX 61TS	NEC	TSST	(8p)	60 K	SPC	SERVICE	1979

Source: Chapuis, 1982

* Ericsson Telephones- Australia

Table 3.7: TDM Digital Switches Local Office

Manufacturer	Code	Year Introduced	Country	Max line size (1000's)
CIT-ALCATEL	E 10	1970	FRANCE	30 (E 108)
STROMBERG-CARLSON	DCO	1977	U.S.A.	28
NORTHERN TELECOM	DMS 10	1977	CANADA, U.S.A.	7.5
ITT-BTM-FACE	SYSTEM 12	1977	BELGIUM, ITALY	12
SIT-SIEMENSSCELT	PROTEO	1978	ITALY	30
VIDAR	ITS 4/5	1978	U.S.A.	12
ITT-NORTH TELECOM	DSS 1	1978	U.S.A.	28
NIPPON ELECTRIC CO.	NEAX 61	1979	U.S.A.	100
NORTHERN TELECOM	DMS 100	1979	CANADA	100
PLESSEY-STC-GEC	SYSTEM X	1980	U.K.	50
GTE-AE	N0.5 EAX	NA	U.S.A.	150
WESTERN ELECTRIC	NO. 5 ESS	NA	U.S.A.	NA

3.4.7 Packet Switching

As mentioned in section 3.3, the long-term development of telecommunication infrastructure can be seen as a transition from PSTN to NGN. NGN indicates an high-speed packet-based network that is capable of transporting and routing a multitude of services, including voice, data, video and multimedia (Goleniewski, 2006). From the pure technological perspective this transition can be represented by the transition from a multiple-technology network (where voice and data are transmitted and switched by different technologies) to a unique packet switching network. The magnitude of this transition emerges from the speed at which network operators announce investments for "all NGN migration" (Fitchard, 2003). The main driver of the transition has been the dramatic increase in demand for data transmission since the 1970s until the boost of internet in 1990s.

Data transmission (especially for multimedia) requires high-speed connection and broadband infrastructures, making the equipments presented in the previous sections highly inadequate as they were developed for the switching of traffic mainly constituted by voice. Technically speaking, data and voice can be transmitted and switched on the same infrastructure, however inefficiently. In particular, data traffic[51] often consists in "bursts" of data for few second and the delay to dial a circuit request for each message burst represents a great waste. In this circumstances, circuit switching and its pre-determination of the bandwidth represents a source of inefficiency.

In the late 1950s, engineers working the Advanced Research Projects Agency (ARPA) came across this technical problem while they were working at the development of an efficient time-sharing computer system through a widespread computer network. The obvious way to do it was using the existing leased telephone line. This option was rather costly not only because of AT&T monopolist position but also because the inefficiency of the use of circuit switching (Abbate, 1999). The need for a dynamic allocation of the bandwidth brought the engineers to consider a different switching mode that is the packet switching. As shown in the Technology Box 4, it uses a completely different approach from circuit switching.

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[51] Under the definition of data traffic there are different information type such as continuous media and computer data traffic. These have different basic requirements, in fact, for the former timely delivery is crucial whereas for the latter integrity of information during transmission is the most important feature (Ball, 1997).

Technology Box 4: Packet Switching and TCP/IP

Packet switching was independently invented in U.S. by Paul Baran at the Rand Corporation and in the United Kingdom by Donald Davies at the National Physical Laboratories in the early 1960s. It is a communication method where data (of whatever type) is split up into packets, each one labeled with the complete destination address, and individually routed between nodes over data links. In this way bandwidth is not pre-allocated but dynamically allocated. The efficiency gained in this change is partially counterbalanced by the increase in operative decisions like sorting and routing, and calculation using pathfinding algorithm. In fact, for each packet arriving at a node, an individual routing path needs to be calculated implying a massive use of memories and electronic components. The advances in semiconductors and computers made minicomputers available. Their substantial costs reduction compared to mainframe computers (used by switches) made the packet switching an economically viable solution reducing computing costs.

Particularly important for the internet and therefore for the development of a Next Generation Network was the Internet Protocol Suite, commonly refereed as **TCP/IP**. The Transmission Control Protocol (TCP) and the Internet Protocol (IP) are the two most important protocols for computer networking and internet, and the first two networking protocols defined in this standard.

The Internet Protocol Suite can be represented as a set of layers where the higher layers are closer to the users and dealing with abstract data, whereas lower layers relates more to data physical transmission. The TCP/IP model consists of four layers, from lowest to highest, these are the Link Layer, the Internet Layer, the Transport Layer, and the Application Layer. Each layer solves a set of problems involving the transmission of data, and provides a well-defined service to the upper layer protocols based on using services from some lower layers. Practically speaking, the settlement of this new standard allowed for the interconnection of different networks.

Packet switching resulted in a very successful technique for computer networking in Local Area Networks (LAN), and networks covering a small geographic areas, such as university campuses and hospitals). By 1968, virtually all such LAN networks were using packet switching.

Packet switching was not developed in the telecommunication switching industry and its use will remain isolated between computer professionals and in the domain of computer data network. It was only in the 1980s-1990s with the increase of data transmission demand that the "telephone world" (whose companies are often referred as *Bellheads*) with their legacy in terms of scientific and technological domains, and the "computer world" (*Netheads*) would cross again determining the end of the circuit switching technique.

After the success of packet switching, the ARPA project was challenged by a new technical issue, namely the interconnection of network based on different technologies. Engineers worked on this between 1973 and 1978 when Robert Kahn and Vinton Cerf elaborated the so-called Internet Protocol suite (see Technology Box 4).

3.4.7.1 "Bellheads[52]" first attempt to integrate packet technologies: the ATM

A distinguishing feature of TCP/IP packet switching and other LAN technologies (e.g. Ethernet and Token Ring) is to be connectionless. This means the information is transmitted without preconceived path between the source and destination posing serious QoS issues related to congestion, latency, and jitter[53].

When telecommunication manufacturers started being interested in broadband transmission, they foresaw some of these drawbacks (e.g. the impossibility of guaranteeing a minimum standard quality for voice transmission, system reliability, and costs) and for this reason they were very hesitant in adopting the early generations of packet switching for telephony networks. The most famous of these predecessors are the X.25 and the Frame Relay, whose main differences were the length of the packets, the efficiency of packet processing, and therefore the costs.

Instead, they developed the Asynchronous Transfer Mode (ATM), which was the telecommunication manufacturers' response to the increasing demand for high speed in data transmission occurred in the late '80s and to the technological competition posed by packet switching.

ATM is a series of standards that the ITU introduced in 1988 as part of a larger vision for the future of the networks called Broadband ISDN. ATM was designed to provides one platform, one infrastructure over which all the services (voice, data, video, multimedia, etc. etc.) could be quickly transmitted.

As ATM was developed by telecommunication manufacturers, where traffic engineering (and the control it provides on the network) is essential, it is a connection-oriented technique. Voice and data are both split in small, equal-sized packets, however, a virtual connection is established before these packets can be sent. Packets did not hold the complete address but they just bring the ID of the virtual connection they belong to.

In the intention of the developers, ATM should have overcome the limitation present in both circuit and packet switching. In particular, ATM was meant for overcoming packet switching drawbacks like, the reduced speed transmission due to the huge amount of information it has to manage through software control, and the impossibility of controlling each

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[52] Some of the recent developments in telecommunication industry can be seen as a battle between the *Bellheads* and *Netheads*. The former refers to companies, mainly old telecommunication equipment manufacturers, that think to the network structure from a circuit-switching perspective (the Public Switched Telecom Network presented in the section 3.3); whereas the latter refers to companies active in the computer networking industry, therefore using packet switching.

[53] Jitter is an unwanted variation of one or more characteristics of a periodic signal in electronics and telecommunication and latency is the delay associated with the time a packet takes to travel from an entry point to exit point.

packet's path.

The ATM standards drew on concepts belonging to the telecommunication community, rather than the computer networking community. Therefore, ATM positive features are related to features particularly suitable for telecommunication companies, such as easier network management, possibility of guaranteeing minimum QoS, accounting for (international) interconnection and billing according the usage network. Furthermore, extensive provision was made for the technical integration of most existing telecommunication technologies and their conventions into ATM.

Telecommunication companies have implemented ATM in their Wide Area Network (WAN)[54], close to the network backbone and not as local switches. For this reason, Goleniewski (2006) observes that despite manufacturers have dropped out ATM moving towards IP-based solution, ATM switches are still present in the network infrastructure (and probably they are not going to disappear soon). The reason of ATM failure can be found in the emergence of Ethernet standards (for instance, lately the Gigabit Ethernet) that provide high speed at much lower cost and complexity that ATM. Note than not all manufacturers actually adopted ATM. For instance, AT&T never developed or sold ATM switches.

3.4.7.2 "Bellheads" second attempt to integrate packet technologies: the IP-based switches

With the drop out of ATM, telecommunication companies started planning to integrate voice and data onto IP-based switches.

Nevertheless, IP based networks have some limitations often related to congestion. These may emerge from the routing algorithms and the quality of the paths they calculate (quality in terms of distance and traffic, two determinants of packets speed). Finally, recent services like VoIP and streaming need lot of bandwidth for their good functioning. In fact, in presence of bandwidth limitation latency and jitter emerge, seriously reducing the quality of the information transmitted.

The remaining issues related to the QoS have been solved through the use of techniques such as the Multiprotocol Label Switching (MPLS) that simplified and improved IP packet exchange giving to network operators more flexibility to divert and route traffic around link failure, congestion, and bottlenecks.

3.5 Conclusion

The aim of this chapter was to give an account of the technological evolution that occurred in the telecommunication switching industry from its origin until recent year. Furthermore,

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[54] WAN is a group of computer networks connected over long distances, often by telephone lines. This concept is opposed to LAN.

it provides the technical background for the chapter 5 where technological trajectories and paradigms will be explored.

The chapter has provided an overview of the sequence of switches generations. For each of them different aspects are tackled. Among these: the emergence of relevant technologies and components, their development, and their advantages over previous generations.

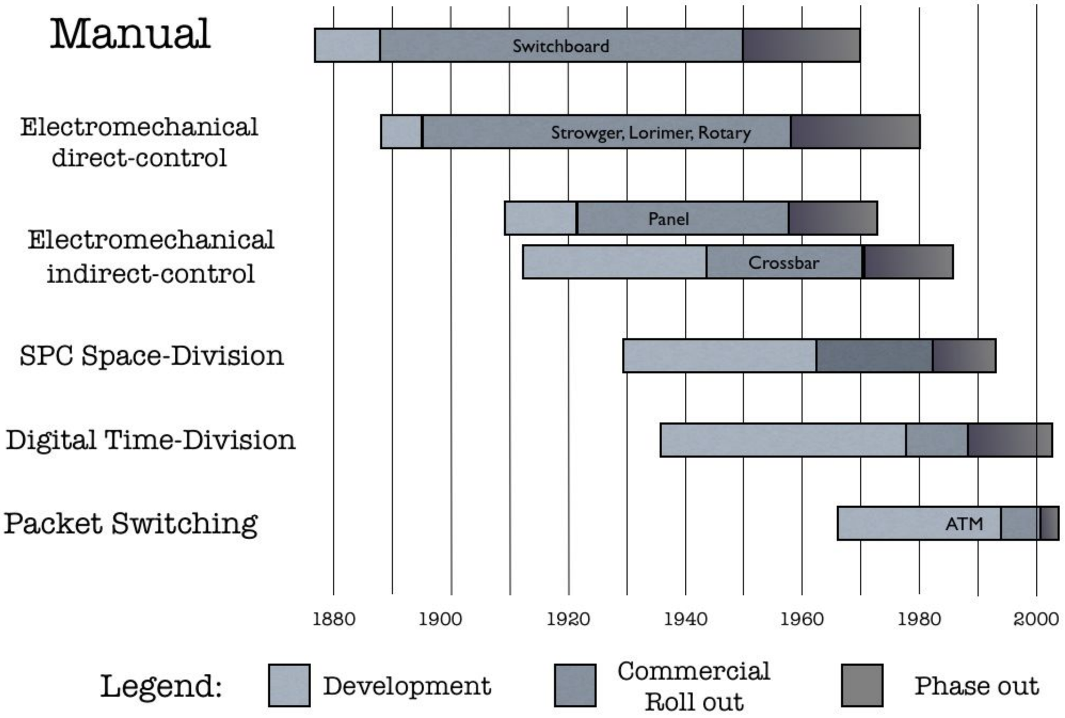

Figure 3.16: Summary of switching platforms

Source: Own compilation. Dates are approximate

Picture 3.16 provides a summary of the development of different switching platforms; in particular it highlights the time-frame of their development, commercial roll-out, and phase down[55].

Moving to the conclusions; *What are the relevant aspects of technological change in the telecommunication switches?*

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[55] Please note that the time span considered, although documented are rather indicative. Especially for the phase down. No data are available about when a platform completely disappeared from the network.

1. Telecommunication switches are complex systems integrated in a large network system. We can distinguish two drivers of technological change: first the engineering logic of “challenge-and-response” to specific technical bottlenecks and second the network operators (the users) whose infrastructure has to incorporate the new equipment. Given the internalist approach of the narration, this chapter focuses on the first one; users, demand and the extent they influenced industry evolution (and technological change) will be the topic of the next chapter. It emerges that several technologies had a very long gestation before being actually integrated in the switches, showing engineers’ perseverance in their ideas about switching design and how to pursue switching efficiency.

2. The history just presented indicates the presence of two sources of technological change: one internal to the industry and the second external. Internal technological change takes place in R&D departments of telecommunication operators and manufacturers; whereas, external technological change relates to specific switching components (in particular, semiconductors and computers), synergies with other network subsystems (for instance, transmission), and finally a competing industry such as computer networking.

3. The co-existence of both endogenous and exogenous drivers affects the innovation process. Firstly, the development of a new switching generation is a long (see figure 3.16) and expensive process. It took manufacturers up to 35 years to recoup their R&D investments in switches (Antonelli, 1991). Secondly, engineers face high technological uncertainty about advances in relevant components. Finally, figure 3.16 shows the overlapping life cycle of several switches generations; manufacturers needed to run several parallel project in order not to miss technological opportunities.

4. Following the previous point, we observe an interesting case of co-existence of several technologies embedded in different equipment vintages. The extent of this phenomenon depends on the users (the network operators), that actually decide the pace of new technologies’ adoption. As pointed out before (especially in section 3.4.5 explaining network digitalization), the adoption of a new switching platforms is not instantaneous, but it follows different rates in different parts of the network. These decisions are taken considering the profit opportunities brought about by the new equipments and the synergies with the other network sub-systems, such as transmission (figure 3.15). Furthermore, as it will be shown in the next section, the adoption process is often driven by several other factors such as: technological uncertainty, demand expectations or regulatory pressure.

5. From the perspective of engineers and historical accounts of the technological history of this industry, there are seven keys technological generations (see table 3.1 and figure 3.16). These are: (1) manual, (2) electromechanical direct-control, (3) electromechanical common-control, (4) Space-division SPC, (5) Time-division digital centralized SPC command, (6) Time-division digital decentralized SPC command, and (7) Packet Switching.

Furthermore, several key technologies facilitating the emergence of new generations of platforms are: switching division and multiplexing technologies, Storage Program Control (SPC), and analogue/digital convertor.

6. Since its early phase, the industry is characterized by the presence of few companies (as shown in tables 3.5, 3.6 and 3.7, each one mainly producing one switching platform for each generation (although, for each platform there are different models depending on their capacity and their position in the network). Furthermore, until recent years, the industry is characterized by one technological leader, the Bell Laboratories. In several cases, the innovation process is characterized by Bell Laboratories running ahead followed by the others.

7. To conclude, engineers working on new generations were looking at the economic viability of the new switches. The adoption by network manufacturers was driven by the economic gain deriving from several dimensions. These were: reducing switching costs (this, beyond the direct equipment cost, involves: installation cost, floor space, power consumption, flexibility in adding capacity or extra features, environmental conditions such as needs of cooling system, and maintenance), increasing capacity in order to meet the increasing the demand (of telephony at the beginning and of data transmission later), and the possibility of offering new services to customer.

Chapter 4

The evolution of the telephone switching industry

4.1 Introduction

According to the SSI approach discussed in chapter 2 there are three levels of analysis for an industry evolution: *specific dimensions of industry dynamics*, *structural dynamics* and *structural evolution*. As already mentioned, we are interested in the highest level, so the aim of this chapter is to provide an account of the *structural evolution* of the telecommunication switching industry from its infancy until the recent years. Recalling what said in chapter 2, this means to not only consider dimensions tackled at the lower level but also the industry as a whole: the emergence of new technologies, changes in firm's competences and skills, firm's diversification and integration strategies, and the role of public authorities and institutions.

This can result in a very complex task that needs some guidelines in order to keep consistency and avoid confusion. For this reason, the account is divided on two complementary parts. In the first part "the industry" is considered as a whole and for each period five dimensions are systematically discussed. These dimension were already presented in chapter 2 and they are: (1) market structure, (2) barriers to entry, (3) demand, (4) relevant actors end their relations, and (5) source of knowledge and technology. These guidelines allow to focus on selected issues, making the text consistent and comparable over time. The second part looks at individual firms; as this industry is rather concentrated with very specific country-characteristics, a qualitative (but also quantitative) analysis of the major players and their institutional context is carried out. The main focus will be on firms and their patterns of specialization and differentiation, internationalization, and market success.

In a nutshell, the aim of this chapter is to to build the basis for the study of the co-evolutionary process in the telecommunication switching industry. In fact, it provides an account of how relevant dimensions of analysis change over time and it sets the basis for the analysis of the assignees presented in section 5.6.

The chapter is structured as follows: section 4.1.1 will put forward and discuss the dimensions analyzed for each period. Section 4.2 is divided in four subsection describing different periods of the industry. These are: (1) the origin of the industry until World War I (1870s-1915), (2) the *Interbellum* between the two World Wars (1915-1945), (3) the maturity phase (1945-1980s), and (4) the years of telecommunications liberalization and internet (since the 1980s). Section 4.3 will move to an other level of analysis focusing on firms. For the most important manufacturers it will be highlighted their history, their competences evolution and strategies, and, when needed, their national context. Conclusions will follow.

4.1.1 Relevant dimension of analysis

From the description above, it emerges that being interested in the *structural evolution* of an industry means to account for several aspects; however, in order to make the history of the next pages consistent and comparable, we will focus on five aspects. From the list (and brief explanation) it appears that some dimension could pertain to the SCP or IO tradition (for instance, point 1 and 2). This is certainly true, in fact we claim that what makes the following pages an account in the SSI tradition, is both the joint consideration of all these five dimensions, and the detailed analysis at firms level in section 4.3. Section 4.2 will focus on:

1. Market structure of the national and global industry. Since the origin of the field of industrial organization market concentration and market structure represent key-characteristics in the analysis of an industry. This interest steamed from the investigation of possible abuse of monopolistic power in concentrated industry. In fact, the way an industry is organized affects firms' behavior and strategies. The literature points out the effect of market structure on innovative performance and profit (Scherer and Ross, 1990). Therefore the next pages we will look at the evolution of the market structure over time. As it was already anticipated in the conclusions of the previous chapter, the market we are interested in is the wireline telecommunication switch. Furthermore, to the extent it is relevant for the description, the structure of the downstream market will be also described.

2. Barriers to entry. The second dimension considered here naturally follows from the previous one; in fact, barriers to entry will affect the number of players active in the industry and therefore market structure. High barriers to entry are characteristic of monopolistic and oligopolistic markets, where cartels can emerge. Moving to general welfare considerations, barriers to entry (and to exit) define the contestability of a market and therefore its level of efficiency (Baumol, 1982). According to Porter's five forces model, the nature and the strength of barriers to entry sizes the threat for new entrants in the industry and therefore characterize the competition in the industry. Barriers to

entry can emerge from different sources and literature specifies several types. The most common are: economies of scale, patents, economies of product differences, brand equity, switching costs or sunk costs, capital requirements, access to distribution, absolute cost advantages, learning curve advantages, expected retaliation by incumbents, and government policies.

3. Market demand. A description of an industry cannot leave aside considerations about demand. In fact, market demand and the expectations about it drive firms' strategies. In the telecommunication switching industry, we can distinguish two relevant levels of demand: the *intermediate* demand and the *end users* demand. The former relates to direct demand deriving from the network operators, who are the actual buyers (and deployers of the new network equipments); the latter refers to the demand for telephony service. These are tightly linked as the latter sizes the former: the higher is the demand for telephony services, the higher is the demand for switch capacity. This mechanism works not only for mere expansion of the market but also through the demand for new or advanced telephony services. In fact, looking at infrastructure evolution we can further qualify demand and distinguishing between two types of demand: one aiming to network expansion of the network and one aimed to substitute/upgrade the existing network. The former refers to the attempt to achieve the universal service goal, whereas the latter refers to offer advanced services to users. This specific distinction is relevant because these two types of demand characterize different phases of the industry evolution. As emerged from the previous chapter, the understanding of demand dynamics is a driver for technological advance in the industry; for instance, the latest switching platforms were designed in order to facilitate the introduction of new services.

4. Relation between relevant actors (manufacturers, operators, and governments). From the previous chapter, besides the switches manufacturers, it appears fundamental the role of the downstream market, i.e. the network operators[1]. They are responsible for the process of adoption and diffusion of switching platforms, and ultimately their success. For this reason, it is of pivotal importance to understand how the relation between manufacturers and network operators has been organized and how this has evolved over time. Another relevant actor is the national government. As the previous chapter is purely technological its role has not emerged yet. However, telecommunications industry was considered a strategic industry for developed country and therefore targeted by national industrial policy, such as: public procurements procedures and R&D subsidies through the state-owned telecommunications manufacturer. Therefore from an evolutionary perspective, it is actually interesting to point out how the relevance of both sectoral and national aspects changed over time. Figure 4.1 provides a representation of the actors we are going to analyze and exemplify some of

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[1] These can be also referred as PTT (Post, Telegraph and Telephone) companies when they indicate the pre-liberalization monopolist (often state owned) incumbents.

the possible relations between them. As this work is centered on telecommunication switching manufacturing, other actors' strategies and behaviors will be discussed to the extent they are relevant for the switching market.

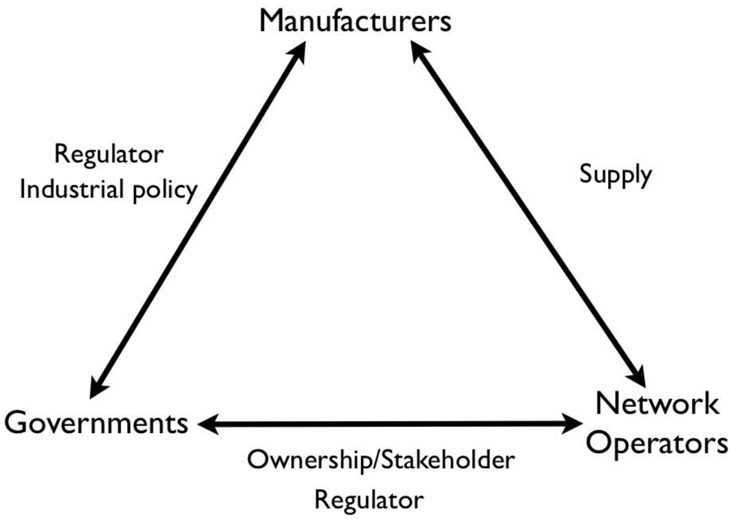

Figure 4.1: Main relation among actors
Adapted from Bekkers, 2001

5. SOURCES OF KNOWLEDGE. Figure 4.2 displays some of these connections pointing out three external source of knowledge. These are: (1) the components industry (particularly the semiconductors industry), (2) the computer and software industry, and (3) the intermediate users (in particular the PTT laboratories). In the description of the evolution of the industry we will focus on these three relations and we will show the relevance of their knowledge flows (represented by the arrows).

4.2 Structural evolution of telecommunication switching industry

This section constitutes the first building block of this chapter as it describes telecommunication switches industry *structural evolution.* This description is structured using as guidelines the dimensions put forward in the previous section.

The history of the industry is divided in different phases and each of them is separately discussed below. The periodization for the description of the industry differs from the one

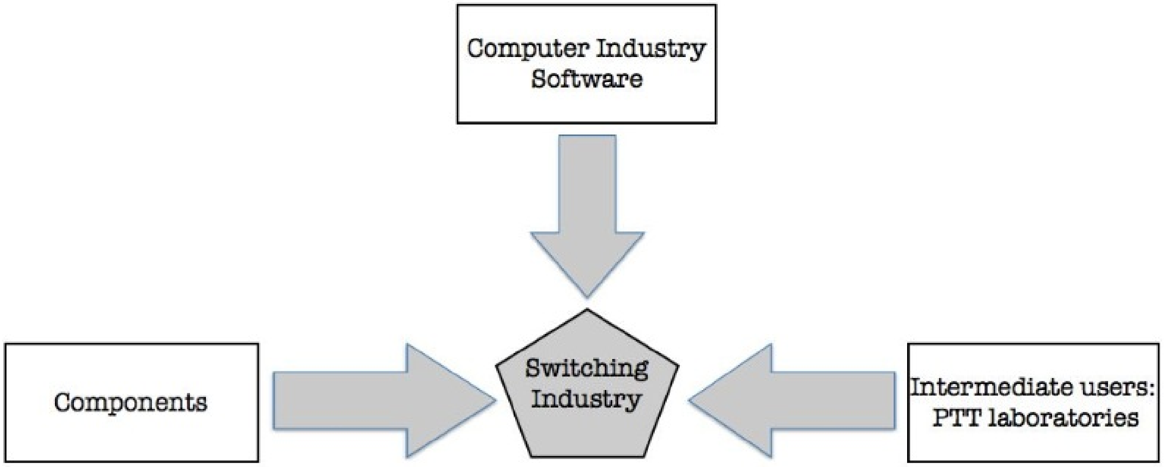

Figure 4.2: Knowledge linkages in the telecommunication switching industry.

used in the previous chapter as it is not strictly related to technological change but it depends on other major events. The periods considered are:

1. Origin of the industry, until World War I (1870s-1915);
2. *Interbellum* period (1915-1945);
3. The maturity phase (1945-1980s);
4. The years of telecommunications liberalization and Internet (since the 1980s).

More emphasis will be placed on the maturity phase, however, as already explained in the previous section it is important to look also at the early phase in order to appreciate the long term stability of the industry.

4.2.1 The origin of the industry until World War I (1870s-1915)

The telecommunication switching industry started in the late 1980s in the United States with the invention and installation of the first switchboard[2]. Unfortunately no data are available about **market concentration and market structure** for this early phase; however,

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[2] The first manual switchboard of a private telephone agency was installed in New Haven, on 28 January 1978 and it served 21 subscribers.

we can describe the process of market creation. The dynamics of the switch market (here, switchboards and Strowger system) followed the dynamics of the telephone service. Therefore, given the *spectacular*[3] annual rate of growth of the telephone station in the United States, this became the first relevant market for telephone exchanges.

In this perspective, it is interesting to devote some attention at the American context and to look at the emergence of the flagship "natural monopoly" that was the AT&T system. With the expiry of Bell's patent in 1893 the monopoly of the Bell Telephone Company ended and several new operators entered the market[4]. From this point on, the U.S. telephony market will be characterized by a dual structure: on the one hand the Bell Operator Companies (BOC) directly or indirectly owned by Bell Telephone, and on the other hand the independent companies (mainly active in rural areas or medium and small cities) organized in the United States Independent Telephone Association (USITA). The potential welfare gain from competition was offset by the lack of interconnection between networks and therefore different handsets (connected to different networks) were needed in order to reach all the customers. Furthermore, Bell Telephone held a monopoly on the trunk network, meaning that only Bell customers could make long-distance calls. Bell Telephone's refusal to interconnect with other network was part of its president T. N. Veil's strategy against the raising competition from the independents and resulted in protests and legal suits pursued by the independents and their customers. This situation rose the attention of the American government, worried about the rising of a monopoly in the industry, especially after Bell Telephone's acquisition of Western Union[5]. The turning point was the Kingsbury Commitment of 1913 that formalized Bell Telephone's monopoly; in exchange, AT&T agreed with the Attorney General to divest Western Union, to provide long-distance services to independents under certain conditions, and to refrain from further acquisitions if the Interstate Commerce Commission objected.

This dual structure provided opportunities for the manufacturers to compete. For instance, Western Electric was suffering a *"not invented here"* syndrome and independent companies drove the diffusion of automatic switches against manual or semi-automatic (see previous chapter). Therefore the presence of heterogeneous network operators provided a window of opportunity for the entry of new manufacturers such as Stromberg-Carlson, the Home Telephone Company of Rochester (active between 1902 and 1907), the North Electric and the Strowger Automatic Telephone Exchange.

Looking at the European situation, the production and commercialization of switches was initiated through the licensing of American patents to European companies (Kingsbury, 1915). Western Electric was the leader company in the American market and owned some subsidiaries in Europe; among them the Standard Telephone and Cable (STC) in Britain, Standard Elek-

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[3] Chapuis (1982, page. 137) reports 20%.

[4] We should note that the early years of the Bell Telephone companies were rather troublesome, in fact there were several lawsuits challenging the validity of Bell's patents and the conflict with Western Union Telegraph Company. For more details see subsection 4.3.1.6.

[5] Western Union was founded in 1851 in order to provide telegraphic services.

trik Lorentz (SEL) in Germany, Bell Telephone Manufacturing (BTM) in Belgium, and CGCT and LMT in France.

Although we do not have consistent data about firm size, in this period we observe the transition from handcraft to large-scale production (Chapuis and Joel, 1990). The period between 1880 and 1910 saw the mechanization of several manufacturing processes among which also the production of telephone equipment. Therefore, the early switch producers, generally converted from other productions such as sewing machines or organs factory, disappeared. Chapuis (1982) describing the industry structure between 1880 and 1910 points out that:

> [the financial concentration and mechanization] were to bring about the disappearance of all the quasi-craft workshops devoted to production, on a very small scale, of equipment for telegraphy and later, in its wake, for telephony. The only ones to survive would be the big companies, which were frequently interconnected under patent licensing arrangements or even cartel-type market-sharing agreements, or which were simply subsidiaries of a single international trust and whose dependency status was thus even greater. Small national industries which had been set up, in the form of craft workshops, in a number of countries were to be very rapidly absorbed or ousted by companies controlled by foreign capital. This foreign dominance, which, given the free convertibility of currencies then existing, faced no obstacle, was mainly American, due to the economic and financial power of the United States combined with its technological progress (page 100)

The exit of small companies and the concentration in few (capital intensive) corporations (even rather geographically concentrated) will constitute **barriers to entry** for the next years in the industry.

Turning now to the **end users demand** we can see a general upward trend, with some distinction in the pace.

Figure 4.3 shows patterns of telephony diffusion in the United States and Europe, where for technical reasons[6], it was difficult to demonstrate telephone network. Specifically, about the English case, Sir William Preece[7] noticed:

> The telephone had been used in this country [meaning United States] to a large extent, but there does not appear to be the want of it in England that there is in America. One thing which strikes one in America is the enormous extent to which they apply the telegraph and the telephone for their own *domestic* purposes (Kingsbury, 1915, page. 208 emphasis added)

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[6] In the United States, the presence of district telegraph made possible the demonstration of interchangeable connection between few subscribers, lowering the uncertainty about the concept of telephone network. By contrast, in Europe, the absence of such district telegraph system obliged the adoption of the entire (and very expensive) telephone exchange (Kingsbury, 1915).

[7] Sir William Henry Preece was an electrical engineer, active in the field of wireless telegraphy and telephony. He served as president of the Institution of Civil Engineers between April 1898 and November 1899

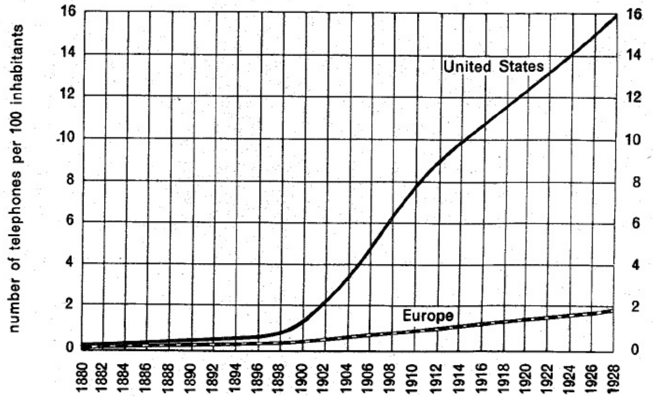

Figure 4.3: Development of telephony in United States and in Europe
Source: Chapuis, 1982 (Reported from the Bell Telephone Quart. 7(3), July 1928)

This quotation highlights not only that the U.S. market was more receptive, but also the presence of two types of users: the business activities and households.

In the previous pages there was already the opportunity to point out some of the features of the **relation among the actors** in the industry and in particular between the manufacturers and network operators in the United States. Again, it is in this early phase that a relation of vertical integration is established between Bell Telephone and its supplier Western Electric. This latter company was founded in 1856 and was rather diversified, producing different electrical products like typewriters, alarms and lighting and had a close relationship with the telegraph company Western Union to whom they supplied relays and other equipment. Western Electric was acquired by Bell in 1881 and until 1991 it would be the manufacturer for whole AT&T.

In Europe the situation was different, as we see the emergence of state-owned PTT in almost every country (table 6.7 summarize the process for some countries). From the manufacturing perspective, it is this the time that a tight relation between manufacturers and network operators emerged. Noam (1992) points out the monopsonistic position of the PTT in the market for telecommunications equipment, and he describes the procedures throughout which several PTT companies[8]) organized their public procurement tenders sharing the market among the national suppliers and few other foreign manufacturers.

At the origin of the industry, **sources of knowledge and technology** were internal to the industry. Innovations were carried out first in handcraft laboratories and later in the R&D laboratories at the manufacturers facilities.

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[8] For details see Noam (1992) at page. 82-83 for the Bundespost in Germany and 124-125 for the Post Office in the United Kingdom.

Table 4.1: Towards the PTT

Country	First initiator	Initial network construction and use	Intermediate step	Nationalization of the network(s)
Germany	The government (Reichspost), which integrates postal, telegraphy and telephony services	In-between rural post offices, as an alternative for telegraphy offices	Network roll-out for private usage, starting in Berlin	Not applicable, since there were no private networks
United Kingdom	One private party (UTC), with a concession, quickly followed by competing state-owned network (Post Office)	In larger cities. UTC had problems to lay out the network in certain city districts	Government urged municipalities to build their own networks, resulting in a failure	Government bought the private network at a price far below its real value (1911)
France	One private party (STG) with a concession, under strong regulatory limitations	In a dozen large cities only	Government builds networks in smaller cities, and long-distance lines	Government nationalizes the private network after the concession expired (1889)
The Netherlands	Several private parties with local concessions	In most larger cities	Municipalities take over local private networks or build new networks	Government had bought private and municipal networks by 1927, except for the 3 largest networks. These remains under municipal control until 1940

Source: Bekkers, 2001

4.2.2 *Interbellum* period (1915-1918)

The *interbellum* period consisted in a period of consolidation for the telecommunication switching industry. In particular, it is in this period that basically all the existing switches manufacturers emerged.

The changes in the map of Europe after the World War I brought about changes in the ownership of several domestic subsidiaries. For instance, the production plants set by LM Ericsson and Siemens in Russia were confiscated, and Siemens also lost the control of several other plants located in Italy, Great Britain and Belgium (Chapuis, 1982). Looking at the **worldwide market structure** we can observe that the market for automatic switches was very concentrated and dominated by a few companies; those were: The International Automatic Electric Corporation of Chicago (the Strowger company), the International Western Electric Corporation of New York (owned until 1925 by AT&T and than by ITT), Siemens & Halske in Berlin, and L.M. Ericsson in Stockholm. These companies were rather specialized in their production. The International Western Electric Corporation and L.M. Ericsson were supplying other automatic systems than Strowger type; the former developed the ROTARY system and the latter the LME 500-point system.

Table 4.2 shows the size of the investment (expressed in number of workers) these companies were ready to undertake in the foreign market and it gives an idea about the power relation among these companies.

Table 4.2: Size of manufacturers (number and percentage of employees) around 1925

Company	Workforce	%
Western Electric	13,000	53%
Siemens	6,000	24.2%
Ericsson	3,800	15.4%
Automatic Electric	1,800	7.4%

Source: Huurdeman, 2003

The worldwide market was rather competitive, however in 1921 some negotiations started in Amsterdam in order to create a cartel and equally share the world market[9].

However, because of licensing agreements, negotiations were not successful and they terminated with a litigation in front of the Court of Appeal in London. We can therefore conclude

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[9] "... It was thus planned to divide the market up as follow:

- the two American companies would get the American continent, Japan, China and Belgium;
- besides Germany of course, the German company would get Central Europe, Italy and Spain;
- the Swedish company would get the Nordic countries, Holland and Poland, as well as Spain and an opening to Latin America and the Balkan countries of Europe..." (Chapuis, 1982, page. 261)

the presence of a dual relation between these manufacturers: on the one hand collaborating and licensing technologies, on the other hand fiercely competing outside the respective domestic markets.

It follows that this industry was characterized by high **barriers to entry**, and the only entries we observe in this period from a regulatory intervention. As pointed out before, Western Electric owned several foreign subsidiaries, which were at the centre of a regulatory intervention in 1925. In fact, the antitrust regulator obliged the divestiture of the International Western Electric acquired by ITT for $30 millions. The two main plants acquired were the STC (Standard Telephones and Cables) in London (United Kingdom) and the BTM (Bell Telephone Manufacturing Company) in Antwerp (Belgium). As consequence, ITT would develop into a leading *multinational* company, lacking a preferred domestic market and based on a network of national subsidiaries.

Figure 4.3 is partially covering the period here considered showing the steadily increasing path of the **end user demand**. Looking at the **intermediate demand**, figure 4.4 displays the expansion of the automatic lines. Despite the data do not correct for the size of population it shows the geographical distribution of these lines and a faster expansion in the United States.

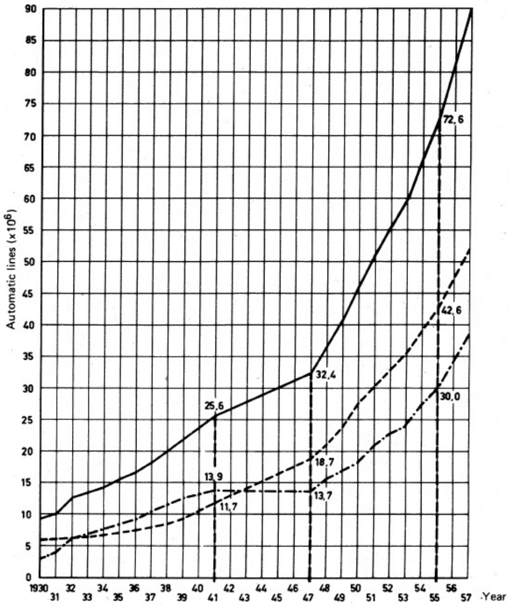

Figure 4.4: Expansion of automatic telephony. Number of installed automatic lines

Source: Chapuis, 1982. Legend: —- World; - - - - U.S.; -.-. Other countries.

Additional evidence[10] shows also an other interesting trend that is the phase out of manual

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[10] See Chapuis (1982) at pag. 286-287

switchboard from national networks. In particular, it emerges how in the 1930s the German network was rather advanced compared to other European countries, with half of its subscribers line automatized. One of the main driver of this technological shift was the increase in labor cost that brought about a substitution of a labor-intensive technology with a more capital intensive ones.

In this period the **relations among the actors** continued to be tight. In particular, each telephone market of developed countries started being served by a state-owned monopolist[11] whose network is built using preferred suppliers. Following the trend established in the previous period, procurement with pre-defined market shares continues to regulate the relation between PTTs and the manufacturers (Noam, 1992).

As consequence of the tight relation between PTTs and manufacturers, in this period we see the emergence of PTT's laboratories as **source of knowledge**. Starting from the flagship case of the Bell Laboratories, these laboratories would represent a source of science-based research, necessary for the development of the latest switching platforms. The most important PTT laboratories were:

1. The Bell Laboratories in the United States;
2. The GPO Dollis Hill Research Centre in United Kingdom;
3. The Electrical Communication Laboratory (ECL) established by NTT in Japan.

The establishment of PTT laboratories will determine a path of vertical specialization between PTT and manufacturers: the former will be involved in basic research whereas the latter in development and production research (Fransman, 2002).

4.2.3 The maturity phase between World War II and the 1980s

World War II impacted the telecommunications industry as some countries not only lost their infrastructure (French government recognized the destruction of the 90% of the network) but also their manufacturing industry. Similar to the consequences of World War I, Siemens lost some foreign subsidiaries located in winning countries, whereas Philips had the opportunity to enter the industry taking over Siemens-type system in order to replace the ones destroyed by the war. Furthermore, the Marshall Plan played a fundamental role in the reconstruction, facilitating financial and technology transfers. In this scheme, engineers from Western Electrics and Bell Telephone Laboratories instructed Japanese engineers and executives on network reconstruction and equipment quality manufacturing. In general, pre-war levels of phone-penetration were achieved again in 1950 (Noam, 1992).

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[11] PTT (Postal Telephone and Telegraph) generally indicates the monopolistic company providing telephone and telegraph service in most of the country. Apart the case of AT&T, PTTs were generally state-owned.

The period following the Second World War can be considered the maturity phase of the industry, however, punctuated by radical technological change. In fact, the previous chapter points out the commercial development of three switching platforms in the period here considered. These are: crossbar, SPC space-division (for simplicity called the "electronic switch") and digital time-division (from now on simply "digital switch"). Each of these platforms represents a radical innovation as it involves radically different technologies (as explained in the previous chapter) and new firm's competences (Clark et al., 1988). In this section, we will look at the extent these technological discontinuities have actually affected the industry.

Table 4.3 present the evolution of the worldwide public switching market share[12]. As the data are taken from different sources we should compare them carefully, nevertheless they depict some changes in the industry **market structure**. In fact, there is an evident increase in the number of firms but it is difficult to assess to what extent these are real entries (compared to table 4.2). In fact, Northern Telecom and ITT emerged from a regulatory intervention of the U.S. authority. Fujitsu (Fuji Telecommunications Equipment Manufacturing) was spun off in 1935 from a joint venture between the Furukawa Electric Company and Siemens (see section 4.3.1.10 for details). Finally, CIT-CGE (that will later became Alcatel) looks like the only "genuine" entry in the industry, however it is the result of the merge of CIT and ITT subsidiaries coupled to the French government's explicit effort to create a French telecommunications manufacture industry (see section 4.3.1.1 for details).

Moreover, this table shows the exit of some companies; these are ITT, GTE, Plessey and GEC[13]. Their exit took place around the same time and it can be related to the difficulties of developing and commercializing new digital switching platforms. In the next section, dedicated to individual firms, it will be described these exits, focusing on the motivations, the ways they occurred, and their "inheritance".

Secondly, looking at surviving firms we can notice the long lasting leading but declining role of AT&T. This decline is coupled with the success of some firms like Siemens, Ericsson and Northern Telecom, which were able to gain growing share of the market. Furthermore, data shows that Alcatel was actually able to finally surpass AT&T.

Given the importance of domestic markets it is also interesting to look at the manufacturers' share for selected domestic markets[14]. Graph 4.5 depicts suppliers share of installed digital ports in six countries up to 2001; it points out that almost each relevant country has a preferred *domestic* suppliers[15]. Furthermore, it appears that AT&T was particularly strong in its domestic market but not really effective in entering other markets (especially in Eu-

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[12] With a strict definition of the time-frame only the first column would be relevant. However, the last columns refer to digital switches, a platform commercialized since the early 1980s but developed since the 1940s (see the previous chapter).

[13] Also Philips and Stromberg-Carlson left the market, but this is not visible from the above table.

[14] Selection is carried out considering developed countries with a domestic switch manufacturer.

[15] The results should consider that ITT is not considered because in 1999 had already left the market. As its switching platform was taken over by Alcatel, we could consider part of the Alcatel share as actually ITT's share.

Table 4.3: Approximate shares for worldwide public switching market

Company	Country	1960-1965	1986-1988	1995-1998
AT&T	USA	26-28%	21-24%	15%
ITT	USA, Europe	12%		
CIT-CGE	France	1%		
Alcatel	France		12-14%	18%
Siemens	Germany	10%	9-10%	14%
Ericsson	Sweden	5%	9-10%	12%
Northern Telecom	Canada	2%	10-11%	14%
GTE	USA	6-7%	2-3%	
NEC	Japan	3%	5-6%	
Fujitsu	Japan	2%	3-5%	
GEC	UK	2.5%		
Plessy	UK	2.5%	5-6%	
Italtel	Italy	2%		
Other		25-30-%	15-25%	28%

Source: Chapuis and Joel, 1990 and Dittberner Associates, Inc. (2003)

rope). This is consistent with the numerous complaints that the U.S. government filled with the European Union because of the non-reciprocity of market opening (Noam, 1992). It also shows the success of Northern Telecom able to penetrate foreign markets, and in particular the U.S. market. Finally, the only country displaying a more balanced group of suppliers is Japan, however this is only appearance as all the suppliers are Japanese and all of them collaborating in the Electrical Communication Laboratory (ECL) established by NTT (the Japanese network operator).

The figure and the graph above suggest the presence of high **barriers to entry**. It is difficult to disentangle the effect of barriers arising from different sources; however for descriptive purposes we can distinguish two main types of barriers. The first type is mainly “technical” whereas the second is related to the procurement procedure.

Telecommunication switches are integrated in a large technical system, namely the telephone network, meaning that they have to be compatible with the existing deployed equipment. The technical literature points out that different switching platforms are hardly compatible and that can be incompatible with the transmission system too. In practice, it means that once a network operator chooses a supplier there are very high switching costs because of the extra development cost for integrating new equipments. In the previous section, we highlighted the presence of two transmission standards, the E1 diffused in Europe and the T1 diffused in United States and Japan. Switches designed for these two environments are

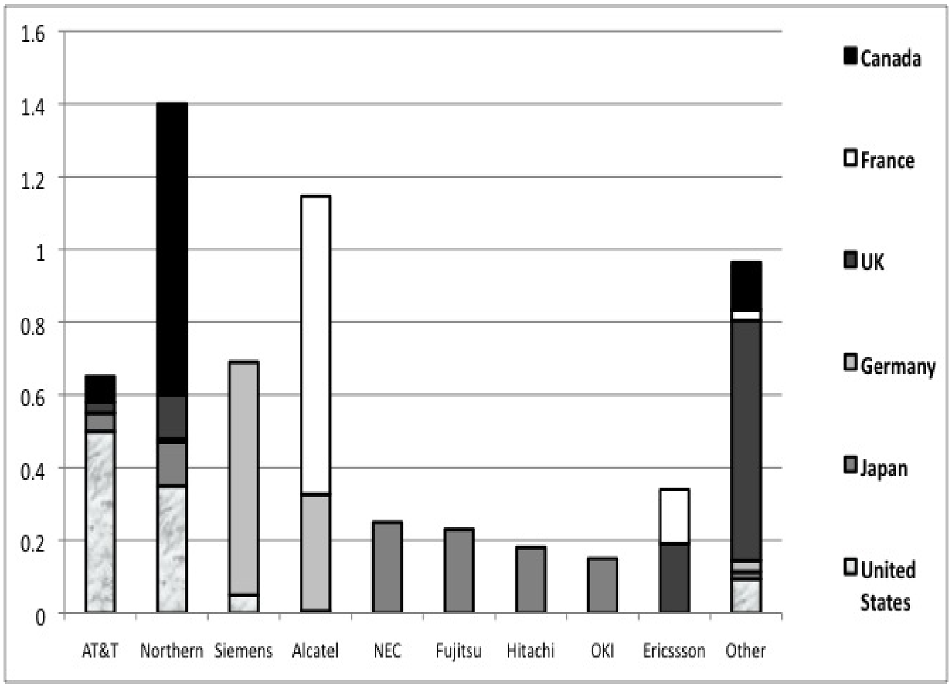

Figure 4.5: Suppliers for relevant domestic markets

Installation base of digital ports. Source: Dittberner Associates, Inc. 2003

not compatible, therefore the strategic decision of a firm to enter a foreign market should be combined with extra development expenditures in order to adapt the in-house switching platform.

Another relevant technical barrier to entry is represented by the high R&D costs firms have to undertake since the inclusion of electronic components. A well known example is the cost involved with the development and production of the No. 1 ESS, for which AT&T spent in total over $100 millions (Chapuis, 1982). This figure gives an idea of the size of the investment required in order to enter the switching market.

In this context, public procurement rules constituted a further barrier to entry. Noam (1992) reports several requirements a manufacturer had to fulfill in order to be able to participate to international tenders. For instance, in some countries only national companies could participate or each piece of equipment (object of the tender) was required an approval from the (often state-owned) network operator. The ultimate purpose for these rules was to maintain the *"status quo"* and to keep the established market shares.

In order to understand more about these barriers it is useful to look at one example, such as the attempt made by the Canadian Northern Telecom and the Japanese NEC and Fujitsu to access the U.S. market (Fransman, 1995). All these companies tried to exploit a window of opportunity emerging from regulatory pressure[16]. A first barrier was the need for manufacturers other than Western Electric to obtain the approval on their equipment. Northern Telecom, already present in the American independent market and also exploiting its special ties with the AT&T system[17] was willing to undertake the procedure and to invest in the required technical modifications. Finally, the first DMS10 in a BOC's network was installed in 1980. According to Chapuis' book published in 1990 (therefore written rather close to the period under examination), other firms tried to follow Northern Telecom strategy, investing around US $ 100 million per year. On the other hand, NEC attempted to access the same market and in the late 1980s it held only 0.1% of the market. According to Fransman (1995) part of the failure was because of the *interpretive ambiguity* related to the success of digital switches; the late decision of NTT to move to digital switches (opposed to the early move of Canadians) gave to Japanese manufacturers a disadvantages in term of development (and reliability) of their own switching platforms.

In the first five years after the end of World War II the drivers for **intermediate demand** were the reconstruction of the infrastructure destroyed by the conflict and the full automatization of the network through the adoption of crossbar switching systems. The implementation of nationwide automatic switching networks was delayed by the World War II (apart the United States, as shown in figure 4.4) but taken up again in the 1950s and completed (in developed countries) in the 1980s. In fact, between the 1940s and the 1950s the average annual production of automatic lines increased from 1 million to 5 million per year (estimation provided by Chapuis (1982)). The decay of the 1950s was characterized by widespread economic growth, followed by an increasing demand for phone lines that determined long waiting lists (Bekkers, 2001); however, these expensive processes were undertaken with budget constraint imposed by the financial provision for telecommunications allocated in tight national budgets and this directly affected the amount R&D done by the operators (Chapuis and Joel, 1990).

In this period we see the beginning of a trend that will become one of the main drivers of future transformations of this industry: the emergence of data communication. This demand was linked to the diffusion of advanced services such as (among the others) telex, electronic mail and remote data processing. These services can be provided both on the Public Switched Telephone Network (PSTN) and on private networks (that depending on the type of technology, we can refer them as LAN). The growth of both these networks will be rather fast, as well as the revenues from these types of service. Estimations show that common carriers revenues from public data communication increased from about 1% in 1960 to 10% in 1987 (Dunn and

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[16] Despite Western Electric was the first in developing a tandem digital switch (the famous No. 4 ESS) was late in developing a digital local switch (the No. 5 ESS). This delay, coupled with the early adoption of digital local switch produced by Stromberg-Carlson and Northern Telecom by the independents, rose the attention of the regulatory authority worried about the service quality of Bell system customers. Chapuis reports:

> "...Regulators were asking why independent telephone companies, but not the BOCs, were buying time-division digital systems (Chapuis, 1982, page. 351)..."

[17] Until 1949, Northern Electric was owned by Western Electric.

Johnson, 1989). These substantial rates of growth were similar in private networks.

The importance of private networks both for telephony and data communication is related to the growing importance of the *large users*[18] such as corporations, government organizations and universities. In the 1960s, European and American economies experienced a decrease in the importance of their manufacture industries and a growth of services[19]. This change in specialization transformed telecommunications infrastructures in production assets[20], so companies started developing communication capabilities and establishing specific positions such as (tele)communication managers. In order to enjoy advanced services (like short term dialing, call forwarding, and unmetered internal calls) and in a cost-cutting perspective, large users started to look at different solutions and to build private networks. At the early phases the PTTs were not interested in this market and therefore large users started using Private branch exchange[21](PBX) looking directly to manufacturers and contracting external firms for network maintenance (Noam, 1992).

The **relation among the relevant actors** further consolidated in this period. In these years PTTs flourished because of what Noam calls "postal-industrial-complex", a system of economic and political relations that enforce their dominant position. In fact, on the one hand, in many countries, PTTs represented one of the biggest company with a noticeable bargaining power in term of political votes; on the other hand PTTs often shared their economic benefits with some other groups, like manufacturers in a monopsonistic relation. Again this was the time of consolidation of the vertical or quasi-vertical relation between PTTs and manufacturers. More integration was pursued through cartels; for instance, in France, the participation of French manufacturers were improved toward the creation of SACOTEL, whose main purpose was to "prohibit ruinous and savage competition" through the control of patents and equipment specification (Noam, 1992). Developed countries started to consider telecommunication infrastructure as pivotal for economic development and for this reason, telecommunication manufacturing industry became a strategic industry to nurture and protect. In particular, during the 1960s, national governments tried to establish *national champions* favoring them through export credits, subsidies for R&D (often through the PTT laboratory) and the public procurement.

The PTT monopolistic position was justified not only using the concept of "natural monopoly" but also the "universal service" one[22]. The latter established the access to telecommunication service as a basic right and need beyond any questions of economic efficiency (OECD, 1991*b*). This concept would be often used in order to support the monopolistic

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[18] In U.S. the largest 3% of users typically account for 50% of all telephone revenues (Noam, 1992)

[19] Noam (1992) cites different studies in which it emerges that in 1980 the 37% of the work force was engaged in information jobs (Beniger, 1986) and in the U.S. this percentage is even higher, 54% (Strassman, 1985)

[20] For instance, for Citicorp, after salary and real estate, telecommunications is the third major expenditure.

[21] The PBX is a switch system owned or leased by an organization and generally installed on its premises, which provides lines for internal communications between local extensions and a smaller number of lines to the public network.

[22] Both were conceived by Theodore Vail, at AT&T, in the late 19^{th} century.

mark-up that allows cross subsidies from long distance-calls to local call and therefore to delay liberalization. From a regulatory perspective, AT&T enjoyed a regulated monopoly through the 1950 and the 1960 and in Europe, the Commission's attempt to play a role in telecommunications failed (Noam, 1992; Evans, 1983).

In order to evaluate the **source of knowledge** relevant for this period we need to look at the type of technologies underlying each switching platform emerged during this period. In general, we can see a growing degree of complexity and the need to master and integrate an increasing number of technologies. The substitution of mechanical parts with electronic parts, will make electronic industry a fundamental source of new components both for the development and the economic feasibility of new switching platforms. An other example is the use of Storage Program Control (SPC) that will make computer memories (and software) relevant for the switching industry.

Comparing this period with the previous ones, we can see the expansion of the external knowledge sources and the increasing importance of the components industry whose embedded contribution became crucial. Following this point, manufacturers faced a new strategic decision concerning the relation with their suppliers from the computer and semiconductors industry. Whether some companies (such as AT&T, NEC, Fujitsu, Siemens) were vertically integrated with their suppliers, other companies like Northern Telecom and Ericsson were dependent on external suppliers (for instance, Ericsson had a strategic alliance with Texas Instruments). According to Fransman (1995) none of these strategies turned out to be a good predictor for future success.

4.2.4 The latest days covering the years of telecommunications liberalization since the 1980s

Since the 1980s the telecommunication industry has gone through a turmoil that also affected the manufacturing industry. In this period we register both technological discontinuities, with the emergence of packet switching boosted by the fast diffusion of Internet, and institutional discontinuities, related to the wave of liberalization undertaken in the service sector.

Looking at the **market structure** of the industry we can examine two switching platforms commercialized in this period: the digital and the "broadband[23]" switches.

Data about the former are reported in table 4.3 and table 4.4. They indicate not only the end of the leadership of AT&T but also the entry of two "new" manufactures from China. Despite their small market share they represent one of the few examples of successful entry in the worldwide market and technological catching up (Mu and Lee, 2005).

What these tables are not capturing is the shrinking of the market for this platform; table 4.5 looks at the technological distribution of ports installed in 2005 and shows, in fact, the almost complete disappearance of TDM (digital) switches.

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[23] More precisely, we focus on switches using packet switching.

Table 4.4: Top 10 manufacturers for TDM digital switches in 2001

Company	Country	Rank	Ports (Thousands)	%Total
Alcatel	France	1	275,555	18%
Lucent (AT&T)	USA	2	267,724	17.5%
Northern Telecom	Canada	3	219,877	14.4%
Siemens	Germany	4	214,252	14%
Ericsson	Sweden	5	151,180	12%
NEC	Japan	6	76,812	5.0%
Fujitsu	Japan	7	55,561	3.6%
Huawei	China	8	39,668	2.6%
Great Dragon	China	9	37,214	2.4%
Marconi	UK	10	34,068	2.2%
Other			159,218	10.4%

Sources: Dittberner Associates Inc, 2003.

Table 4.5: Ports shipped in 2005, by protocol

Protocols	Total (thousands)	Market Share (%)
VoIP Ports	92,368	90.03%
ATM Ports	3131	3.05%
TDM Ports	7,089	6.91%
Total	102588	100%

Sources: Dittberner Associates Inc, 2003.

Table 4.6 displays the top-five vendors for IP-based switches in 2005. Compared to the digital market we can notice different names and leaders, for instance, Tekelec is a company that was active in providing SS7 signaling solutions[24] and through a series of acquisitions entered the switch market providing both TDM and IP-based switch (Meyers, 2005). Furthermore, the Chinese Huawei looks successful in quickly gaining almost one third of the whole VoIP market.

In order to look at relevant patterns of **demand** for this period we can concentrate on three markets: the first one relates to digital lines, the second to broadband communication and finally (even if out of the general scope of this thesis) to mobil telephony.

Graph 4.6 shows the pattern of diffusion of digital lines in some selected OECD countries.

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[24] See the previous chapter for an explanation of what is a signaling system and what is SS7.

Table 4.6: Ports shipped in 2005, by company

Company	Country	VoIP Ports	ATM Ports	TDM Ports
Huawei	China	30.75%	0.00%	0.00%
Northern Telecom	Canada	18.21%	36.64%	0.00%
Siemens	Germany	12.77%	0.00%	0.00%
Tekelec	U.S.	6.30%	43.07%	55.49%
ZTE	China	6.34%	0.00%	0.00%
Others		25.63%	20.29%	44.51%

Sources: Dittberner Associates Inc, 2003.

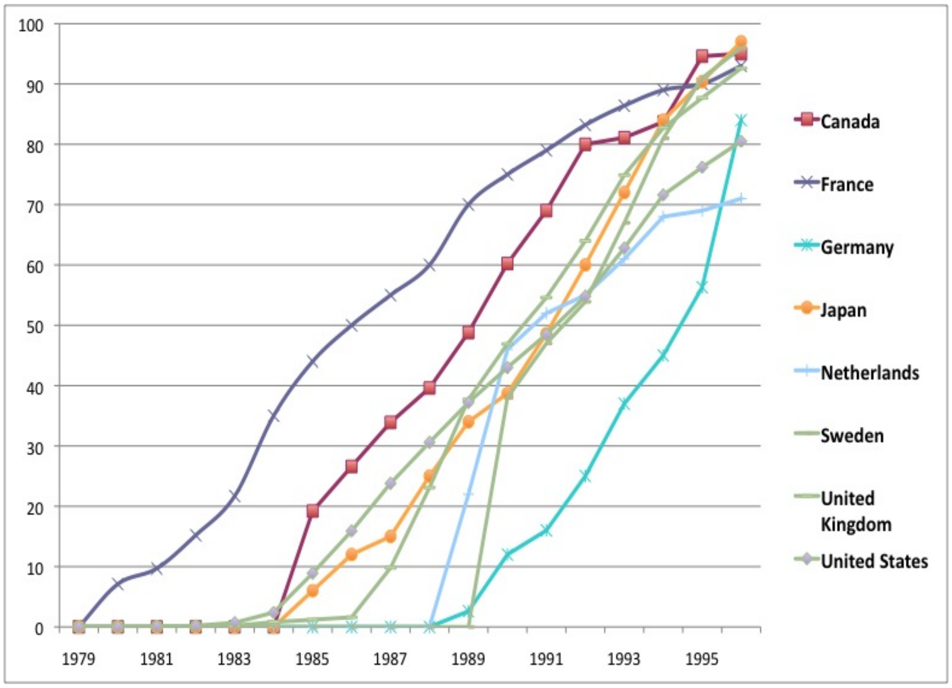

Figure 4.6: Percentage of digital lines

Source: ITU, 2005

It emerges that the diffusion took place quickly and saturated in the middle 1990s. Looking at the United States, the adoption of digital switches was driven by several factors such as regulatory setting (Greenstein, McMaster and Spiller, 1995), the size of the network, and the population distribution (Shampine, 2001).

The increasing demand for data communication traffic called for the upgrade to a higher data transmission rate (Noam, 1992). One response to this was the full digitalization of the

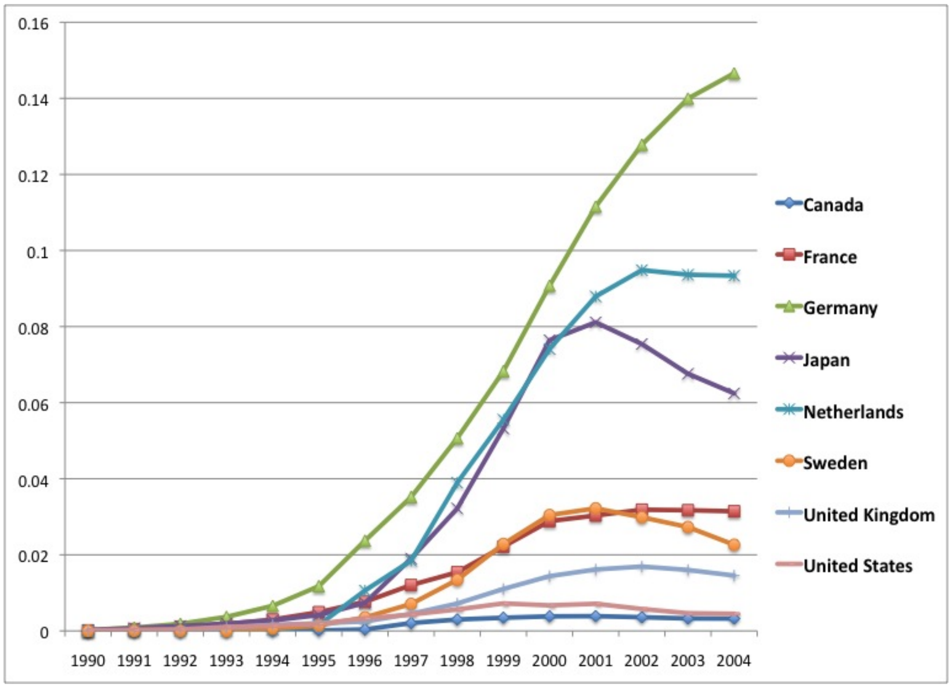

Figure 4.7: ISDN subscribers divided by population

Source: ITU, 2005

telephone network through the introduction of ISDN. Graph 4.7 plots the evolution of the percentage of the population subscribing ISDN. We can notice that the penetration rate was always rather limited, with only Germany achieving more than 10% penetration rate. This is not particularly surprising if we consider the technological competition rising from more efficient technologies for building a voice and data integrated network.

Data about market structure highlights the entry of new vendors in the switching market, suggesting the reduction of **barriers to entry**. The opportunity for new companies to access this market is twofold: on the one hand the emergence of a new radical innovations (such as packet switching and all the IP-based switches), and on the other hand, the change in public procurement and the liberalization of downstream markets.

In the period considered here, we can identify two regulatory trends that will re-shape the industry and the relations among the **relevant actors**: first the privatization of the state-owned PTTs and second the liberalization of the service market.

The privatization of the PTTs changed the nature of the relation between the PTTs and the national government. The rational for this operation was the need to fund-rise on the public market in order to finance the network digitalization and the belief that private owned firms are more efficient than the government owned (Buckley, 2003).

The wave of liberalizations started in the United States under the influence of economic theories of the Chicago School, which challenged the AT&T monopolistic system. The process started in 1968 with the *Carterphone Decision* ruling the possibility of also connecting to the AT&T network not-AT&T terminal equipments and followed in 1971 with the opening of private line services. However, the climax was achieved in the early 1980s with the opening of an antitrust suit by the Justice Department that will bring about AT&T's voluntary divestiture materialized in 1984 (Evans, 1983).

With different "intensity" and with some frictions the European Union moved also some steps towards market liberalization and between 1978 and 1983 the Commission accepted to play a major role in the information industry through antimonopoly and industrial policies. Looking at European telecommunication policy and regulation we can distinguish three phases, corresponding to different objectives and degree of liberalization:

1. THE INTRODUCTORY PHASE OF COMPETITION (1984-1992). In this period the *White Paper on Telecommunication*[25](1984) established the preliminary objectives of European regulatory policies; among them: the creation of a community market for telecommunications equipments, the promotion of common and coordinated programs for advanced networks infrastructures development (e.g. broadband networks), and the development of a pan-European networks and service market. These goals were made more explicit in 1987 with the *Green Paper of Telecommunication*[26], where the European Commission proposed to liberalized some services and the terminal equipment markets. However, there were not still evident attempt to attack the monopolistic position of the PTTs;

2. THE ACHIEVEMENT OF FULL COMPETITION (1992-1998). In this period, two new green papers (*Infrastructure Green Paper*[27] in 1994 and the *Green paper on Convergence*[28] in 1997) promoted the revision of some precedent positions, in favor of a more widespread liberalization. In particular, the Commission announced the abolition of all the exclusive rights of the telecommunication sector and the full liberalization of all services and infrastructures;

3. THE REVISION OF THE REGULATORY FRAMEWORK (SINCE 1998). Finally, the *Directive on access and interconnection*[29](2002) and *Green Paper on Services of General Interest*[30](2003) tackled problems related to the entry of new operators and the provision of service to the whole population. In particular, the development of alternative

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[25] COM(84)277

[26] COM(87)290

[27] COM(94)145

[28] COM(97)263

[29] Directive 2002/19/EC

[30] COM(2004) 374

networks and the lease of the incumbents' one posed new regulatory issues related to interconnection and local loop unbundling.

Despite the American and European regulatory interventions focused mainly on the service market, they also affected the equipment market. For instance, network operators changed their strategy towards corporate R&D, drastically reducing their expenditure. In the first half of the 1990s, major network operators undertook different strategies in the relation with their preferred suppliers (details about this process will be given in the next section). For instance, British Telecom (BT) decided to rely on a market relation, AT&T to stick on vertical integration and NTT to persist with the cooperative competition (Fransman, 1994*a*; Fransman, 1994*b*; Lera, 2000). In the second part of this decade, further changes occurred and they converged toward a common intermediate position. AT&T spun off Lucent, its manufacturing branch (formerly Western Electric), recognizing the lack of synergies from vertical integration, BT acknowledged the need of a closer relation with suppliers and NTT increased the number of specialized suppliers.

In the United States, this radical change gave opportunities to new (and also foreign) entrants. Furthermore, new rules about suppliers' eligibility removed the need of formal approval in favor of a simpler registration to the Federal Communications Commission (FCC) and the disclosure of some technical specifications. Finally, the transition from price-cap to rate of return regulation in the service market, gave to RBOCs[31] a stronger incentive towards cost cutting strategies and practically terminate the over-pricing of telecommunication equipments in the domestic market.

This process was not reciprocal and AT&T found hostile competition in the European market: in 1987 Northern Telecom was the only not European company able to achieve 18% of the private European switching market. In fact, changes in public procurement law fostered by the European Union and the General Agreement on Tariffs and Trade (GATT) brought about the use of non-tariff protection for national manufacturers (Noam, 1992). This obliged AT&T to undertake some, lately unsuccessful, alliances with European partners (like Philips and Olivetti) in order to access national markets. In the 1988, in response of reiterate German and French resistance to AT&T operation in Europe some proposals for reciprocity clauses were examined (Noam, 1992).

The technological and regulatory changes brought about changes in the **sources of knowledge and technologies**. Packet switching, the new key-technology for switching platforms has diffused in telephony since the 1990s, however, it has been the standard technology for data communications since the 1970s. In this case, the source of the new technology was external and precisely in the data networking industry. In order to catch up with the new technology, several "old telecommunication manufacturers" started to acquire new technology companies from this industry (Lazonick, 2007).

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[31] Since 1 January 1984, as result of the U.S. Department of Justice antitrust suit against AT&T, local operations were split into seven independent Regional Bell Operating Companies (RBOC).

Finally, also established sources of new technologies, like the PTTs laboratories, became also less important. The open structure of the Internet network and the growing competences of specialized suppliers determined a process of vertical specialization for the innovative activities. As a consequence, network operators drastically reduced their R&D expenditures, whereas manufacturers increased them.

Table 4.7 shows the trend of two measures of R&D intensity for some firms and sectors. It emerges a sharp decrease in R&D activities by network operators (comparable with low tech sectors like beverages) coupled with an intensification of R&D performed by manufacturers.

Furthermore, it reports data about new network operators, such as WorldCom, Qwest, Level 3 and Global Crossing, entering the market after the liberalization. Their complete outsource of the innovative activities related to infrastructure highlights their expectation on their innovativeness in providing new services.

4.3 Analysis at the firm level

The aim of this last section is to broaden the dimensions discussed in section 4.2, adding the firm and NSI perspective. In fact, the previous section pointed out how national governments have (directly or indirectly) intervened in the telecommunication switching industry. Furthermore, firm's analysis will help to characterize them looking at their history, strategies and relations.

As explained in section 3.4.7.1, the recent development of the telecommunication switching industry can be seen as a battle between "Bellheads" and "Netheads". The formers refer to telecommunication manufacturers which think to communication infrastructure from a circuit switching perspective, the latter refers to companies active in computer networking industry, therefore using packet switching. Next pages will focus on eleven "Bellheads", corresponding to "old" switching industry incumbents. This rough (but shared) distinction between the manufacturers will be also useful in discussing the assignees of the "important" patents identified in part III of this book.

Figure 4.8 summarizes some[32] of the links among the companies active in the industry. From this graph we can conclude that:

1. The companies present in the industry are rather old, several of them were established in the 19th century. Also "younger" companies (like Thompson, GEC or Philips) were actually active in other industries and only later entered the telecommunication equipment market;
2. Since its origin the industry is characterized by the presence of several links among the manufacturers;

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[32] The figure mainly highlights, merges, acquisitions or joint ventures and do not consider eventual licensing agreements.

Table 4.7: Evolution of R&D intensity.

Sources: Source: Fransman, 1994 and OECD, 2005.

Sector	Company	1987^1	1991^1	1997^2	1999^2	2001^2	2003^2
PTTs	AT&T	7.3	n.a	1.6	0.9	0.6	0.8
	BTT	2.1	2.1	2	1.6	1.7	1.8
	NTT	3.8	4.1	3.1	3.4	3.3	3.2
	DT			1.8	2	1.9	1.6
	FT			3.5	2.2	1.3	1
New Entrants	Qwest			n.a	0.9	n.a	n.a
Specialized Suppliers	Ericsson	9.1		14.5	16	20.1	24
	Motorola			9.2	11.1	14.3	14.5
	Lucent			11.5	13.2	16.5	21.1
	Northern Telecom	12.3		13.9	13.9	18.8	21.1
	Fujitsu			7.8	7.6	7	6.2
	Alcatel	9.8		8.9	9.5	11.3	13.5
	Siemens				18.8	10.1	11.8
Specialized Suppliers (New entrants)	Qualcomm			10.4	10.6	15.5	13.2
	Juniper Network			n.a.	40.4	17.5	27
	Cisco			12.4	13.7	17.6	16.6
Telecom Operators					2.6		
Automobiles					4.2		
Beverage					2.2		
IT Hardware					7.9		
Pharmaceutical					12.8		
Software and service					12.4		

Note: ^{1} and ^{2} indicate different measures of R&D intensity. ^{1} refers to R&D as % of sales (Fransman, 1994*a*) whereas ^{2}, refers to R&D as % of revenues (OECD, 2005).

3. Finally, it appears that all the existing companies emerged from a group of "core companies" that includes: AT&T (Western Electric), Ericsson, and Siemens.

Furthermore, we will not look only at the history of the companies but also focus on three aspects: firm's technological competences, its degree of internationalization, and its performance.

For the analysis presented in the next pages, we retrieved the patents granted by the

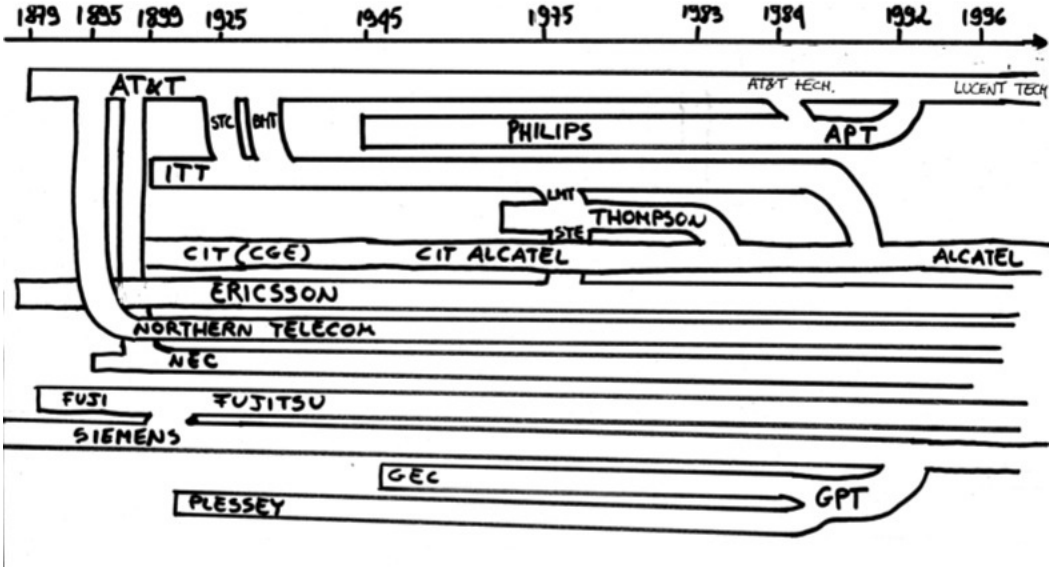

Figure 4.8: Firm's genealogy (related to only telecommunication switching industry)

USPTO between 1969 and 2003 to telecommunication manufacturers and their subsidiaries[33]. Following the NEBR classification[34] (Hall, Jaffe and Trajtenberg, 2001), each patent was assigned to a specific technological subcategory.

The sample includes 125599 patents issued between 1969 and 2003. Graph 4.9 displays the evolution of the number of patents granted to twelve companies active in the industry[35], the number of the patents in the class "Telephony" (see footnote 34), and the percentage of the this class (this should be read using the secondary axe). The number of the total patents granted per year, shows an upward trend, with a sharp increase in the 1990s. This acceleration is noted also considering the full patent database and the peak at the end of the period considered, is the result of the truncation problem common to patents data (Hall et al., 2001). The patents assigned to the "Telephony" category follow a similar upward pattern. The fact that this series does not appear to be remarkably affected by the right-truncation (as the series is upward also in the last part) suggests that patents in this class are quickly examined.

Following the seminal paper by Granstrand, Patel and Pavitt (1997) we use patents in order to represent firm's technological competences, classify them, and to look at their evolution over time, highlighting patterns of diversification or specialization. For each company i

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[33] The subsidiaries were identified using the Compustat matching file in NBER patent data and the matching subsidiaries used in Bekkers and alt. (2009).

[34] See Appendix A for the details.

[35] These are: Alcatel, AT&T-Lucent, Ericsson, Fujitsu, GEC, GTE, ITT, NEC, Northern Telecom, Philips, Plessey and Siemens.

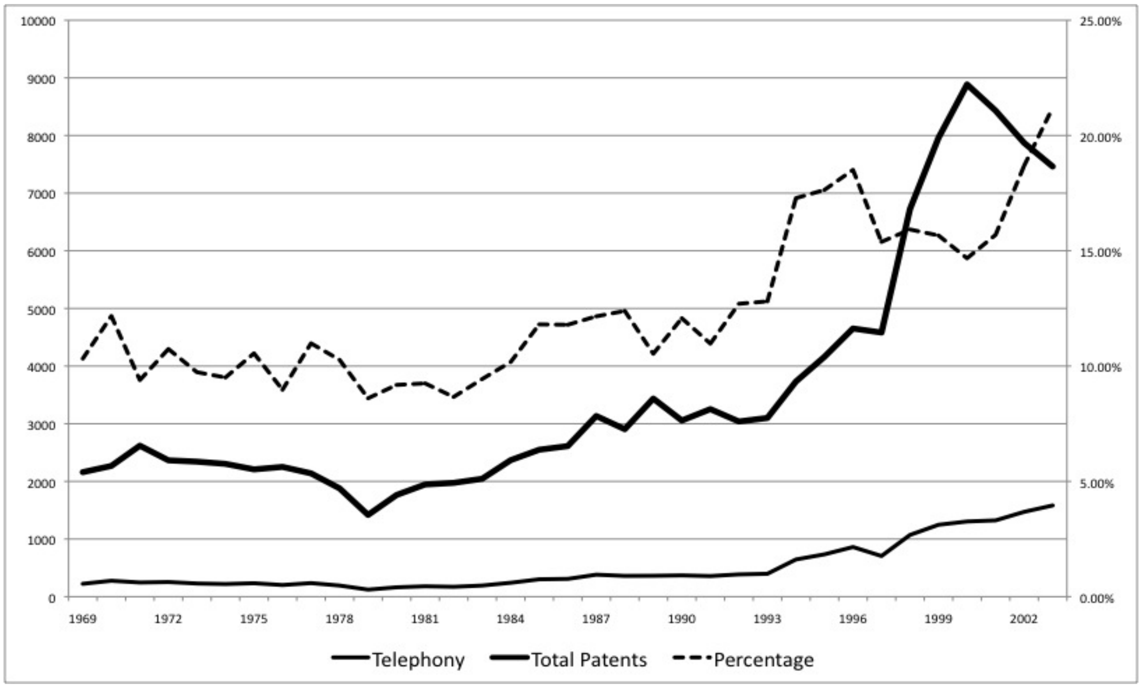

Figure 4.9: Number of patents

and technological field j, two indicators were calculated:

1. the **patent share** (PS) of a company i in the technological field j:

$$PS_{i,j} = \frac{p_{i,j}}{\sum\limits_{j} p_{i,j}}$$

   where $p_{i,j}$ is the number of patents granted to firm i in the technological field j. This indicator shows how "important" a firm is in a technological field.

2. and the **revealed technological advantage** (RTA):

$$RTA_{i,j} = PS_{i,j} \div \frac{\sum\limits_{i} p_{i,j}}{\sum\limits_{i}\sum\limits_{j} p_{i,j}}$$

   where, again, $p_{i,j}$ is the number of patents granted to firm i in the technological field j. This indicator is calculated as the ratio between PS and the specific technology's share of the total patenting. If this indicator is larger than one, the firm's patent share in a technology is larger than that technology's share in the total patenting; which reveals the importance of a firm in a specific technological field.

   In order to simplify the plotting of this indicator we symmetrize it, fixing the minimum and the maximum at -1 and 1, respectively. The transformation used is:

$$RTA_{i,j}^{sim} = \frac{1 - RTA_{i,j}}{1 + RTA_{i,j}}$$

Firm's technological competences are represented with a scatterplot using the $RTA_{i,j}^{sim}$ and the $PS_{i,j}$ as coordinates. Using figure 4.10, these competences can be classified, according to the quadrant they fall in. The axes are draw at specific thresholds: 2.7% for PS, that is the average of the sample, and 0.33 for RTA, mimicking Granstrand, Pavitt and Patel's paper. Using these values, we can distinguishing 4 types of technological competences: (1) *distinctive*, (2) *background*, (3) *marginal*, and (4) *niche*. Dividing the sample in 4 periods we will look at how the distribution of these competences (and therefore firm's specialization) changed over time.

The category of interest for the switching industry is here called *Telephony* and in the scatterplots in the next pages will be indicated with the number 212. However, scatterplots are firm-specific therefore not useful for comparing firm's competences in the *Telephony* area. Figure 4.11 displays the firms share of patents in this specific technical area in different periods. The graph shows that this portion of patent portfolio varies both along firms and

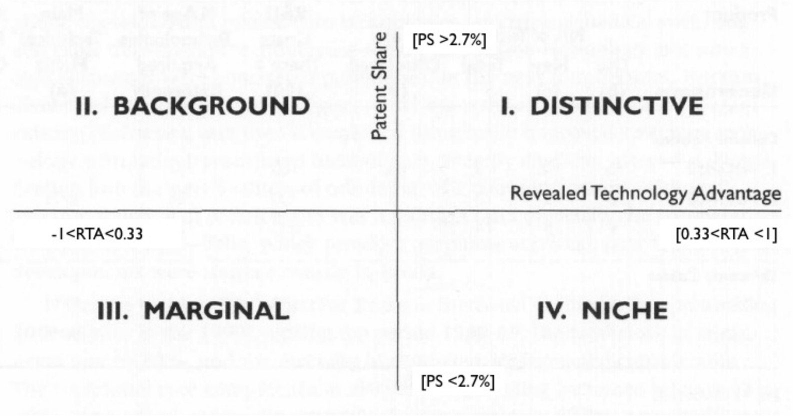

Figure 4.10: Firm's competences taxonomy

Adapted from Granstrand et al. (1997).

period, however the average percentage tends to increase over time (from 9% to 16%), however, firms display different behaviors: on the one hand there are firms shrinking their competences in the area and eventually leaving the market (such as Plessey, GEC, and ITT, which will be analyzed in detail in the next pages), and on the other hand firms deepening their competences (such as Alcatel and Nortel).

The second aspect we will systematically examine is firm's internationalization. Looking at the nature of the competition in the industry it is worth pointing out that, from a manufacturer's perspective, there are two distinct markets: the domestic one and the international one. Firms typically compete in both markets but to a different extent depending on the type of manufacturers they are. In fact, it is possible to distinguish two archetypes of manufacturers: the *national suppliers* and the *internationally-oriented firms*. The *national supplier* is the type of firm that, because of the special relation with the network operator and government's industrial policies, enjoys a monopolistic position in the domestic market. If the domestic market is big enough, this represents a substantial advantage in term of expected sales. Furthermore, seeing the complexity of integrating a new platform in a network, the opportunity to have a domestic "preferred network" for testing purposes provide other significant advantages (Chapuis and Joel, 1990). Examples of this type of firms are: Alcatel in France, Siemens in Germany and AT&T in the United States. Opposite, the *internationally-oriented* firm is a firm with either no or small domestic market. In both cases these companies have to directly place their sales in (numerous) foreign markets, or through several national subsidiaries. Examples of these *internationally oriented* firms are ITT and Ericsson[36].

Table 4.8 reports telecommunications turnover for selected firms, the percentage of rev-

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[36] Sometimes in the literature, these companies are referred also as *multinational companies*(Fransman, 1995).

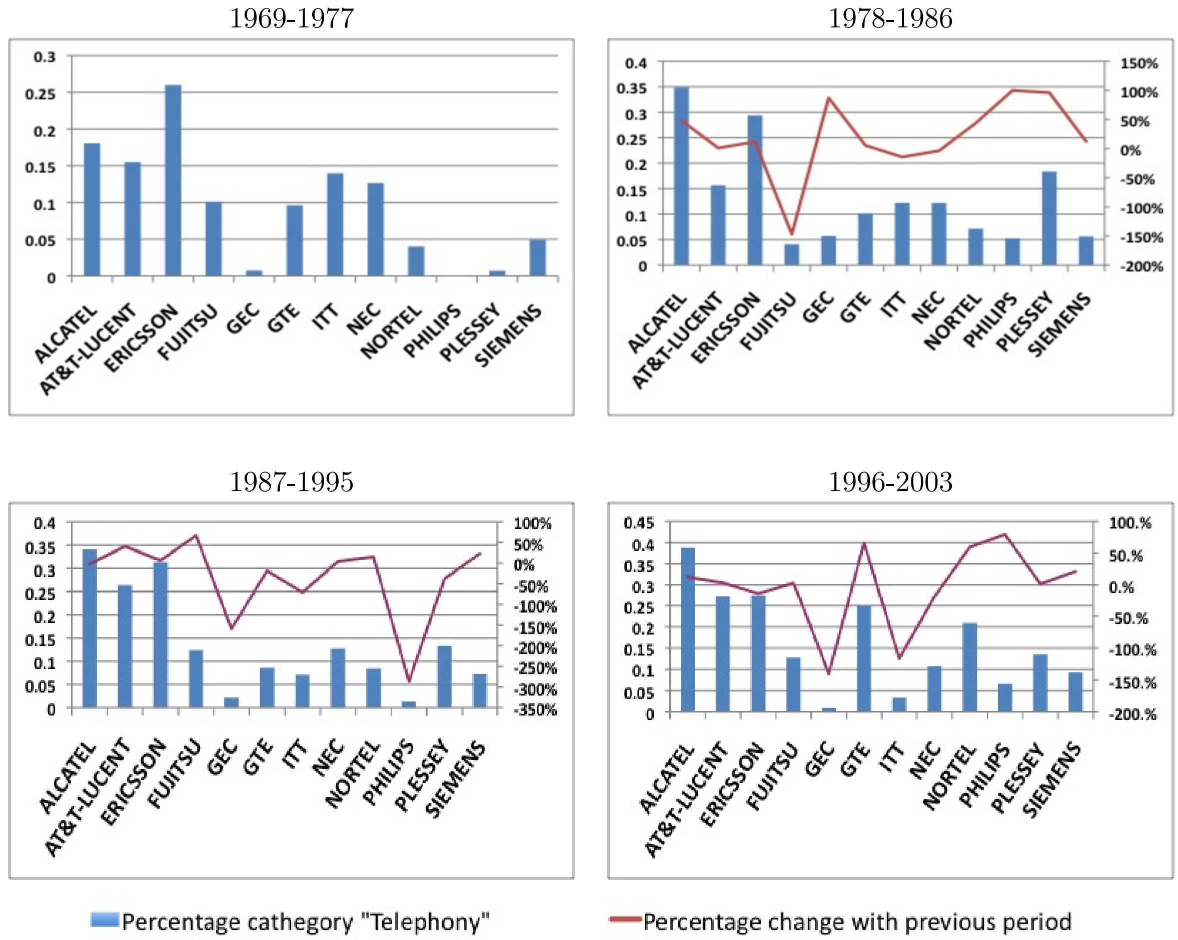

Figure 4.11: Percentage of patents in the *Telephony* category per firm and change from the previous period

Table 4.8: Main switch suppliers and their switching share

Company (Domestic base)	Telecom-related turnover[1]	in % of total turnover[2]	Switching share[3]	Non-domestic switch share [4]
Lucent (U.S.)	36,100	29	10%	10%
Alcatel (France)	8,200	79	35%	30%
Siemens (Germany)	5,100	24	39%	56%
Northern Telecom (Canada)	4,800	100	54%	67%
NEC (Japan)	4,100	32	29%	50%
Ericsson (Sweden)	3,300	90	46%	91%
GPT/GEC (UK)	2,300	19	38%	20%
Fujitsu (Japan)	1,600	16	50%	30%
Italtel/STET (Italy)		[?]		5%

In million US$. Source: Bekkers (2001) reported from OECD (1991) page 18, 22, 23.

Note: [1], [2], [4] refer to 1987, whereas [3] to 1986.

enues from switching, and the percentage of non-domestic switches revenues. It highlights the presence of great heterogeneity among the manufacturers both in term of their business diversification and internationalization. In particular, we can notice the co-existence of companies highly specialized in telecommunications (like Northern Telecom or Ericsson) with more diversified companies. Furthermore, the same companies display a different degree of internationalization. The extent of the latter distinguishes between *national suppliers* and *internationally-oriented firms*.

The importance of the domestic market becomes clear, from the financial point of view, looking at table 4.9. The price for domestic installations is much higher than foreign installations (for the same model). This is not surprising if we consider a telecommunication switch as an example of complex product and system (CoPS). This type of product is tailor-made, entailing a strict interaction between users and producers. For this reason the first user generally bear almost all the development cost (Hobday, 1998).

This table, taken from Bekkers (2001) is based on Noam's calculation (Noam, 1992). The author explains these data are just indicative as they are taken from different sources and therefore difficult to compare. Nevertheless, they give some hints about the premium gained by firms in their domestic market. It is therefore clear why, beyond technical reasons, the presence of a domestic market gives firms a sizable advantage.

Data about internationalization are calculated from the *Digital Switching Evolution* pub-

Table 4.9: Switching system: Domestic price versus lowest bid per line, early 1990s

Company	Domestic price per line (US$)	International lowest bid per line (US$)	Premium for domestic market (%)
Siemens	450	100	450
Alcatel	335	110	304
Fujitsu	290	110	263
Ericsson	325	130	250
Northern Telecom	250	100	250
NEC	290	140	207
Lucent	110	100	110

Source: Bekkers, 2001

lished by the Dittberner Associates (2003). This report provides a census of all the TDM (digital) switches installed worldwide until 2001, it therefore reports how many foreign (opposed to domestic) countries each vendor supplies. This might look as a crude proxy, as it does not account for the size of the foreign markets, however, given the high entry barriers discussed before, just account for the access to a foreign market can be considered a remarkable success for a manufacturers.

Finally, we will focus on firm's performance. The only consistent data available are about market share in the TDM (digital) market.

Before moving to the actual analysis and results it is important to discuss the similarities and differences with existing studies. In particular, this chapter has some similarities with the study by Schmoch and Schnöring (1994) that infers firms technological specialization and internationalization by looking at patents issued by selected telecommunication manufacturers (and network operators) at the European Patent Office (EPO). Their methodology differs from the one used in the next section; as the firms considered greatly overlap it is useful to discuss their methods and results. Companies specialization is studied by using MDS for representing firms similarity in term of their specialization in four telecommunication technologies. From the mapping results that Nortel, Siemens, and AT&T rather specialized in switching. This result does not quite match the one obtained in applying the Granstrand's, Patel's, and Pavitt's methodology (1997), however, the two methods can not be easily compared because of the different technological classification (EPO vs. IPC), the focal categories, and the size of the sample. Company internationalization is studied by looking at international applications reported in each patent of the sample: the registration to a national patent offices indicates the interest of the company to access that market. The results obtained agree with the one presented in the next pages; in particular, companies show some heterogeneity in internationalization intensity and in the destination countries. A main result of the above mentioned paper is that European companies seem more oriented towards US than Japan, whereas American companies (including Nortel) equally tried to access the European and Japanese market. An explanation for the phenomenon (that the two authors seem to overlook) is merely technical and related to the different transmission systems present in Europe, US, and Japan. As explained in the previous section, two incompatible transmission system exists worldwide: the T1 adopted in Japan and US, and the E1 adopted in Europe. A company developing a switching platform for a specific transmission system had to further invest to make it compatible to the other system. Therefore American companies had an advantage over the European ones in accessing the Japanese market.

4.3.1 Individual firms

The next pages will focus on twelve "Bellheads" analyzed in their national context; these were selected looking at the largest players with an international outlook (therefore not companies that are active only in domestic markets). Each subsection will provide a short history of the company since its origin, however, more attention will be devoted to the development of the electronic and digital switch. Finally, as already mentioned above, special attention is devoted to firm's technological specialization (and diversification) and internationalization.

4.3.1.1 France and the emergence of Alcatel

After World War II, the French switching market was rather open, with at least four manufacturers serving it. According to Llerena, Matt and Trenti (2000), 60% of the market was covered by foreign companies and the remainder by French companies. However, French companies also were not independent as they were French subsidiaries of foreign manufacturers; in particular, ITT owned Le Materiel Téléphonique (LMT) and Compagnie Générale de constructions Téléphoniqus (CGT), whereas Ericsson owned (STE) Société de Téléphone Ericsson. French manufacturers, the Companie Industrielle de Telephones (CIT, part of the larger CGE group) and the AOIP produced crossbar switches under license of the foreign LM Ericsson. These manufacturers were organized in a "supply" agreement, the SOCOTEL.

Between 1950 and 1975, French industrial policies were devoted to *"...the transfer of technological competences to the private industry..."*(Quelin (1992), reported by Tsipouri, Hommen and Edquist (2000, page. 204)) and *"...in order to create an independent industry, France first needed to end its reliance of foreign technology"* (Griset (1993) reported by Tsipouri, Hommen and Edquist (2000, page. 204)).

The process of creation of national capabilities in telecommunication equipment was led by the Centre National D'Etude des Telecommunications (CNET), a R&D facility created by the French Government in 1945. Its contribution was fundamental for the development of later digital switching platforms. Since 1958, CNET and SOCOTEL worked on two prototypes: the Socrates and the Aristote. These were based on two different multiplexing technologies, Socrates using space-division multiplexing, and the Aristote time-division multiplexing[37]. The manufacturers involved were also different: Socrates involving both SOCOTEL and CNET, and Aristote only CNET and the Societété des Lannionaise d'Eletronique (a CIT-Alcatel subsidiary).

In 1967 new projects, the Pericles and Platon, were undertaken. The latter was a direct follower of the Aristote and presented a forward-looking design, foreseeing the future importance of decentralized control and therefore using minicomputers. A prototype was installed in Lanyon in 1970 and two years later Alcatel was ready to commercialize it with the name E10.

In 1975 the Directorate General of Telecommunications (DGT, now France Télécom) started to promote a strategy of fostering competition and supported the creation of a second national manufacturer, considering CNET's strategy too "centralist". The second French manufacturer emerged from Thompson-CSF (a French company involved in consumer electronics), which acquired ITT's LMT Company and Ericsson's STE. These mergers were posed as counterpart to Ericsson and ITT in order to access the French market with their space-division electronic switches[38]. The objective was to create a company able to produce the E10 and to take advantage of some form of controlled competition. However, because of the increasing R&D costs related to digital switches in 1983 Thompson gave up its telecommunication interests and it was bought by CIT-Alcatel. Contextually, because of management changes ITT sold its telecom interests to CIT-Alcatel that was able to take over the ITT's digital switching platform (called System 12). As consequence of these take overs, Alcatel became one of the largest telecommunication manufacturers in the world.

Graph 4.12 illustrates the evolution of Alcatel's technological competences and a stable pattern of specialization of this firm in telephony and communications[39] as *distinctive* competences.

Figure 4.13 and 4.14[40] point out that Alcatel accessed the TDM market rather early (covering it entirely until 1976) and later stabilizing around the 12% from the middle 1980s. In particular, Alcatel shows a rather international focus with a peak in the first half of the 1990s, when it was supplying about 100 different countries.

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[37] See previous chapter for technical explanation.

[38] Given the high uncertainty related to time-division switches, DGT decided to focus on space-division switches. In 1975 at the international bid for the modernization of the French network, it was decided to share the transit market between the ITT's Metaconta and the Ericsson's AXE (both space-division switches) and the E10 was relegate only at the margin, in the rural area (Tsipouri, Hommen and Edquist, 2000).

[39] The technological categories are 21 and 212. See Appendix refclass for the complete list.

[40] Note that these graphs include only five of the twelve firms considered; the remainder firms are displayed in the (complementary) graphs 4.22 and 4.21. Firms were split just for displaying purposes.

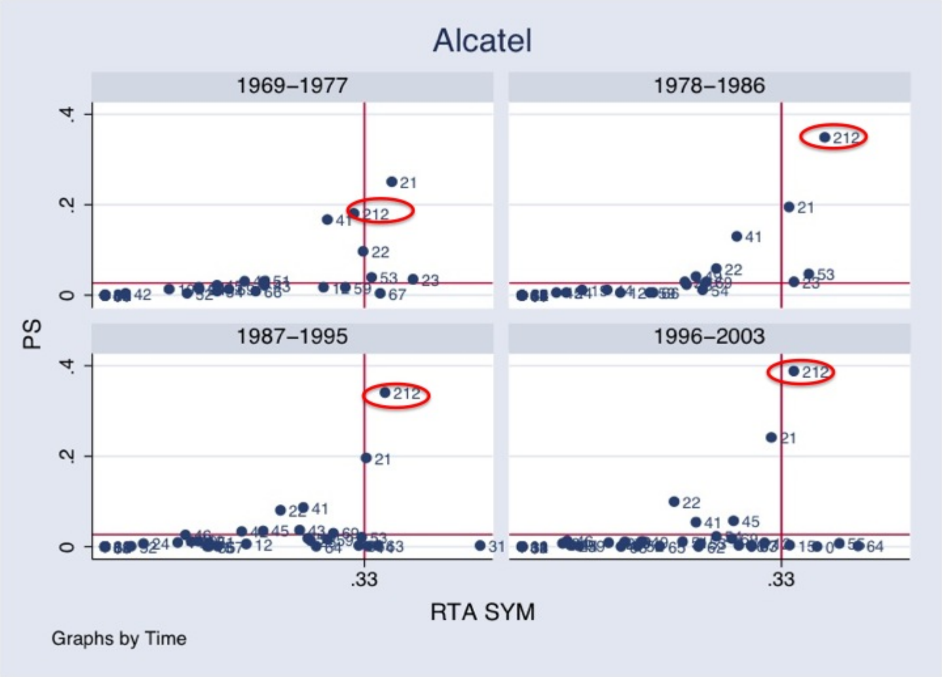

Figure 4.12: Patent portfolio analysis

The circle indicates telephony competences

4.3.1.2 Germany and Siemens

The German telecommunications industry was characterized by a high degree of centralization, and, as suggested by Chapuis (1990), the behavior of the *Deutsche Bundespost* (DBP) can be summarized in the slogan *"... one country, one administration, one system..."* (Chapuis and Joel, 1990, page 205).

This "standardization" was pursued throughout the organization of cartels, which, according to Noam (1992) represented a German common practice in several fields, such as electric equipment, incandescent lights, and the cable sector.

A central actor for these cartel agreements was Siemens, a German company active in the switching industry since the early phase (see section 4.2.2). In order to have only one system in the network but more suppliers (to promote some degree of competition), the DBP asked Siemens to license its system to other German manufacturers, such as SEL, DeTew, and Telefonbau Normalzeit. In exchange, Siemens would enjoy a fixed quota of the domestic market (for the procurement in the 1920s, this was 60%).

This cartel practice was never openly admitted by the DBP and would last several years[41].

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[41] For instance in 1955 the DBP decided to adopt only the Siemens' EMD (electromechanical step-by-step)

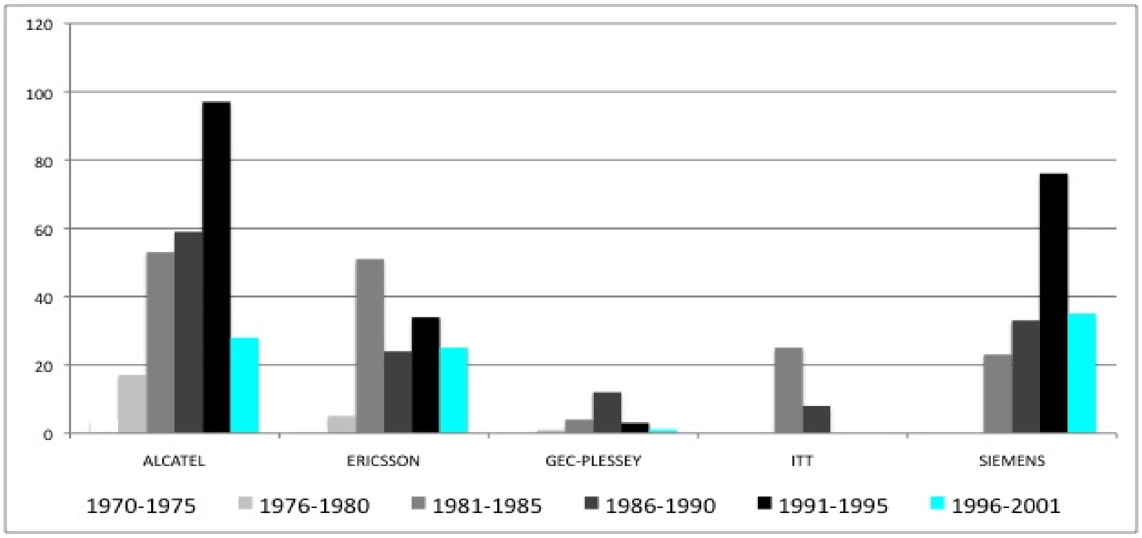

Figure 4.13: Number of countries supplied by vendor

Source: Dittberner, 2003.

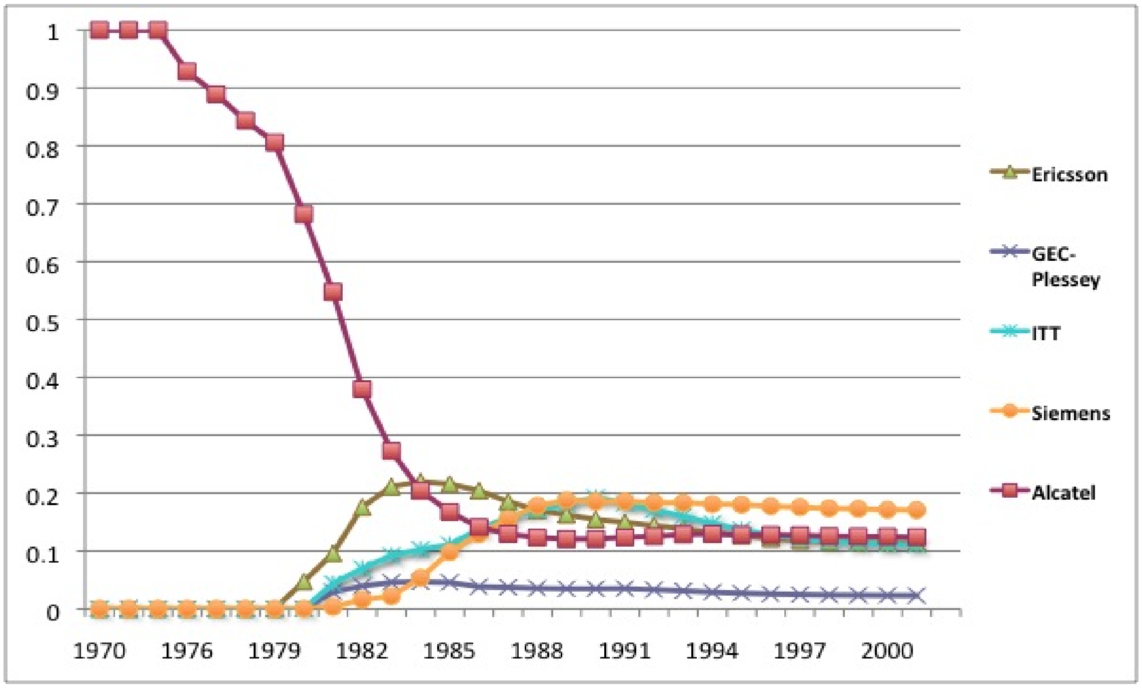

Figure 4.14: Evolution of Market Share in TDM digital switches (Worldwide)

Source: Dittberner, 2003.

This agreement was challenged by the pressure of the Federal Accounting Office and by outsider companies like AT&T (which was finally admitted in 1954).

German manufacturers independently started research about electronic switching but it was only in the late 1960s, after the success of No.1 ESS by AT&T, that DBP established a joint collaboration among them. In this project Siemens held a special leading role and several prototypes, based on different technologies, were tested[42]. It is important to notice that they already considered the development of a fully digital switch but because of the high uncertainty the proposal was dropped in favor of a space-division switch, the EWS system (Chapuis and Joel, 1990). The first EWS was installed in 1974, however the plans for its adoption in the entire network were postponed several times because of technical problems and lack of coordination. However, with the general consensus about TDM digital switches in 1979, the DBP suddenly called off the plans for adopting the EWS platform and eventually moved towards the full digitalization of its network and the adoption of time-division (digital) switch. This step was jointly pushed by German manufacturers that started to see the development of numerous digital platforms by competitors (Chapuis and Joel, 1990). The EWS-D was not designed from scratch but it was an evolution from the analog space-division EWS system and it was already designed with full ISDN capabilities.

It is in those years, that DBP finally moved away from the “one system” strategy and in order to foster competition an international and open tender was called for a supply of TDM switches. However, new barriers to entry were posed to limit competition, as potential suppliers should be German or to have industrial connection in West Germany (Chapuis and Joel, 1990; Noam, 1992). Finally, in 1982 two systems were selected: the EWS-D by Siemens and the System 12 produced by the ITT’s German subsidiary SEL.

Figure 4.15 highlights that Siemens has very diversified technological competences; in particular, the *distinctive* competences ranged from power systems to surgery and medical instruments[43]. Looking at the telephony equipment (class 212, indicated with the circle), we can notice that this was always a *background* competence. Telephony-related competences were rather important within the firm, however Siemens did not have any technological advantage compared to the other firms. Graph 4.14 shows the late entrance of Siemens in the TDM market, however it also highlights a fast catching up, bringing Siemens’ market share to a rather stable 18%. Again, graph 4.13 points out a late and slow entry in the worldwide market, however in the early 1990s, Siemens was supplying about 80 countries, resulting in the third most internationalized vendor in that period.

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switch and in exchange to the licensing to three competitors it granted to Siemens a quote of 46%.

[42] See Chapuis and Joel (1990) at page 210 for a summary.

[43] Indicated with the number 44, 45, and 32. See Appendix A.

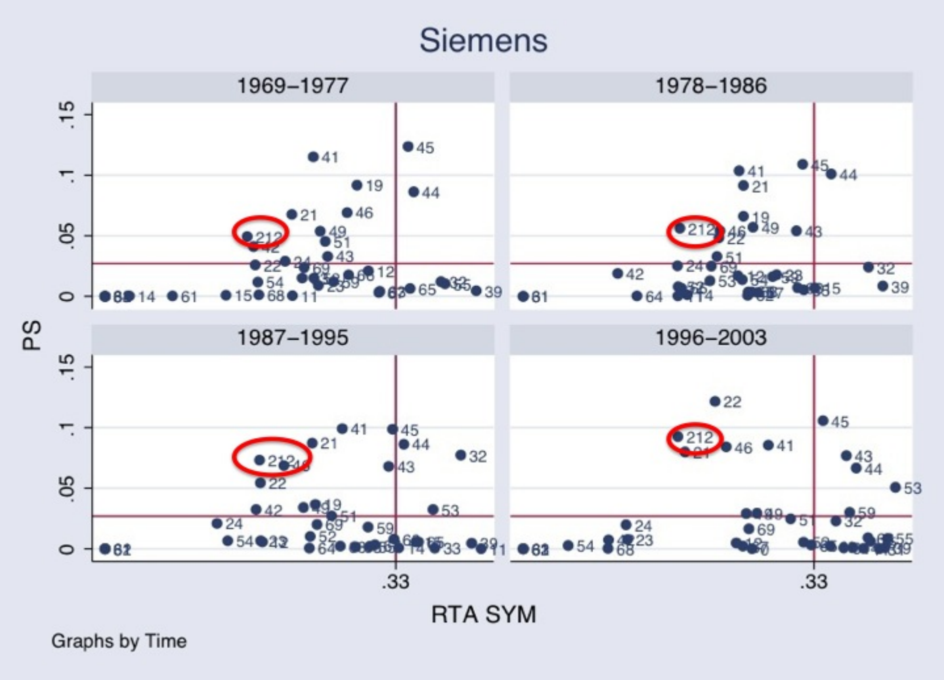

Figure 4.15: Patent portfolio analysis

The circle indicates telephony competences

4.3.1.3 United Kingdom

The case of the United Kingdom represents a very good example of failure because of too much reliance on technological foresight. Furthermore, it clearly shows how important previous generations of switching platforms are in order to have a balanced and sustained upgrade of the network.

At the end of World War II, the United Kingdom had very strong electronic capabilities. These were built developing the Colossus, the digital computer used to decipher German messages encrypted using the Enigma machine. Several of the engineers working on Colossus were working at the Dollis Hill Research Centre (the British Telecom laboratory), generating an over-confidence about the diffusion of electronic switches. In fact, it was decided to eventually leapfrog a switch generation (the crossbar system) and to develop an electronic switch.

The uneven path toward electronic switching strongly affected British performance in the digital one. The attempt to build a TDM switch using thermionic tubes, instead of transistors, resulted in a failure[44], which made BT very cautious and conservative about future technological choices. The result was that British telephone network was locked into

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[44] See Chapter 1 for the details.

an obsolete technology. In fact BT had to cope with the increasing demand in the 1970s and decided to install crossbar and Strowger systems[45].

These measures not only provided just a palliative solution for network expansion, but they locked suppliers (Plessey, GEC and STC) and their resources to a technology that was quickly becoming obsolete.

BT was aware that the future switching platform would be electronic, therefore it did not stop research in that field. However, previous debacles and the tight financial constraint imposed "prudent" technological choices in the design of the TDM digital switch. For instance, in 1963 they decided to rely on wired-logic control instead of the SPC (turning back only in 1976).

The British case is also peculiar because of the relation between the PTT (BT) and the manufacturers. Following the policy adopted in several countries (especially in Japan), during the 1960s BT tried to organized its suppliers' R&D effort in the Bulk Supply Agreement. Differently from the Japanese case, the British one was not successful; in fact BT was not able to cope with the emerging trade-offs manufacturers were facing (cooperation in order not to waste resource but still being able to independently produce a switching platform to sell abroad) and exacerbated competition among the suppliers just in a phase where the huge increase of R&D expenditures call for cooperation. The numerous conflicts among the participants determined the end of the agreement in 1969.

This failure would impact on the development of the digital generation and the whole British switching industry as they compromise the delicate structure of trust that is necessary of the long-term R&D procurement contracts (Fransman, 1995).

When BT realized the mistake, it took some other 7-8 years of discussion and deliberations in order to start the join development of System X. The cooperation was based on a strict division of labor among the manufacturers, with GEC taking care of the processor utility subsystem, Plessey being responsible for the digital switching subsystem, and finally STC for the message transfer subsystem.

The first System X was installed in 1981 (quite late, compared to other digital systems) and all the manufacturers planned to start exporting the system. However, graphs 4.14 and 4.13 show the limited diffusion of the System X and the failure of the British manufacturers to enter the TDM market.

The System X failure and regulatory changes brought about by the Telecommunication Act that in 1981 (and the privatization program of 1984) determined the restructuring of the British telecommunication manufacturer industry. Firstly, STC was excluded from the System X program because two manufacturers were enough in order to achieve efficient levels of production and secondly, in 1985 GEC launched a takeover bid for the Plessey Company. Both Plessey and the Ministry of Defense were against the merger because of the threat of

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[45] The last Strowger system installed in the world, was in UK, in 1985, more than 100 years since the original patent was granted.

the emergence of a monopoly, so in 1986 the bid was referred to the Monopolies and Mergers Commission and eventually stopped. Finally, in 1988 Plessey and GEC created a joint venture (GPT) that brought together their telecommunication interests. However, in the same year, GEC and Siemens paid $3.1 billion for Plessey and the 50% of GPT moving abroad (to Germany) a consistent part of British telecommunications industry.

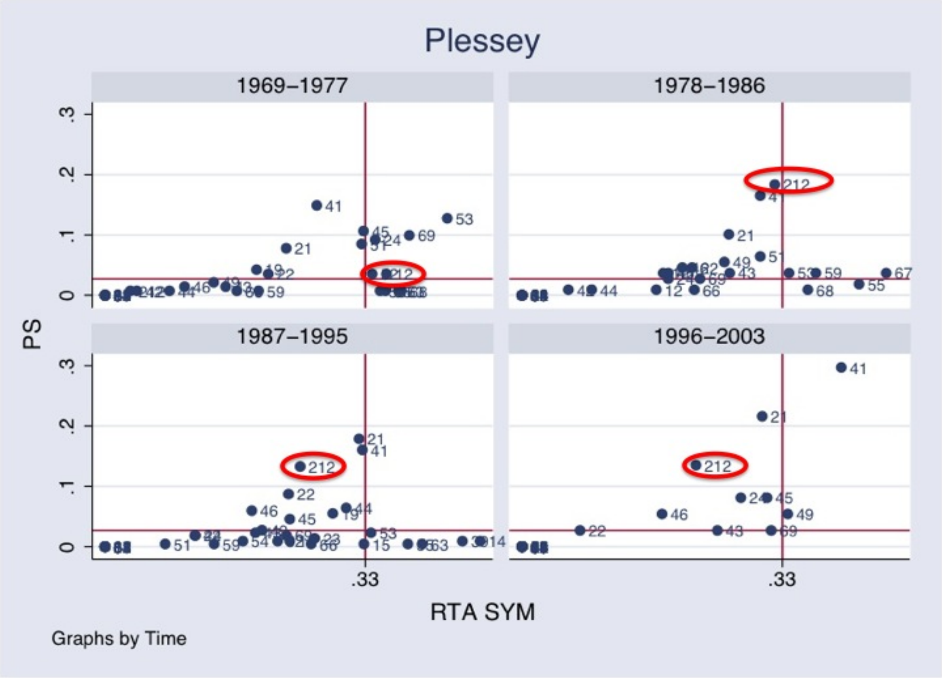

Figure 4.16: Patent portfolio analysis

The circle indicates telephony competences

Figures 4.16 and 4.17 display Plessey and GEC's technological profile (an its evolution). Some differences emerge; in particular, only Plessey had distinctive competences in telephony (though its RTA diminishes over time). GEC's distinctive competences, although in the Electric and Electronic categories, focused on measuring and testing, and nuclear and X-ray, leaving telephony as a marginal area of competences.

4.3.1.4 ITT

The details of the ITT's early history are reported in section 4.2.2, here we will focus more on the late development and on some peculiar features of this company. Recalling the differences between *national supplier* and *internationally-oriented* companies, we can consider ITT an example of the latter. In fact, it has never enjoyed the privilege of having a preferred domestic

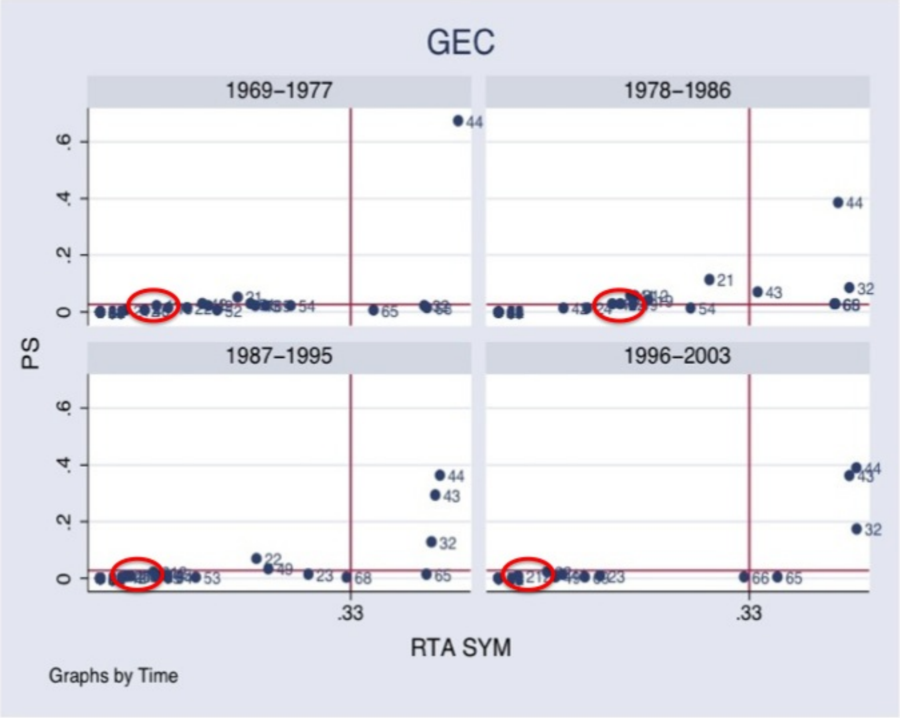

Figure 4.17: Patent portfolio analysis

The circle indicates telephony competences

market for telecommunication switches, and it accessed foreign markets through a red of subsidiaries (listed in table 4.10).

Table 4.10: ITT's subsidiaries and its location.

Country	Company
France	Compagnie Générale de constructions Téléphoniques (CGT)
	Le Materiel Téléphonique (LMT)
	Laboratories Central de Télécommunications (LCT)
United Kingdom	Standard Telephone and Cables (STC)
Belgium	Bell Telephone Manufacturing Co. (BMT)
Germany	Standard Elektrik Lorentz A.G. (SEL)
Spain	Standard Electrica S.A. (SESA)

Source: Chapuis and Joel, 1990

Although the largest R&D projects were undertaken in United Kingdom, Belgium and United States, each subsidiary was involved in "decentralized" R&D projects, fostering some degree of competition within the company.

ITT commercialized several switching platforms, like the crossbar Pentaconta system designed by BMT and SEL. This system despite some difficulties in the early stages was used by 17 millions subscribers around the world, and the countries with the largest number of Pentaconta systems were France, Spain, Italy, and Brazil. This figure makes the Pentaconta the most widely distributed system (Chapuis, 1982).

Following this success, it was announced in the 1966 annual report that the company had been designing a SPC quasi-electronic switch, which could be economically competitive with conventional elecromechanical systems and more reliable. These efforts would materialize in the Metaconta switching family. As showed in the previous pages about the French NSI, it seems that Metaconta's competitiveness was not only strictly related to its characteristics but also to political aspects that fostered PTTs' decision to adopt a foreign switch. By 1975 1.4 millions of Metaconta lines were deployed over the world (Chapuis and Joel, 1990).

With the emergence of digital technologies, all ITT's subsidiaries were involved in the development of a digital platform, the System 12. According to the engineers involved, the main feature of the System 12 was an architecture that would be economical over a wide range of size and future (advanced) services. It was realized by a "software-based architecture", highly modular and able to efficiently integrate VLSI and microprocessors components.

Despite this promising start, ITT in 1987 dismissed 87% of the telecommunication business and the System 12 was taken over by Alcatel. The reason of ITT's drop-off derives from the interplay of both financial and managerial causes. As pointed out several times in the previous pages, the development of a digital platform was an expensive business: by March 1985 the company had spent \$1.1 billion for the development of its System 12 (Fransman, 1995) and \$200 million on the adaptation of the system for the U.S. (as it was designed for Europe) (Chapuis and Joel, 1990).

From the managerial perspective, starting from the 1970s, ITT has a *conglomerate* structure, growing through expansion in very diversify business, such as hotels (Sheraton hotels), food, etc. The lack of focus in telecommunication manufacturing or electronics determined a lower commitment to this business and to the understanding the natural slow-phases of the industry. The difficult time of the middle 1980s for the telecommunication industry and the subsequent slow down in the System 12 sales made the telecommunication equipment line loss making. For this reason in 1987 it was sold to Alcatel.

The technological profile of ITT shows that telephony was never a *distinctive* competence of this firm, which until the 1990s shows a very diversify profile with only one distinctive competence. Moving to discuss firm's performance we can see a low level of internationalization of the company (see graph 4.13) and a worldwide market share of about 12% (see graph 4.14). This results contrast with the description of the company as an *internationally-oriented* company with a strong focus on the foreign market. However, we have to point out that this data refer exactly to the market in which ITT was not successful and therefore, because of it,

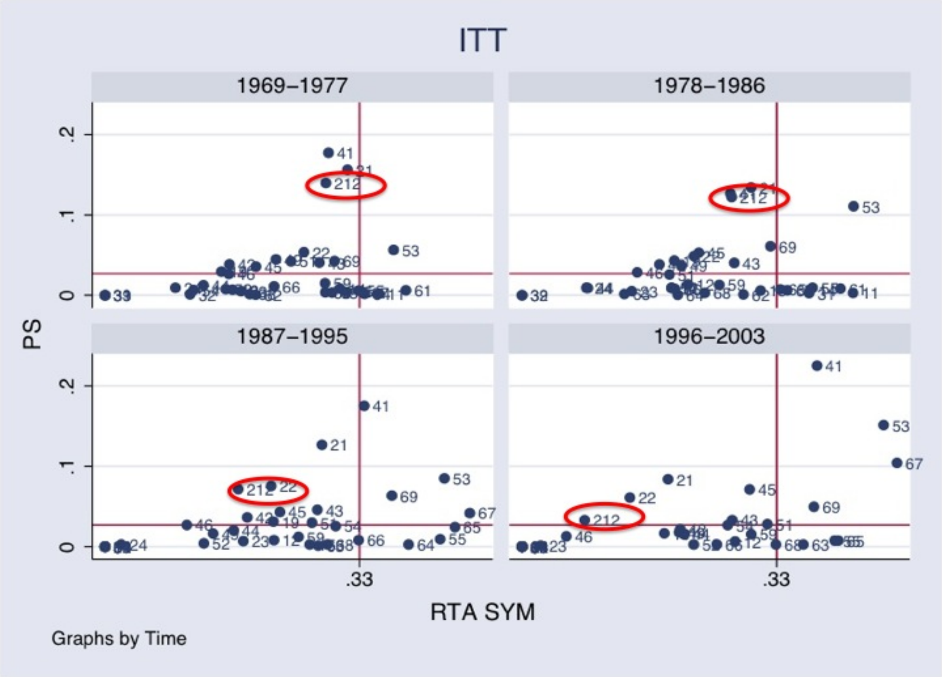

Figure 4.18: Patent portfolio analysis

The circle indicates telephony competences

ITT dropped out from the market.

4.3.1.5 Ericsson

Ericsson, together with AT&T, Siemens, and GTE, is one of the oldest firms in the industry, and because of some peculiarities of the Swedish network operator (STA[46]), it has never really served its domestic market, but instead it focused on export. In fact, STA manufactured most of its own equipment, developing therefore competences both as users and producers. As pointed out by Fridlund (2000), together with AT&T it was the only telecommunication service company having both these expertise.

Since the 1950s, these two companies collaborated in several ways. Informal collaborations were rather common because of the large mobility of engineers between the two companies. Later more formal commitments to collaboration were fostered through the establishment of a joint Electronic Council, and since 1970, through a joint company (Ellemtel[47]). In the early

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[46] STA was founded in 1953 as a public agency responsible for telephone service. Technically, it was not a PTT as it was not involved in the post service.

[47] Notice the name is a combination of the two parent companies' name.

phase of the collaboration, the expectation for the two firms where rather different: if on the one hand, STA really believed in the use of electronics for telecommunication switches (as in 1955 STA's director of research spent six months at the Bell Laboratories), on the other hand Ericsson perceived the R&D expenditures in electronics just as an insurance for eventual future technological breakthroughs. Ericsson's resistance to electronics was simply derived by the success of its crossbar platforms, which were developed by STA and licensed to Ericsson for the foreign markers.

The active collaboration started on the development of a digital switching platform, in fact electronic platforms were separately developed but meant to be complementary: the STA's A210 for cities and the Ericsson's AKE12 for rural areas. During the trial phase, both companies experienced similar problems relate to poor programming. The first A210 installed did not work because of software errors and after 7 months the project was withdrawn and all the engineers transferred. The first AKE12 was inaugurated in 1968 but several errors in the program made difficult to plan its sales. The solution was found during the installation of the transit AKE13 in the Netherlands (the transit switch was reliable much earlier) and it consisted in dividing the large program in modules, each one controlling one function. After the first AKE13 was installed, several countries adopted it, like Sweden, Finland, Mexico. Furthermore, the AKE 13 presented an element of novelty both in the hardware and software as it adopted the multiprocessor distributed control, which would determine an advantage for the development of digital switches.

In the late 1960s, both Ericsson and STA started to realize the magnitude of a necessary research project for the development of a digital switch and observed the emergence of numerous joint projects between PTTs and manufacturers in order to develop it (for instance, in Germany, Japan and in the United Kingdom (Fridlund, 2000)). Furthermore, about the same time Ericsson lost an important international bid with one of its established clients; the Australian Post office preferred ITT's Metaconta over the AKE13 (Chapuis and Joel, 1990). All these facts put Ericsson under pressure for a more formalized joint collaboration with STA in order to de developing a digital platform.

The design of AXE platform did not start from scratch but was an evolution from the previous AKE13. The first installation of this platform was in 1977 and it took place without major problems.

It is interesting to report the details of the joint agreement between these two companies regarding the exploitation of patents granted during the collaboration. In fact, conflicts emerged as STA wanted, eventually, to access foreign markets, whereas Ericsson did not want to fund a potential competitor. Finally they agreed that Ellemtel owned all the Swedish patents and both companies had the right to use them, and Ericsson retained the ownership of foreign patents. This was balanced by an agreement for "equal growth" of manufacturing: Ericsson was allowed to sell abroad as much a STA was selling in the Swedish market. All the exceeding foreign demand was shared (in the manufacturing) and sold by Ericsson. Given the disappointing sales of the AXE switch in the early phase this agreement lasted only 2 years.

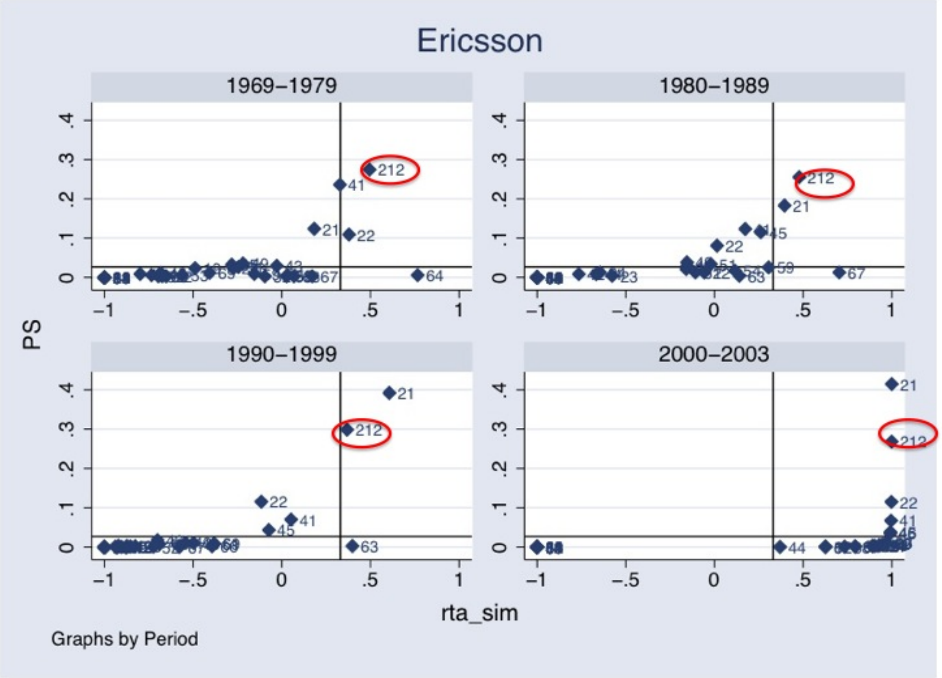

Figure 4.19: Patent portfolio analysis

The circle indicates telephony competences

The analysis of Ericsson's patent portfolio (figure 4.19) shows that telephony (and more in general communication) is distinctive competences of the firm that shows low level of diversification.

Data about market share and internationalization (graph 4.14 and 4.13) shows a good market performance and level of internationalization, however, with a downward trend.

4.3.1.6 The AT&T System[48]

AT&T, together with its Bell Laboratories and Western Electric, played a central role in the telecommunications switching industry. We can talk about AT&T "system" because the three entities listed above were vertically integrated with a specific division of labor: Bell Labs performing research, Western Electric manufacturing telecommunication equipment, and AT&T using it for providing telephone service to American customers. This setting would last until 1984 with the voluntary divestiture following an antitrust lawsuit.

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[48] In this section we refer to AT&T meaning Western Electric first and Lucent later. As in the first paragraphs it is explained the nature of the relation between AT&T and its manufacturer, we think that, for simplicity, we can refer to the AT&T's manufacturer as AT&T.

The origin of the AT&T system goes back to Alexander Graham Bell, who, together with some partners, founded in 1879 the National Bell Telephone Company, which will became the American Bell Telephone Company in 1880. Already at that early stage, the American Bell Company had a controlling stake in the manufacturing company, Western Electric Company. Looking at "research activities", AT&T was always involved in research aimed to solve emerging technical problems, however it is only in 1907-1911 that Western Electric and AT&T consolidate this activity. After World War I, in order to keep promoting AT&T as a "research oriented" company (also in spite of the monopolistic position it was holding), the Bell Laboratories were created[49](Hoddeson, 1981).

Looking at Western Electric, it is interesting to note its early international outlook as it was involved in several foreign subsidiaries[50]. However in 1925, following an antitrust law, some of these international interest were separated into the International Western Electric Company, and later sold to, at the time insignificant firm, International Telephone and Telegraph (ITT).

Despite some regulatory threats[51] between 1920s and 1960s (since the presidency of T. N. Veil) AT&T retained its monopoly power[52] under the assumption that it was a natural monopoly (Evans, 1983). However, since the middle 1950s, regulatory changes allowed third party equipment to be connected to the AT&T network[53]. Furthermore, the emergence of new technologies like microwaves made transmission cheaper opening opportunities for competitors. The AT&T monopoly ended in 1984 with the voluntary divestiture, as result, AT&T's local operations were split into seven independent Regional Bell Operating Companies (RBOCs). In return, AT&T had the chance to go into the computer business, founding AT&T Computer Systems.

Moving to recent technological development (bearing in mind that most of them are already discussed in the previous chapter), AT&T developed the first electronic switch, the No.1 ESS, in 1963 and commercialized it in 1965. The innovative features of this platform (particularly the use of SPC) made the platform very successful and it quickly diffused,

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[49] Bell Laboratories were owned by AT&T and Western Electric in equal share.

[50] Among all the Western Electrics' foreign investments we can find:

1. Nippon Electric Company (NEC), a Japanese Joint Venture of which Western Electric owned the 54% in 1899;
2. the Western Electric factory in London, established in 1883, which will became the Standard Telephone and Cables (STC);
3. the Bell Telephone Manufacturing Company of Antwerp (Belgium) established in 1882.

[51] See Bornholz and Evans (1983), for a detailed account of the regulatory suits against AT&T, in its early phase.

[52] In 1921, 64% of the existing telephone lines were controlled by the AT&T systems (Evans, 1983).

[53] These changes refer to the Hush-a-Phone v. FCC ruling in 1956 which allowed third-party devices to be attached to rented telephones owned by AT&T. This was followed by the 1968 Carterphone decision that allowed third-party equipment to be connected to the AT&T telephone network.

substituting the panel switching system introduced in 1921.

In the field of digital switches, AT&T was also an early player. Research and prototypes started in the 1950s but for numerous reasons (already mentioned in the previous chapter) it was only in the 1976 that it was able to commercialize a digital toll switch, the No. 4 ESS. Despite the early entry in the digital toll switch, it was a latecomer in the development of a central office, the No. 5 ESS. The first reason for the delay were the difficulties encountered in interfacing digital and analogue lines in an economic way. This problem was not faced with the toll switch as it connects long distance lines that are often already digital. The second reason was the institutional change after the AT&T divestiture. AT&T had to learn how to deal with customer relations in a competitive environment and faced some hostility from the new RBOCs, which for the first time were free to choose their suppliers (Fransman, 2002). Despite the delay and the competition by Northern Telecom, by 1988 No.5 ESS had 49% market share in U.S. compared to 35% held by Northern Telecom. The advantages grew as the system started to become economically competitive (Chapuis and Joel, 1990) .

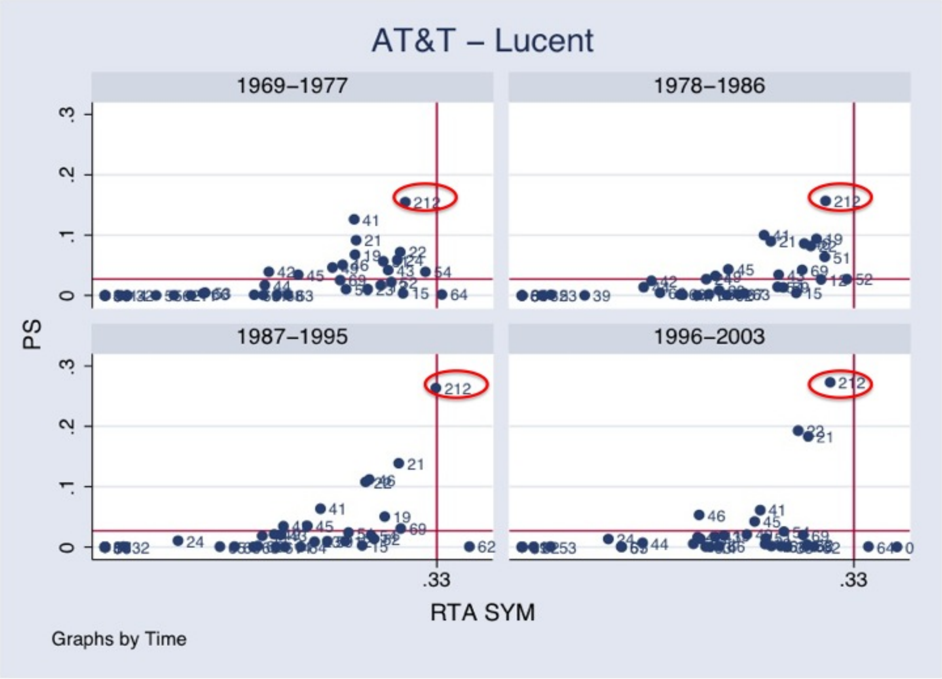

Figure 4.20: Patent portfolio analysis

The circle indicates telephony competences

Graph 4.20 shows the evolution of AT&T[54]. Surprisingly, it emerges that telephony is not a *distinctive* competence, however, its degree of specialization increases over time. In

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[54] It includes patents by Lucent, since it was spun off in 1996.

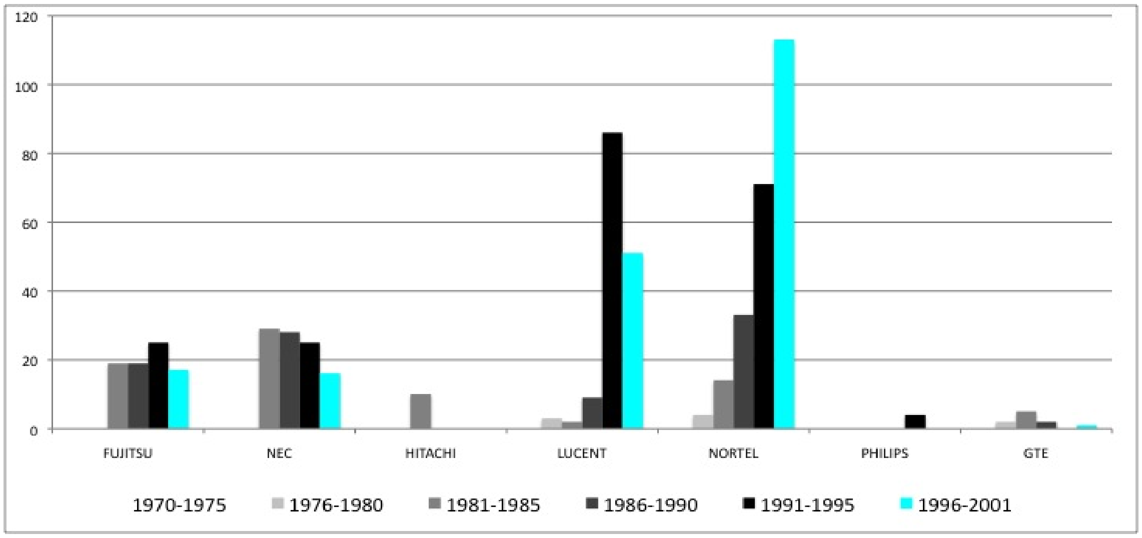

Figure 4.21: Number of countries supplied by vendor.

Source: Dittberner, 2003.

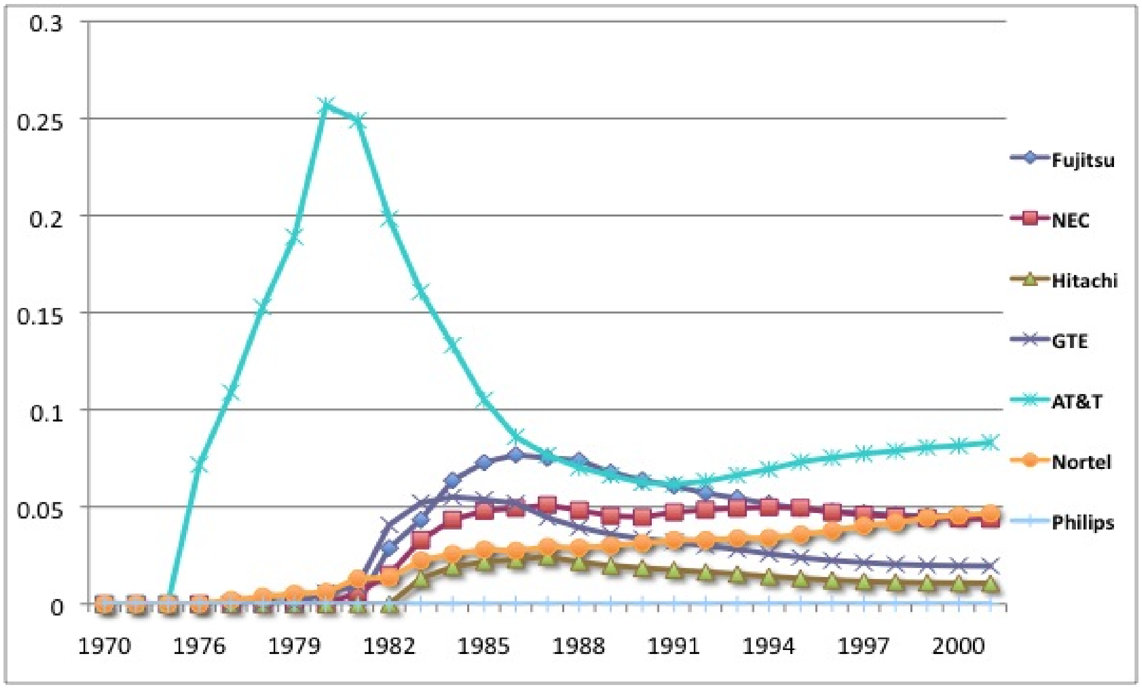

Figure 4.22: Evolution of Market Share in TDM digital switches (Worldwide).

Source: Dittberner, 2003.

general, as company it appears rather diversified. This is consistent with the large spectrum of research undertaken at Bell Laboratories leading to revolutionary technologies such as radio astronomy, the transistor, the laser, information theory, the UNIX operating system, and the C programming language.

Moving to firm's performance, graph 4.22 and 4.21, shows the high penetration of AT&T and a rapid increase of its internationalization. It was only after the divestiture and also after some initial difficulties that AT&T was able to sell its product abroad; other national operators were reluctant to be supplied by a manufacturer (the Western Electric) owned by a competitor network operator (Fransman, 1994*b*; Fransman, 1994*a*).

4.3.1.7 The U.S. independent market: GTE

For long time U.S. telephone market was characterized by the coexistence of a a monopolist (AT&T) and hundreds of independent companies; in 1983 there were 1500 independent companies serving one fifth of the market and covering the 51% of the country. Among these independent companies many of them were part of the GTE group (General Telephone and Electronics Corporation). This duality reflected in the telecommunication equipment market, where independent companies where supplied either by GTE or foreign companies (such as Northern Telecom).

In switching manufacturing, GTE inherits a long tradition as, since the 1955, it acquired Strowger's company Autelco. In the early 1960s it started developing its own electronic switching system with the objective to supply its service companies with a profitable (as able to offer new services) and compatible switch. In 1972 the EAX No.1 was put in service and quickly adopted by GTE's operators, other independent companies, and some foreign network operators in Taiwan and Iran (Chapuis and Joel, 1990).

Looking at the digital switching platform, GTE entered this market in a niche that is the Private Branch Exchange (PBX) and started the development of a digital toll office switch when AT&T announced the development of its No.4 ESS. Given the differences in the market served by AT&T and GTE (the latter focused more on rural areas), the GTD (firstly called No.3 EAX) platform was rather different from the AT&T equivalent as it was capable to serve only 16,000 trunks. However, capacity could be easily increased combining more units. Given the close relation between GTE and its own network operators, GTD was quickly adopted and exported to some foreign countries in the Caribbean area and Europe (Belgium and Italy) (Chapuis and Joel, 1990). In 1987 GTE decided to concentrate on services and therefore it sold all the interest in network infrastructures. It sold its PBX business to Fujitsu and its switching interest outside the U.S. to Siemens.

Figure 4.23 indicates that telephony was not a core competence of GTE and that the company had *distinctive* competences in electrical lighting and metal work. This is in line

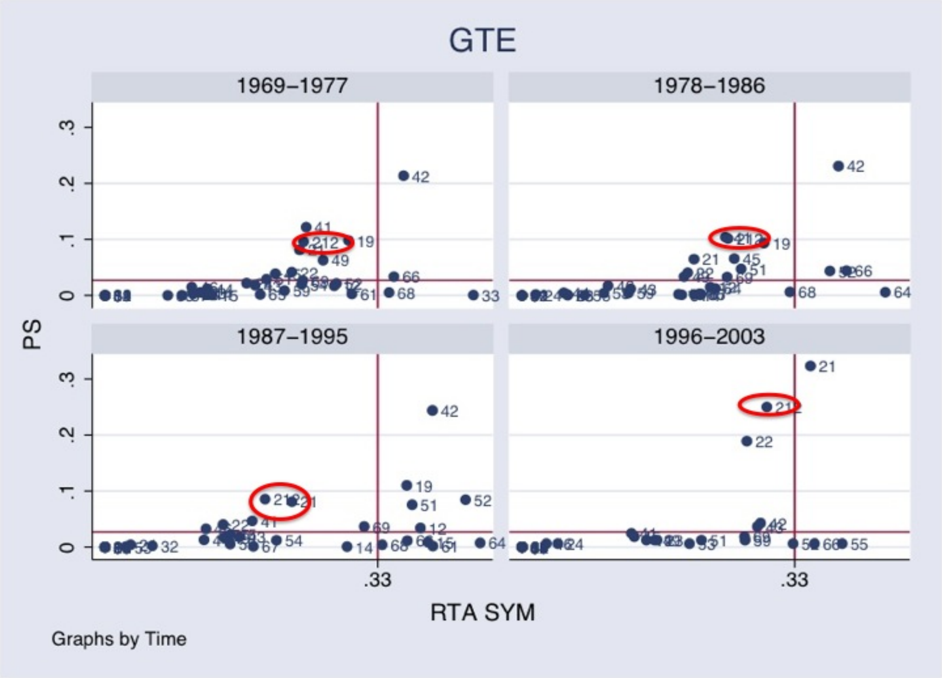

Figure 4.23: Patent portfolio analysis

The circle indicates telephony competences

with the history of this corporation that merged and acquired some companies[55] in these fields and in the middle 1980s decided to focus on three specific (but diversified) lines of business: telecommunications, lighting, and precision metals (Fundinguniverse, 2008).

4.3.1.8 Northern Telecom

Northern Telecom was founded in 1895 when the Bell Telephone Company of Canada spun off its manufacturer. This company was incorporated by Northern Electric and later, in 1914 became part of the Bell system, as Western Electric obtained 44%.

Despite the privileged relation with AT&T, Northern Electric developed its own electronic switching platform. In fact, the No.1 ESS was not economical for Canada, as it did not meet the size range requirements. The main characteristics of the SP-1 put in service in 1971 were the use of SPC, the medium (but expandable) lines capacity and comparable costs with

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[55] It is actually in 1959, after the merge between General Telephone and Sylvania Electric Products, that the name of the company will become GTE. As Sylvania was a leader in such industries as lighting, television and radio, and chemistry and metallurgy, the merge enlarge GTE competences beyond telephony and in particular it expended into electronics.

crossbar system (especially for installation and maintenance).

Despite the wide success and adoption of its electronic switching, Northern Telecom was an early comer in digital switches and in 1976 announced the development of the first digital switching system displacing all the competitors (Fransman, 1995). Furthermore, as also pointed out in section 4.2.4, Northern Telecom was able to exploit some regulatory changes and to enter the U.S. market (in 1988 it had 42% of the North American market).

Beyond these special circumstances part of Northern Telecom's success was related to its vision and market strategy. In fact, Northern Telecom developed an aggressive market campaign about the "digital world", opposed to the "analogue" (the clearly negative way to refer to space-division switches), whose purpose was to create a "digital hype". Furthermore, Northern Telecom was rather confident about the diffusion of digital switches and therefore started commercializing them in 1977 (two years before the ISS in Paris) with a price focused on market penetration rather than initial profit. In fact, the DMS10 would become profitable only in 1985 thanks to the sale to the RBOCs and the decrease of components costs.

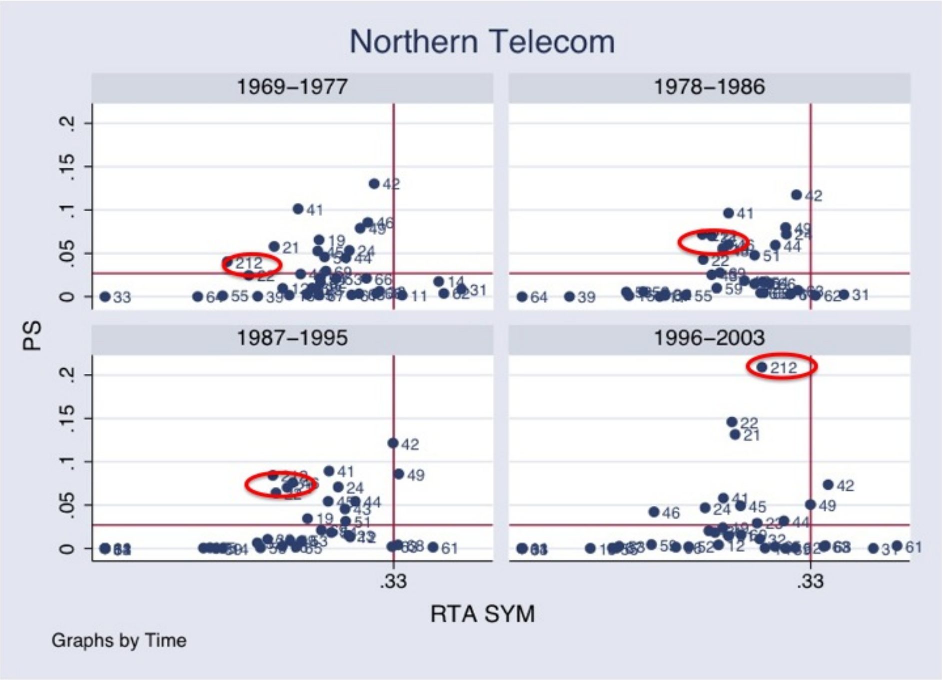

Figure 4.24: Patent portfolio analysis

The circle indicates telephony competences

Figure 4.24 shows Northern Telecom as a rather diversified company, where telephony competences moved towards being *distinctive* only in the recent time. Looking at the degree of internationalization, figure 4.21 shows Northern Telecom was supplying several foreign countries, a result compatible with the strategy pursued by the company.

4.3.1.9 Philips

Philips is a Dutch, long established firm, active in consumer electronics. It entered the switching industry after World War II, with Siemens-type, step-by-step exchanges, for the reconstruction of the Dutch network.

During the 1950s, Philips started the development of an electronic switch, the PRX, which was approved by the Dutch administration (and therefore adopted) in 1973. Because of its technical characteristics this switch was suitable for fairly small installations.

Following other manufacturers, Philips started developing its own digital platform, the PRX-D. While development costs started to increase rapidly, electronic consumer products (Philips' core business) faced a crises, and in 1979 the German public procurement bid was lost, Philips started to look for an alliance with a company with strong telephony competences. As already described in the previous section, AT&T was looking for a commercial partner in order to facilitate its entry in the European market, so this was the base for the creation of the ATT-Philips Telecommunication (APT) joint ventures in 1984.

This join venture was not very successful as APT was never able to capture a significant stake in the European market; therefore Philips withdraws form APT in 1990.

Not surprisingly,figure 4.25 highlights that telephony was not Philips' core business, even marginal still during the 1970s. Graphs 4.22 and 4.21 confirm the story, showing a very poor performance, both in term of market share and internationalization.

4.3.1.10 Japan

The Japanese telecommunication manufacturing sector is a good example of the "cooperative competition", actually a rather common setting in the Japanese NSI (see Kogurt (2000) for an analysis of the Toyota case). In fact, in order to upgrade its network with Japanese electronic SPC switches, NTT (the Japanese PTT) literally organized the relation among its suppliers (NEC, Fujitsu, Hitachi and Oki), and set up the largest co-operative project ever established at its Electrical Communication Laboratories (ECL). The outcome of this joint collaboration was the commercialization of the D10 platform (NEC's equivalent for No.1 ESS) in 1972.

Japanese research about digital switching did not start at ECL as NTT's engineers had a rather pessimistic view about the pace with which digital transmission would be deployed and therefore the company adopted a cautious approach (Fransman, 1995). However, NEC was an early mover into digital switching and its first prototype (the DEX-T1) was ready in the early 1964. At that time, its components costs made it not economically competitive with electronic switches. It was only in 1979, with a significant delay compared to early movers like Northern Telecom, that the DEX-T1 was installed. The reason of this late move was the NTT's caution

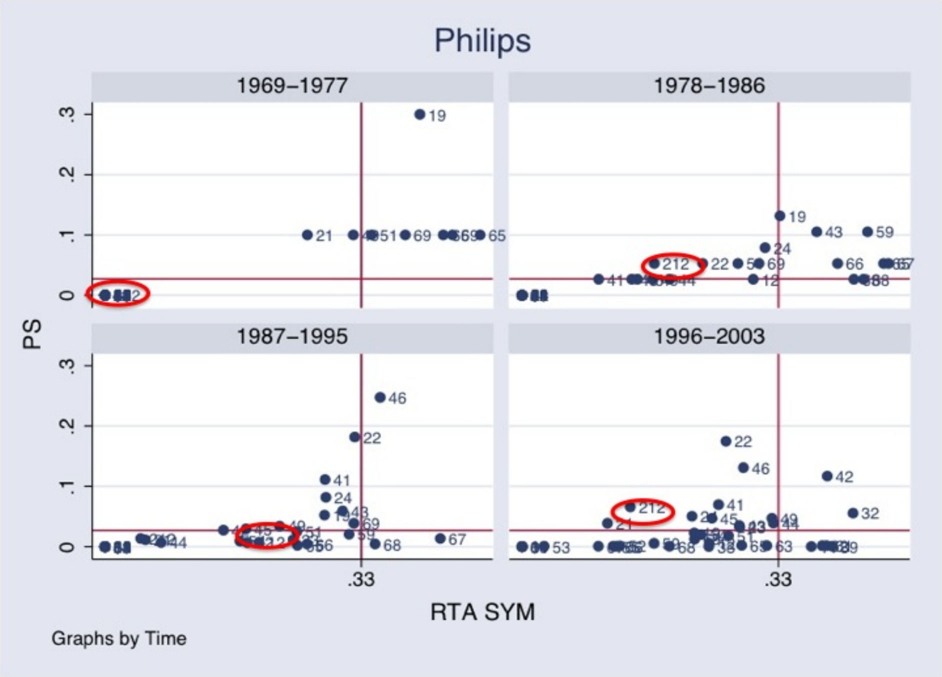

Figure 4.25: Patent portfolio analysis

The circle indicates telephony competences

this technology, so NEC had to bear all the costs and it did not have the opportunity to test the switch in the domestic market, lacking of the learning-by-doing process of the deployment. Because of this delay and some problems in the software development NEC was not able to successfully enter the U.S. market and in the late 1980s its share of the U.S. market was no more than 0.1%.

The history just mentioned refers to NEC's experience in developing and marketing its digital switch platform and its marketing in the U.S. The story of the D60 and D70, the digital platforms developed by ECL, is rather different. NTT was able to use a controlled competition relation for fostering healthy competition without undermining the trust relation.

After cell's engineers worked to an overall design, individual companies were appointed for the development of specific subsystems. Each subsystem was developed by at least two companies. NTT's objective was that all the four companies were able to provide a complete and interchangeable switch. Individual companies were free to decide what to develop and what to license from the other companies in the project. However, this decision had to take in account that the suppliers had to build their own competence for competing outside the domestic market. They had to fully bear the R&D costs and they were repaid with fixed procurement (in 1988: 26.1% for Hitachi, 25.5% for OKI, 25% for NEC, 22.8% for

Fujitsu and finally Northern Telecom with 0.6%) and fixed (not public) rate of return on sales. A specific strategy was also followed by NTT regarding the software; in order not to be dependent for further upgrading, NTT wanted to own the software and therefore paid the 70% of development costs (Fransman, 1995).

With the advent of broadband switches a similar scheme was used. The research on ATM started independently in 1986 at NTT and in three years a fully-fledged experimental ATM switching system was prepared and the following year NTT officially invited partners for the joint development. For the development of an ATM switching platform NTT was required to have a transparent and non-discriminatory procurement bid therefore foreign companies were also involved. In 1991 the selection was made and for the ATM Node System (directly related to switching). Fujitsu, Hitachi, NEC, Northern Telecom, Oki and Toshiba were selected. NTT wished to implement the cooperative competition that brought about the success of its digital switch but in this context there were some differences: firstly it was not economically efficient to divide the platform in subsystems, and secondly newcomers companies would have less easily shared new information. The problem was solved by NTT through common meetings for the common multi-vendor interfaces and separate meetings for hardware and software details. This process would be resulted in different compatible and exchangeable switches[56].

Figures 4.26 and 4.27 represent the technological profile of two of the major players of the ECL, NEC and Fujitsu. These companies show a rather similar profile as both do not have telephony as *distinctive* competence but just as *background*. Furthermore, NEC does not display any distinctive competence, revealing therefore a rather diversified profile. Fujitsu, instead, until the 1990s, display semiconductors and computers as core competences.

Looking at their performance (graphs 4.22 and 4.21) we can see a very limited global market share (with a peak of Fujitsu of 8% in 1986) coupled with a limited internationalization.

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[56] Also in this case, NTT decided to design the development of the ATM with the specific intent to be completely autonomous for the software development.

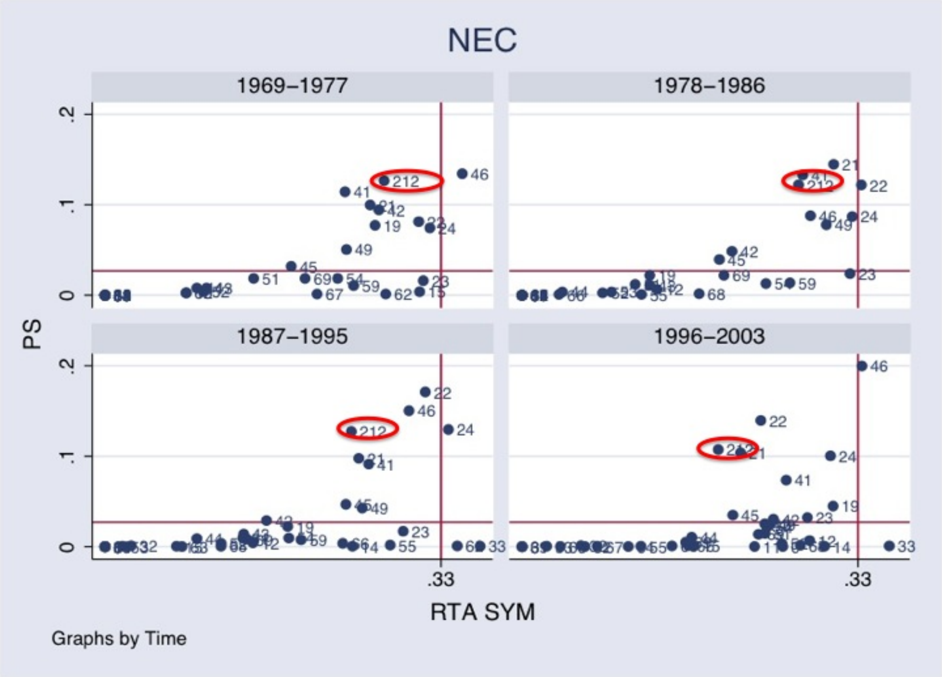

Figure 4.26: Patent portfolio analysis

The circle indicates telephony competences

4.4 Conclusion

The aim of this chapter was to provide an account of the *structural evolution* of the telecommunication switching industry. This chapter complemented the previous one, describing the institutional and economic context in which technological change took place. The structure of the chapter reflects the importance of considering two descriptive levels: the industry as a whole, and the firm (as embedded in its national system of innovation). It was important to also include the micro level, not only because its dynamic shapes the industry, but because of the nature of the industry. As pointed out several times before, this industry has very few well-established players, and they are embedded in a tight network of relations (see figure 4.8). Therefore, only a detailed description both at the industry and firm level allows to accounting for these factors. Finally, the detailed account of the firms history presented in section 4.3 will provide the basis for discussing and interpreting from the assignee (i.e. firm) perspective the results obtained using the patent citation analysis.

Table 4.11 and 4.12 summarize some of salient features of the industry evolution and of the companies. Moving to the conclusion; *what are the relevant aspects in the evolution of the telecommunication switching industry?*

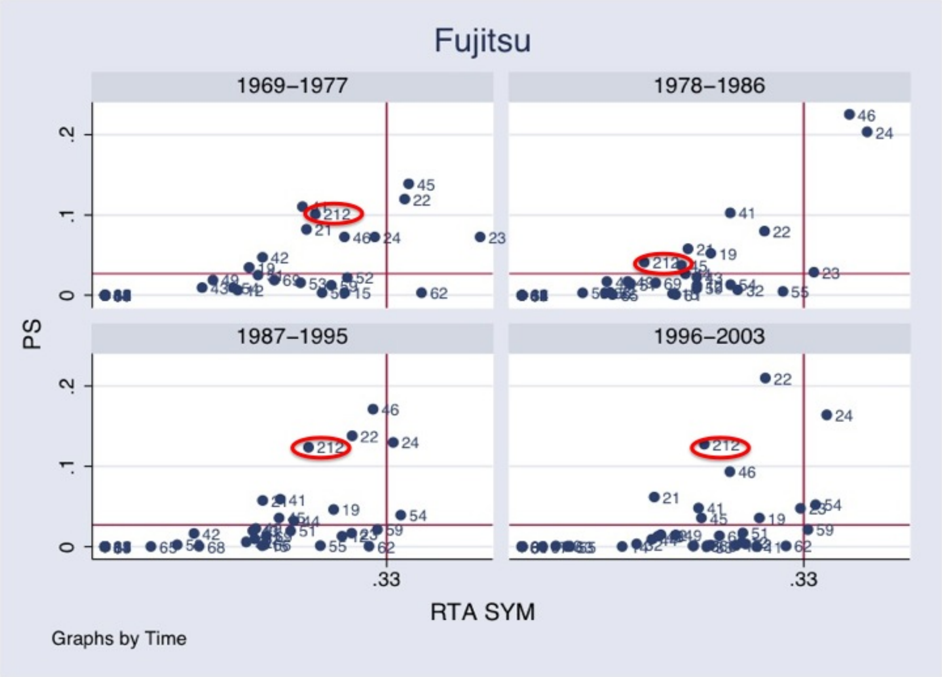

Figure 4.27: Patent portfolio analysis

The circle indicates telephony competences

1. Following the previous chapter, we know that this industry has experienced several waves of radical technological change. However, this has not opened a window of opportunity for new entrants because of high (technical and institutional) barriers to entry. The consequence of these barriers is a rather stable demography.

2. In order to understand the stable industrial dynamics we have to look not only at the manufacturers, but also at other actors involved, such as the network operators (which deployed the switches in their networks) and "the government[57]". The latter influenced the industry in several ways: through the ownership of the network operators (and therefore governing the adoption process), through industrial policies, and regulatory interventions.

3. In several cases (like France, Japan, United Kingdom) "the government" deeply affected the industry structure, being responsible for several of these "institutional barriers" mentioned above. For instance, targeted industrial policies determined the entry of new

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[57] The government is between inverted commas because it indicates a generic *government-related entity*. Depending on the specific case, it can be the Ministry of Telecommunications, or the Ministry of Industry or the Regulatory Agency, etc. etc.

Table 4.11: Summary of industry evolution

	Market structure	Barriers to entry	Market demand	Relation with PTTs	Source of knowledge
Origin of the industry (1879s-1915)	Competition	Low	Expansion	Independent	Internal
Interbellum	Oligopoly/ Controlled competition	High	Expansion	Factual or de facto integration	Internal
Maturity phase (1945-1980s)	Oligopoly/ Controlled competition	High	Expansion and upgrade	Factual or de facto integration	Component industry
Years of liberalization (since 1980s)	Increasing competition	Lower	Upgrade	Vertical specialization	External

companies (e. g. Alcatel) and the nurture of national suppliers. As table 4.9 shows, the premium for domestic lines provides companies with a sizable economic benefit.

4. A specific way through which "the government" affects the industry structure is the public procurement; in fact, tenders were designed in order to favor determined companies. Furthermore, through these bids network operators revealed their technological preferences, affecting the level of technological uncertainty in the industry.

5. Technical barriers to entry are related to the complex system nature of telecommunication switches. For instance, the high R&D of a new switching platform reduced the number of potential newcomers. In the case of digital platforms, high R&D costs caused some firms' shake out and fostered firms' collaboration (for instance in Japan and United Kingdom).

6. This chapter describes an industry with a slow dynamics. This is rooted in a slow innovation process (see the conclusion of the previous chapter) and adoption through long-term procurement contracts.

7. Table 4.12 summarizes some features of the major players in the industry. Looking at the dimensions analyzed it emerges firm's heterogeneity. If on the one hand, most of the firms have a preferred domestic network they can use for testing and learning; on

Table 4.12: Summary of industry evolution

Company	"Domestic" network[1]	Intern. (1987)[2]	Platforms developed[3]			Telephony Competence Specialization[4]	Exit by 1955[5]
			cros	el	dig		
Alcatel	Yes	Moderate		x	x	Yes	No
Siemens	Yes	Moderate	x	x	x	No	No
GEC	Yes	Low		x	x	No	Yes
Plessy	Yes			x	x	No	Yes
ITT	No	n.a.	x	x	x	No	Yes
Ericsson	No	High	x	x	x	Yes	No
AT&T		Low	x	x	x	No	No
GTE	Yes	n.a.		x	x	No	Yes
Northern Telecom	Yes	High		x	x	No	No
Philips	No	n.a.		x	x		Yes
NEC	Yes	Moderate	x	x	x	No	No
Fujitsu	Yes	Low	x	x	x	No	No

[1] This column refers to the "mature phase" (1945-1980s).

[2] International turnover (Table 4.8 last column): 0-20%= Low, 21%-59%= Moderate, 60%-100%=High.

[3] Legend: cros=Crossbar; el=electronic (SPC space-division); dig= digital (digital time-division).

[4] Yes-Technological subcategory 212 is *distinctive* for two or more periods, No=otherwise.

[5] Exit includes also merges and acquisitions.

the other hand the degree of firm's internationalization is more skewed, ranging from domestic-focused to export-oriented companies.

8. Finally, looking at the last columns and in particular at the exiting firms, what do they have in common? All the exiting companies are not specialized in telecommunication switching. As there are some successful not-specialized firms we cannot infer a causal relation, however, the slow dynamics (also in profitability, seeing the long payback-period (Antonelli, 1991)) highlighted before requires some "foresight" and long-term planning that not-specialized firms might lack.

Part III

Empirics

Chapter 5

Technological paradigms and trajectories in telecommunication switches: a patent citation network analysis

5.1 Introduction

We have already argued several times for the existence of a technology *inner dynamics* that might prevent instantaneous adjustments to market changes. According to the technological paradigm and trajectory approach this happens because of the local, cumulative, and irreversible nature of technological change (Dosi, 1982; Dosi, 1997) that constrains the search and technology space. Therefore, in order to study how technologies evolve it becomes crucial to explore how these designs and cognitive boundaries emerge and change over time. Following the line of reasoning presented in chapter 2, this corresponds to developing an empirical *microview* on technological change, based on the investigation of engineering heuristics (and their evolution over time).

The analysis is performed using patent data, which proved to be a suitable data source, as they can be used both as "count units" and sources of qualitative data. Furthermore, their use allows an analysis at the very micro level, which might be label the "technical problem level". In fact, patents contain a well specified technical problem and its proposed solution. Finally, patents (and citations) are not simply used as counting units, but their technical content is analyzed in order to identify patterns of technological change, heuristics, and technological bottlenecks.

The aim of this chapter is to use patent citation networks in order to map technological trajectories for the telecommunication switching industry. Furthermore, the results obtained are discussed from the assignee's perspective in order to link technological change and industry evolution.

This chapter is structured as follows: the second section reviews the literature (and the issues) on the use of patents data and patent citation networks. Section 5.3 will introduce the algorithm and data used. Section 5.4 will re-phrase the history presented in chapter 3 in term of paradigms and trajectories. Section 5.5 will present the empirical analysis. Section 5.6 will discuss the ownership of the patents in the technological trajectories and the the innovative performance of selected "Bellheads". Conclusions will follow.

5.2 Patents as indicators of innovation

A patent is a document that gives the right to an entity (the assignee) to exclude others from the use and production of a specific new device, apparatus or process for a stated number of years (Griliches, 1991). The fundamental requirements the new device, apparatus or process have to fulfill are novelty and utility. A patent is granted by a governmental agency (the patent office), which establishes a legal monopoly in exchange for the full disclosure of the innovation. The rationale is to promote innovation: the possibility of appropriating the results of R&D activities through patents should provide incentives to actors to invest in innovative activities.

Despite some caveats that we are going to discuss below, the use of patent statistics in innovation studies has accelerated, due to their availability for long periods, the quantity of information they carry[1], and their homogeneity.

The first issue relates on "what patents are actually measuring". Given the definition, patents look like a natural indicator for inventions. However, researchers are interested in innovations rather that inventions. What discriminates between the two is that the latter should be successfully applied, meaning that it is marketable and therefore it has an economic value. If on the one hand a patent marks novelty, it bears no information about the economic value of what is protected. In this sense, innovation is something more than a simple invention and it follows that, if we consider innovations as the subset of the valuable inventions, the use of patents as a measure of innovation tends to overestimate the phenomenon. In order to overcome this problem, some alternative indicators have been used such as the SPRU data bank on British innovations since 1945 (Townsend, Henwood, Thomas, Pavitt and Wyatt, 1981) or the catalogues of the World fairs (Moser, 2005).

Looking at the innovative process, patents represent a measure of its output; after carrying our some R&D activities, an invention emerges and this is eventually patented. However

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[1] From each patent it is possible to extract information about: the assignee (the entity which can actually exploit the patent), the inventor(s), the country, the technological area, the number of claims, etc. Furthermore, their qualitative analysis gives information about the technical problem tackled.

this intuition has been challenged: in fact, given the strong correlation between patents and R&D, patents can be used as indicator of both input and output for innovative activities (Griliches, 1991). In this line of research, R&D expenditures and patent counts (also weighted by citations) have been used for measuring firm's knowledge stock, and ultimately, its impact on a firm's productivity and market value (Bloom and Reenen, 2000; Hall, Jaffe and Trajtenberg, 2005).

The second issue about the use of patents regards the sectoral differences in patenting propensity. In particular, not all sectors appropriate their innovations through patents; some use other means such as secrecy, secondary services, etc. (Levin, Klevorick, Nelson and Winter, 1987). It follows that, despite their availability, patents are not suitable for all sectors and research should be aware of this.

Undoubtedly, the most serious caveat about the use of patents as indicators of innovation is the lack of information about their value, and, it is in this field that the effort of scholars has concentrated. Griliches (1991) reviews early empirical studies tackling this issue using surveys of patent holders or data about renewal fees. Recently, the availability of citation data has mitigated this problem. Among the information carried in a patent there is what is called *the prior art*, which is the available information relevant to a patent's claims of originality; therefore, patents cite previous relevant scientific literature, bulletins and patents. It was shown that through the counting of patent citations received (also called forward citations) it is possible to assess the importance and the value of a patent (Jaffe and Trajtenberg, 2005). The same rationale is applied to scientific publications: crucial patents constitute the building blocks for further innovations or open up new fields of research, therefore, they are highly cited by subsequent patents.

Recently, in the PATVAL survey, inventors were asked to evaluate their patents *ex post* (after 10 years). Results confirmed that citations constitute a good proxy for the economic value of a patent (together with other indicators such as the number of claims) (Gambardella, Harhoff and Verspagen, 2008).

The use of citations raises further issues, such as the meaning of citations, the person who is actually placing the citation, and the database used. The literature points out that citations can be used not only for assessing the value of a patent but also for: (i) mapping of knowledge flows and (ii) for investigating firms' strategic behavior (Marco, 2007). Given these meanings it is important to understand what type of incentives inventors have to disclose *prior art*, especially because different rules apply for the European and American Patent Offices. In particular, in the European system inventors are not obliged to add citations to *prior art* as the patent examiner will add it. Thus, it is difficult to consider European patents and their citations as a proxy for "conscious" knowledge spillover as only 7-14% of the citations are actually added by the inventor (Criscuolo and Verspagen, 2009).

Finally, scholars have increasingly started studying patents as strategic tools. In particular, recent literature suggested that not only patents can be use to deter entry but also cumulative technological change (Rockett, 2010).

Before moving to the next section, it is necessary to understand in what way the caveats put forward here affect and limit the analysis provided in this chapter. It appears that none of the them is of great relevance for this study. Telecommunication switches are a technological domain where patents were extensively used in order to protect inventions. Furthermore, interviews with engineers showed that researchers working in the field were always very interested in knowing what their competitors were patenting. As emerged from the description in the previous chapter, licensing among these firms was also used for exchanging technologies (Schmoch and Schnöring, 1994). Regarding who actually made the citations, we have to point out that given the nature of the investigation it does not matter very much, in fact, as we are interested in the technical link and not whether the inventor was aware of previous inventions. Furthermore, this study is based on a USPTO patent sample and in this case, inventors are obliged to cite *prior art*, incurring penalties in case they omit it.

As regard patents as a strategic tools we need to observe two things. First of all, in telecommunications strategic patenting is a recent phenomenon, as the traditional role of IPRs in telecommunications was a "Gentlemen's agreement" (Bekkers, Duysters and Verspagen, 2002; Granstrand, 1999). Second, according to the method, what actually matters are citations, and more specifically, the network citation structure. In this respect, it is doubtful to what extent a single company is able to influence such structure. Finally, backwards citations represent a delicate issue for patent attorneys (and inventors). In fact, they result from considerations about a clear trade-off: to maximize both its scope of a patent and its strength in case of litigation. Differently from scientific publications, patent citations have a specific legal meaning that leaves little room to further strategic considerations.

5.2.1 Knowledge networks: patent citation networks

In this work we depart from patent (and citation) counts and we look at them as a network: if patent A cites patent B, we can imagine a directed link between them indicating a knowledge flow. The advantage of this approach is the possibility to extract (and use) more information from citations. From a network perspective, a citation count corresponds to counting direct ties. Of course, this is informative about the importance of a patent at local level[2], however if does not consider the position of a patent respect to all the others and to knowledge flow within the network. Fontana, Nuvolari and Verspagen (2009) observe that the use of patent citation network can be seen as complementary to simple citation counts. In fact, they find the presence of not-highly-cited patents as pivotal junctions of the knowledge flow network.

This field of research is relatively new, excluding some explorative papers such as Ellis, Hepburn, and Oppenhein (1978). In this study, the analysis of patent citation networks is presented as a study about technological relatedness, which can be interpreted as an applica-

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[2] See next section for further details on the use of network centrality measures.

tion to technology of the approach pioneered by Garfield (1979) for the study of links among scientific disciplines. However those scholars already admit the difficulty of an extensive use of this method because of the lack of a systematic database of patent citations (unlike the possibility of using the ISI database for publications). Probably, it is for this reason that until recent years there has been limited scientific work on patent citation networks.

The challenge posed by patent citation networks is not only their size[3], but also other characteristics such as directionality and acyclicity. The former refers to the fact that ties are not symmetric but they have directionality (and therefore are edges). The latter means that no cycles are present in the network. This derives from the fact that patents can only cite previous patents, therefore directionality embeds the time dimension. These characteristics make their study difficult with standard network analysis techniques, as these mainly deal with undirected networks, meaning that most of the usual indicators cannot be applied in a straightforward way to a directed network[4].

Recently, researchers in complex systems began to be interested in the patent citation network as a whole, as it constitutes an example of a complex system emerging from human activities. They apply mechanical statistics in order to study network dynamics (i.e. the study of the organizing principle) and to model a system so as to replicate specific properties such as the power distribution of the number of forward citations (Valverde, Solé, Bedau and Packard, 2007)[5]. This was done by the modification of the famous "preferential attachment" proposed by Barabási and Albert (1999; 2002)[6]. In this case, the probability of a patent to be cited depends not only on the number of current citations (k) but also on the age of the patent (τ)[7].

These studies are rather recent and if on the one hand they shed some light on the structure and dynamics of patent networks, on the other hand, their approach is poorly grounded into innovation studies. For instance, they are not interested in estimating (and explaining) sectoral differences in τ. For these scholars the patent citation network is just an example of a complex system emerging from individual (innovative) behavior and their aim is to find potential commonalities with natural complex systems.

However, also in the innovation studies domain, there has been a recent interest in patent citation networks, and in a short time several empirical articles have been published. All

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[3] Notice that the whole NBER patent dataset has 3 774 768 nodes and 16 522 438 links.

[4] For instance, centrality betweenness in a directed network is based on the assumption that directional ties can be transformed into unidirectional (Wasserman and Faust, 1994).

[5] The number of forward citations follows a scale-free distribution, meaning that a few patents have most of the links, whereas the large majority has just a few.

[6] They explain the emergence of such property by the combination of two (necessary) forces: network expansion and "preferential attachment". According to this organizational principle, each new node probability to have k links decays following a power law distribution, namely $P(k) \sim k^{-\gamma}$. Therefore new nodes have a "preference" in connecting to already well-connected nodes.

[7] Formally it results: $\Pi(k_i, \tau) \sim k_i^{\beta} \tau^{\alpha-1} e^{-(\frac{\tau}{\tau_0})^{\alpha}}$, where the according to the values of τ_0 old or recent patents have an advantage (Valverde et al., 2007; Csárdi, Strandburg, Zalányi, Tobochnik and Érdi, 2007).

of them use connectivity measures in order to map technological trajectories within a patent citation network (Mina et al., 2007; Verspagen, 2007; Fontana, Nuvolari and Verspagen, 2009). These works have been reviewed in chapter 2 along with the empirical literature on technology evolution. From the methodological perspective, it is good to recall that all these studies use the indicators developed by Hummon and Dorein (1989) for identifying the main flow of knowledge within a publication network. Therefore, these studies apply a bibliometrics method to patents. As the analysis of section 5.5 uses the same methodology, the technical details are shown in the next section.

5.3 Mapping technological trajectories using patent citation networks

The rationale of a patent citation network is that if patent A cites patent B there is a flow of knowledge going from A to B (see figure 5.1[8]). Patent A and B are indicated as the cited and citing patent, respectively. This relation is displayed in figure 5.2.

Figure 5.1: Representation of a patent and citation

Formally, a patent citation network corresponds to a directed graph, $\mathscr{G}_d(\mathscr{N};\mathscr{L})$, where $\mathscr{N}$ represents the set of vertexes and $\mathscr{L}$ the set of arcs[9]. In particular, $\mathscr{L}$ is defined as the *"citing"* relation $\mathscr{L} \subseteq \mathscr{N} \times \mathscr{N}$ for which

$$uRv \equiv v \; cites \; u \tag{5.1}$$

In this notation $|\mathscr{N}|$ and $|\mathscr{L}|$ represent the number of vertexes and arcs.

This network has three relevant properties[10]:

1. As no patent can cite itself it is *irreflexive*, $\forall u \in \mathscr{N} : \neg uRu$
2. As patents cannot cite forward patents, it is *acyclical.* This means there are no cycles in the network and therefore each vertex is not reachable from itself by a non trivial

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[8] Note that the arrow indicates the flow of knowledge.

[9] In this part of the section we will stick to the general notation for directed networks not explicitly refer to patents (vertex) and citations (arcs), unless we are providing examples or commenting one of the figures.

[10] For a more rigorous treatment of the subject and for some extension of the method to acyclical network see Batagelj (2003).

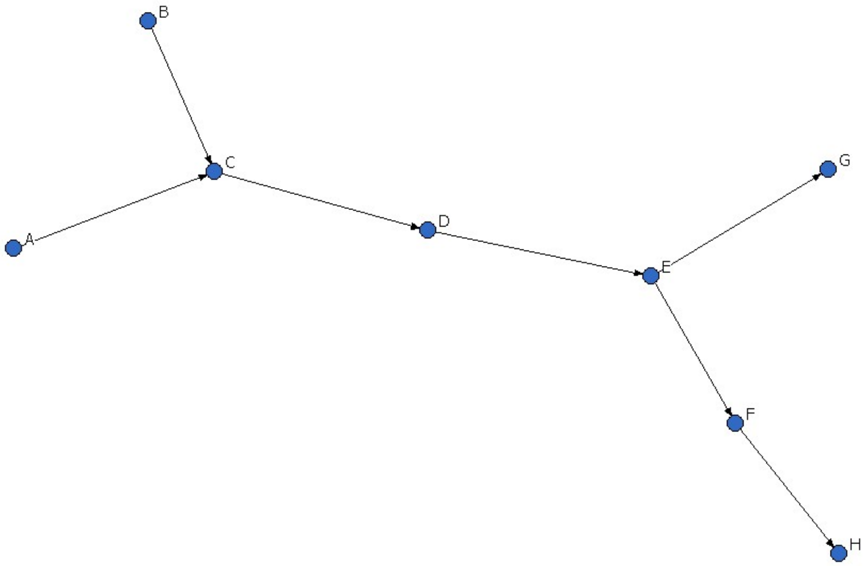

Figure 5.2: Example of patent citation network

path[11], $\forall u \in \mathscr{N}\ \forall k \in \mathbb{R}^+ : \neg u R^k u$

3. The set of vertexes $\mathscr{N}$ can be *topologically ordered* using a permutation $i : \mathscr{N} \rightarrow 1, 2, \ldots, |\mathscr{N}|$ for which:

$$uRv \Rightarrow i(u) < i(v) \tag{5.2}$$

Intuitively, this last property is reflected in the progression of patent number: given the fact that it is not possible to cite forward patents the patent number of a cited patent is always smaller than its citing patents.

The other side of the same coin is the representation of the graph as a binary matrix **C**, where $|\mathscr{N}|$ represent the columns and the rows[12] and $|\mathscr{L}|$ is the number of elements different from 0. Given the relation 5.1, $c_{i,j} \in \mathbf{C}$ is equal to 1 if *i cites j* and therefore the arc $< j, i >$ exists.

Within a directed graph we can distinguish three types of “special” vertexes:

1. *Startpoints* are vertexes whose indegrees are equal to zero ($d_I = 0$), meaning that no arc ends in that vertex. From a matrix perspective, this means that for each column indicating a *startpoint*, the values are all zero, $\forall j \in \mathbf{C} : c_{i,j} = 0$

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[11] A path is a walk where no vertex and no arc is included more than once. It follows that there are no cycles and therefore the graph is actually a *tree*.

[12] This matrix is therefore square with dimension equal to $|\mathscr{N}|$.

2. *Endpoints* are vertexes whose outdegrees are equal to zero ($d_O = 0$), meaning that no arc starts in that vertex. From a matrix perspective, this means that for each row indicating an *endpoint*, the values are all zero, $\forall i \in \mathbf{C} : c_{i,j} = 0$

3. *Isolates* are vertexes whose indegrees and outdegrees are equal to zero[13].

In figure 5.2 *startpoints* are patents which do not cite any previous patents but they are cited by forward patents, these are A and B. *Endpoints* are patents which are cited but they do not cite any other, just like G and H. No *isolate* is displayed and the remainders are *intermediate* points. Therefore, the question here is *"from a network perspective, are all the citations the same or some links are more important than others?"*. A way to answer this question is to weight citations accounting for their structural connectivity. Intuitively, this means putting higher value on citations that carry more information because they connect a larger number of patents (Hummon and Doreian, 1989). In this way it is possible to identify the sequence of patents that connect the largest number of patents, representing the "main flow of knowledge" within the network. From what is said in section 2.3.2, this represents the technological trajectory for the technology under study. Using the metaphor of a river and its tributaries, the main flow of knowledge corresponds to the path carrying the largest amount of water. Again, this means departing from a simple patent or citation count[14] and looking at indicators that evaluate the whole network structure.

The methodology here used for the identification of technological trajectories within a patent citation network is constituted by three building blocks, which are:

1. The calculation of a connectivity indicator for each citation, which means transforming the binary matrix $\mathbf{C}$ in the weighted $\mathbf{C}^{\mathbf{SPX}}$[15].

2. The identification of the so-called *network of main paths*;

3. The identification of the so-called *top main paths* and the analysis of its evolution over time.

5.3.1 From a binary to a weighted network

Hummon and Doreian (1989) propose three indicators for evaluating the connectivity properties of a citation[16]. These indicators are: (i) the *node pair projection count* ($NPPC$), (ii) the

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[13] Technically, this is both a startpoint and endpoint.

[14] It is interesting to notice that for each patent the number of backwards and forward citations corresponds to the number of arrows terminating and starting a specific nodes. From a network perspective these correspond to indegrees and outdegrees centrality.

[15] SPX is the generic indicator for one of the two connectivity measures ($SPLP$ and $SPNP$) introduced in the following pages.

[16] It is worth noticing that their application in the above mentioned seminal paper is in a small publication network of 40 scientific articles about the discovery of DNA.

search path link count ($SPLC$), and (iii) the *search path node pair* ($SPNP$). However, the NPPC can be considered a special case of the $SPLC$ and for this reason we will focus on the last two measures. The calculation of these indicators for large networks requires an efficient algorithm; in this section we will focus on their description and their intuition, leaving aside computational efficiency[17].

The two indicators are based on the concept of *search path count* (SPC), which, given the set of *startpoints* S and the set of *endpoint* E, weights each arc $< u, v >$ by the number of different paths between $\forall s \in S$ to $\forall e \in E$ it lies on. In order to compute this we indicate with $N^{-}(v)$ the number of different paths connecting $\forall s \in S$ s to v and $N^{+}(v)$ the number of different paths connecting v to $\forall e \in E$.

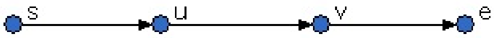

Figure 5.3: Example of a simple patent citation network

As it is shown in figure 5.3, we can consider all the paths from $\forall s \in S$ to $\forall e \in E$ as a composition function $\pi = \sigma \circ (u, v) \circ \tau$, where σ represents all the paths from s to u and τ all the paths from v to e. It follows that

$$SPC = w_d(u, v) = N^{-}(u) \cdot N^{+}(v) \tag{5.3}$$

The fact that the network is topologically ordered ensures that all the components are completed with all the possible paths.

The description of the two indicators in Hummon and Doreian (1989) is not very precise and Batagelj (2003) observes that $SPLC$ is the SPC originated from each vertex (and therefore not only from *startpoints*). Given the confusion, both interpretations are compatible, however, in this work SPLC is calculated from the *startpoints*, therefore $SPLC = w_d(u, v)$.

Looking at figure 5.2, we can say that the $w_d(D, E)$=4, since $N^{-}(D)$=2 (paths A → D and B → D) and $N^{+}(E)$=2 (paths E → G and E → H).

The second indicator, SPNP *"accounts for all connected vertexes pairs along the paths through the arc* $(u, v) \in R$*"* (Hummon and Doreian, 1989, page 14). However Batagelj (2003) observes some mistakes in the table reporting the $SPNP$, and he defines:

$$w_p(u, v) = L^{-}(u) \cdot L^{+}(v) \tag{5.4}$$

where $L^{-}(u)$ and $L^{+}(v)$ are respectively the number of different paths terminating in u and originating in v. In the figure 5.2, the calculation of $SPNP$ for the arc $< D, E >$ corresponds

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[17] For this aspect see Batagelj (2003)

to the multiplication of the number of downstream and upstream patents (including E and D). We can therefore say that $w_p(D,E) = 16$ since it connects 4 downstream and upstream patents. As reported by Verspagen (2007), $SPNP$ for the $c_{i,j} \in \mathbf{C}$ can be calculated as $m_{i,j} \times n_{i,j}$, where $m_{i,j}$ is the number of nodes for which a path to i exists (including i) and $n_{i,j}$ is the number of nodes to which a path from j exists (including j).

A general property that Batagelj (2003) observes is that, $\forall <i,j> \in \mathbf{C}$

$$w_d(i,j) \leq w_p(i,j) \tag{5.5}$$

and in particular, the two connectivity measures tend to differ more in the "internal" arcs, for which the multiplicative effect of $SPNP$ is larger.

5.3.2 Identification of the network of main paths

The second step is the identification of the main paths in $\mathbf{C^{SPX}}$. The search algorithm selects from each *startpoint* the arc with the highest SPX; in case more arcs have the same highest values, all of them are selected. This procedure is repeated from each reached vertex until an *endpoint* is eventually reached. This procedure is basically a way to reduce the complexity of a network deleting "unimportant" links, where the importance is measured in term of the SPX. Repeating this procedure for all the *startpoints* will identify several main paths (however, some can converge to the same *endpoint*), therefore from a matrix $\mathbf{C}$ is possible to build a matrix $\mathbf{C'}$ representing the "network of main paths". By construction $\mathbf{C'}$ has the same dimension as $\mathbf{C}$, however will be more sparse.

5.3.3 Identification of the top main paths

The seminal paper by Hummon and Doreain (1989) uses a very limited dataset with only 40 nodes (publications) where only one main path emerges, which they identify as the main flow of knowledge, and all the flows converge to the same *endpoint*. However, Verspagen (2007) proposes an extension of this method that is the identification of the so called "top main path" $\mathbf{p^t}$, which is, among the network of main paths, the path whose sum of SPX is the highest. In this way it is possible to determine which among the main paths has the highest overall connectivity. Finally, in order to appreciate changes over time, it is possible to partition the graph into subgraphs $\mathscr{G}_d^t(\mathscr{N};\mathscr{L})$, where $\mathscr{N}$ are all the patents granted up to time t. The union of all the $\mathbf{p^t}$ calculated for each subgraph will display the evolution of the technological trajectory over time.

5.3.4 Data

Before moving to the empirical results, we need to describe how the patent and citation sample was built. Selection was carried out using USPTO technological classes, although other strategies such as the use of IPC classes were also explored[18] The selection of the technological class and technological subclasses was driven by the reading of their descriptions and by the analysis of firms' patent portfolio for companies highly specialized in switch production. In this way the five technological subclasses of class 370 ("Multiplex Communication") were selected[19]. Using this criterion, a search was made in the entire USPTO database (from 1870) and a set of patents was extracted. In order to account for the complexity of a switch and to consider important technologies which might not have been captured by the first search, the first round of cited patents was added to the original set. These cited patents were retrieved from the NBER patent database (Hall et al., 2001); for patents granted before 1975, the citations were manually added. The final sample includes 6214 patents covering the period 1924-2003.

Citations for patents issued before 1975 were manually collected. It is important to note that the citations considered are only the "internal" ones, meaning that once the patent sample is selected, only citations to patents included in the starting sample are considered (the thick arrows in the figure 5.4).

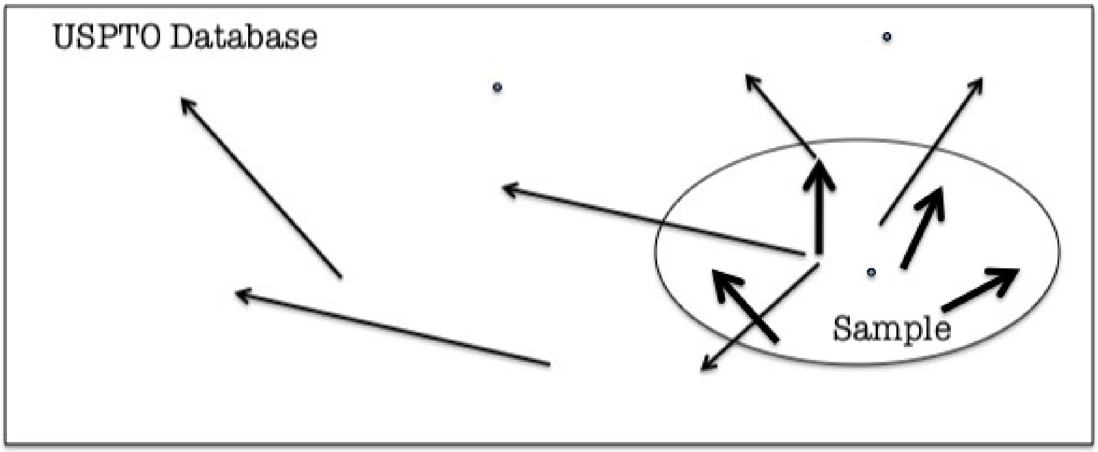

Figure 5.4: Representation of the "internal citations"

The empirical analysis was carried out on a patent citation network composed of 6214 vertexes (patents) and 20 848 edges (citations).

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[18] Results are not displayed as the trajectories show a great degree of overlap in the backbone.

[19] These subclasses are:

1. Having space switch as intermediate stage (e.g., T-S-T, T-S-S, or S-S-T) (370/370);
2. Having details of control storage arrangement (370/371 and 370/378);
3. Using time slots (370/458);
4. Synchronization information is distributed over multiple frames (510/370).

5.4 Reframing the history of switches: a paradigm-trajectory approach

Chapter 3 presented a detailed account of how technological change took place in the telecommunication switching industry. In that chapter an internalist approach was adopted, meaning that the narrative was centered on the engineering side, leaving aside all the considerations about the economic context in which those technological advances took place. In particular, in that chapter not much was said about the emergence of new paradigms in the industry, confining the story to a simple narrative of emerging technical bottlenecks, new solutions, and new technologies. The aim of this section is to reframe technological history of telecommunication switching industry using the concepts of technological paradigms and trajectories. In particular, we aim to distinguish the paradigmatic shifts that occurred and to look at the main competing technological trajectories emerging.

From the conclusion in chapter 2 we can distinguish seven switch generations, namely:

1. Manual;
2. Electromechanical direct-control;
3. Electromechanical common-control;
4. Space-division SPC;
5. Digital time-division centralized SPC command;
6. Digital time-division digital decentralized SPC command;
7. Packet switching.

Now we are interested in grouping these generations into technological paradigms. In order to do so, we first have to look at the way these generations differ. As indicated several times before, telecommunication switches are complex systems, therefore their evolution can occur along several technical dimensions; however, in chapter 3, following the technical literature[20] it emerges that the most referred, and therefore relevant, technical characteristics are:

1. The **switching fabric**, which indicates the nature of the crosspoint at which the information is actually switched within the device;
2. The **traffic logic**, which constitutes the way the call is planned and routed within a switch itself. This aspect is related to the way the signaling function[21] is actually organized in the whole network and within the switching network;

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[20] In particular the books *Electronic Switching: Central Office Systems in the World* (Joel, 1976) and *Electronic Switching: Digital Central Office Systems of the World* (Joel, 1982)

[21] See chapter one for a definition.

3. The **multiplexing technology**, upon which depends the way in which this information is combined and separated again within the switch and how more than one circuit (and therefore more than one call) can actually share single elements or components;
4. The **nature of the end-to-end traffic** that the switch supports (e.g. voice calls are one type of data traffic);
5. The **nature of the service traffic**, which relates to the characteristics of the information switched in the telephone network;
6. **Technical components**, which refers to the components used in the switch and their characteristics and technology;
7. **End user signaling**, which refers to the way a telephone set actually exchanges numbering information with the switch.

So, the first part of this process of classification of switch generations in different paradigms consists in describing how these generations differ over the characteristics above.

Table 5.1 summarizes the differences (notice that the number in the first rows refers to the list of characteristics) and at first sight it clearly appears that different generations cannot be distinguished in terms of differences along all the characteristics considered. Some generations share some features with their antecedents and it is therefore important to set the criteria of a paradigmatic change.

Manual switches (switchboards) could switch only analogue information, in this particular case merely voice. As column 4 and 5 show, this persisted until the emergence of time-division multiplexing (TDM) switches. All the calls were switched through the operator who was performing the control function; in particular, for every call the operator had to manually test whether the receiver was available and not busy with other calls. Looking at the artifact, switchboards were built of wires, cords, and jacks, and the connection was physically established through a patchcord.

The next two generations (electromechanical direct and common control) differ in the way control was organized. In the direct-control switches, subscribers' numbers were "hardwired" in the switch, meaning that each subscriber had a specific inlet in the switch and a fixed, hard-wired telephone number linked to that inlet. With the common control, in particular in the 1960s with the emergence of the crossbar switch, some control functions would become programmable thereby increasing flexibility. In particular, this programmability would start the process of separation between traffic and signal, which would be a distinctive feature for the next generations. Looking at the components, switches became more complex, using different types of crosspoints: mechanical devices such as selectors and connectors (e.g. Strowger and Lorimer types) or reed relays (e.g. Crossbar switch), and finally including electronic devices as tubes. However, the use of tubes was very limited in switches[22] given the severe heating

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[22] In contrast, transmission systems did use tubes extensively for amplification, among other things.

Table 5.1: Generations of switches and characteristics

Generation	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Manual	Patchcord	Manual	No multiplexing	Analogue	Voice	Wires, cords and jacks	Assisted by the operator
Electromechanical direct-control	Relays, mechanical devices, selectors	Hardwired and local	Space-division			Mechanical devices, tubes, wires, amplifiers	Automatic dialing for local calls and operator assisted for long distance calls
Electromechanical common-control		Hardwired or centrally programmable					
Space-division SPC	Electronic circuits	Programmable and local				Reed relays, analogue integrated circuits, transistors	
Digital time-division centralized SPC command			Time-division	Digital, circuited switched, narrow-band	Voice and limited speed data services	Digital integrated circuits (multiplexer), LSI (Large Scale Integration) integrated circuits	Automatic dialing
Digital time-division decentralized SPC command							
Packet Switching		"Intelligent", store-and-forward		Digital, packet switched, broadband	Voice and high-speed, bursty data services	VLSI (Very Large Scale Integration) integrated circuits	Automatic "dialing"

Legend: (1) switching fabric, (2) traffic logic, (3) multiplexing technology, (4) nature of the traffic in the switch, (5) nature of the service traffic, (6) technical components, and (7) signal to the end user.

dispersion.

The space-division multiplexing (SDM) generation displays a long-lasting change in the nature of the crosspoints with the exclusive use of electronic components and circuits: all the subsequent generations would replace all the mechanical parts with electronic ones. Furthermore, in this generation there is the introduction of so-called computerized control systems, dubbed Storage Program Control (SPC). SPC adds a new component to the switch: the software. In particular, whereas the hardware is responsible for the physical connection (switching system), the software is responsible for the control (switching control). The possibility of using SPC was driven by the availability of new electronic components (starting from transistors) with increasing scale of integrating circuits (and therefore capacity). New components offered numerous advantages: the use of electronic cross-points reduces the latency of the network, and lowered maintenance and labor costs. Not less important, it also reduced the size of the switch. In addition, the use of software allowed for more flexibility in routing, easier upgrading, and opportunities for expansion. Finally, it is interesting to notice that this generation, together with the previous one used space-division multiplexing, meaning that the different circuits/calls were separate in space along the same wire.

Moving to the TDM generations we can notice significant changes. Firstly, the multiplexing technology changed from space-division to time-division, which eventually became the dominant technology. The data streams within the switch became digital and also some limited data services for end user services were introduced. This limit was set by the general limits in the transmission speed of telephone network.

The last generation considered in table 5.1 is packet switching, which implies a change in the "switching mode"; in fact, all the first six generations are of the circuit-switched type. The characteristic feature of the latter is that the end-to-end connection is established at the start of the call, and remains until the end of the call. This is not very efficient as fixed and exclusive capacity is allocated for the full length of the call, even if no information is transmitted (e.g. when both speakers are silent). Especially for data traffic, where there are many more "silences" in a given communications session, this is very inefficient.

Packet switching means that information is split into packets of different length that are individually routed to the address they carry in the header. Packet switching is particularly suitable for data communication as it can be efficiently used for data transmission. In particular, it can handle different type of data traffic ranging from bursty data to continuous media. Within this generation even voice is transmitted using packets (often referred to as VoIP service).

Given all these multi-dimensional differences it is not trivial to answer the following question: *How are we going to discriminate along different paradigms?* Following chapter 2, we distinguish a new paradigm when there are changes in the technological knowledge base and in the engineering heuristics. In particular, shifts in the knowledge base of a technology determined the simultaneous obsolescence of engineers' competences and need for new ones.

This implies that the usual technical solutions are not valid anymore and therefore engineers need to apply new heuristics. In order to distinguish technological paradigms within the generations listed before, we are going to focus on three different aspects. These are: (i) the technical skills and competences needed in each generation (which depend on the technical differences highlighted in table 5.1), (ii) the perceived barriers and bottlenecks on which engineers were working, finally (iii) the consequent applied *engineering heuristics*. These aspects are summarized in table 5.2.

Switchboards were initially built in small workshops, often dedicated to other productions such as organs or sewing machine. Therefore no exclusive competences were actually required. The "perceived barrier" related to the possibility of network expansion connecting the whole population. In particular, in this period the so-called *switchboard problem* emerged: the hardwiring of the inlets determined diseconomies of scale, raising the switching cost in highly populated areas (Mueller, 1989). Part of the solution of this problem implied the development of some competences on how to manage traffic and congestion in a telephone network. This would become a required competence for the development of all the subsequent generations, even if with more sophisticated tools and methods.

Electromechanical switches (generation 2 and 3) share several technical characteristics, requiring very similar competences, mainly pertaining to mechanical engineering. In particular, engineers' work was still focused on the provision of what would eventually be called universal service (e.g. a phone for every family, regardless of social class and geographic location), under the constraint of limiting complexity. In fact, large electromechanical systems often required maintenance interventions both for ordinary situations (for instance to grease selectors) and extraordinary one (in case of failure), determining a cut in running costs. In the future, some of the technical improvements and the success of subsequent generation would be driven by the possibility of diminishing maintenance costs. The electromechanical common-control switch emerged in response to a new perceived technical problem that was the need for more flexibility. As explained several times, switches are integrated in a large system and they have a long life cycle, therefore the possibility of adapting them (for instance increasing the capacity) is a central characteristic on which engineers were focusing.

The fourth generation (SPC space division multiplexing switch) brought about an extensive change in the competences needed for the production of new switches. In fact the use of electronic components required the expertise of electronic engineers, making mechanical competences obsolete. Furthermore, some limited programming skills were also necessary in order to organize the control with the SPC. This "electronic revolution" also brought about the need to develop new competences maintenance (and therefore also outside R&D laboratories). Technical books report striking examples of network failures caused by using old methods for the maintenance (for instance old school maintenance staff that lubricate electronic components with grease) (Chapuis, 1982; Clark et al., 1988). The reason for introducing electronic components was the possibility of increasing flexibility, both internal and external. The former refers to routing procedures and changes in the network architecture, and the latter to

Table 5.2: Emerging of new paradigms

Generation	Competences needed	Perceived barriers	Engineering heuristics
1	Handcraft	Up-bound of penetration ($\ll 100\%$) and *switchboard problem*	Connecting everybody
2	Limited knowledge about traffic/routing, mechanical engineers and materials	Maintenance of mechanical parts, lack of flexibility	
3		Modest level of flexibility	
4	Knowledge of electronic circuits and semiconductor components, some programming skills (for the control circuits)	Provision of service, more expensive cost/efficiency, complexity	Exploit the potential of developments in electronics and microcomputing
5	Extensive skills of digital electronic circuits and applied mathematics	Limits in data transmission capacities (speed and efficiency)	Integration of transmission, new services
6	Extensive programming skills		Digitalization of the full chain (ISDN)
7	Computer network skills, more math skills	Quality of Service	Widespread deployment of broadband infrastructure

Legend: (1) manual, (2) electromechanical direct-control, (3) electromechanical common-control,
(4) space-division SPC, (5) time-division digital centralized SPC command,
(6)time-division digital decentralized SPC command, (7) Packet Switching.

flexibility in the provision of new services. Moreover, engineers were focusing on increasing the cost/efficiency of the expensive electronic components, in order to have both a reliable and economic viable switch.

The success of digital switch generations required the acquisition of new competences in digital electronic circuits (vs. analogue circuits) and mathematical skills. In fact, mathematical models and Boolean algebra were the toolbox needed in order to develop and test digital switches. The decentralization of control completed the separation between hardware and software in a switch and called for a strengthening of programming skills. The last columns look alike, showing that the perceived frontier was the integration with transmission and the implementation of new services such as call forwarding and toll free calls. Finally, in the TDM decentralized control switch, engineers started to work at the digitalization of the whole network and therefore at ISDN (Integrated Service Digital Network) in order to build a single network suitable both for voice and data communication, with end to end digital devices. In fact, they failed to convince the end users to purchase the much more expensive digital telephone sets, so the concept of a real integrated digital chain including the end user terminal was never reached.

As explained in the previous chapters, packet switching was developed since the 1960s in the data communication industry and was only recently adopted in the telecommunication switching industry. The external nature of this technology brought about the need to acquire completely new competences in computer networking. Furthermore, the complexity of the routing algorithms used implies a massive use of mathematical modeling and simulations. Given the many software components of these switches the development and testing process was also completely different, for instance, using computer simulations rather than prototypes. The perceived barrier for the engineers was the possibility of guaranteeing a minimum standard of quality for the voice service. In fact, on the one hand, packet switching is optimal for data communication, but on the other, packet losses can deteriorate the quality for voice transmission quite dramatically. Finally the engineering heuristics are related to the widespread deployment of NGN networks[23] boosted by the success of the internet.

The various arguments summarized in table 5.2 were “weighted” in order to support the classification into different technological paradigms. In particular, we can identify four paradigms, which are shown in table 5.3. Moreover, this table mentions the technological trajectories in each paradigm and the generation of switches involved.

In the last pages of this section we will focus on the trajectories, briefly looking at the details of why they do not constitute separate paradigms.

Within the second paradigm (the electromechanical one) we can distinguish different trajectories corresponding to different switching platforms. They differ in some aspects such as the materials, the mechanics, and the movements of selectors, however they are still grouped together because they rely on the same bulk of knowledge and engineers focused on similar

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[23] Next Generation Network (NGN) generally refers to packet switching networks.

Table 5.3: Paradigms and trajectories in telecommunication switches

Time	**Technological Paradigm**	**Trajectories**	**Generations**
1870-1930	Manual	Switchboard	1
1930-1965	Electromechanic	Crossbar - Panel - Lorimer	2-3
1965-1990	Electronic circuit switching	Analogue - Digital Space-division (SDM) - Time-division (TDM) digital *centralized* control - digital *decentralized* control	4-5-6
1990-...	Packet Switching	ATM and IP-based switches	7

Note: Time is indicative and refers to the commercialization of the relevant switch generations.

problems.

The novelty of the third paradigm consists in the introduction of electronic components in the middle 1960s, and the introduction of the so-called computerized control systems, dubbed Storage Program Control (SPC). Within this paradigm we can identify three trajectories and in order to understand them (and their relations) we focus on two technical characteristics discussed before, which are the way in which the information is coded (analogue or digital speech), and the multiplexing technology.

Table 5.4: Possible combinations

		Switching Division	
		Space-division	Time-division
Nature of switched signal	Analogue	(1)	(2)
	Digital	(3)	(4)

Combining these two dimensions, four different switching designs are possible. All these four designs were in fact explored and developed (see Table 5.4). In the end, two designs became dominant: the analogue space-division type (1) and the digital time division type (4). These are what in the jargon are called electronic and digital switch respectively. In the list of the generations at the beginning of this section, they correspond to the space-division SPC switch and the time division digital SPC switch. Both other designs, (2) and (3), were also explored[24], however, they never made it beyond the stage of proof of concept or the prototype

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[24] Research about (2) was widely undertaken at the beginning of time-division. In that case PAM (Pulse

stage. Although the transition in the multiplexing technology and in the information coding is not insignificant, it does not constitute a genuine paradigmatic change because none of the two is affecting the aspects highlighted in table 5.2.

The third dimension along with we can identify a trajectory (within the electronic circuit switching paradigm) relates to the way control is organized; namely centralized and de-centralized control. This determines different time division digital switch generations (five and six, according to the list at the beginning of this section) but it does not constitute a paradigmatic change. In fact, the new design was pushed by the rapid changes in costs and capability of digital technology, and pulled by a huge increase in new services offered and in the software to implement them (Chapuis and Joel, 1990), however, no real new architectural designs or skills are required.

The adoption of packet switching represents a paradigmatic shift for the telecommunication switching industry because it was developed in an other industry, the computer networking sector. In particular, circuit switching and packet switching not only are different technologies because they use different knowledge but they rely on completely different assumptions about the network infrastructure (Kavassalis, Solomon and Benghonzi, 1996). In particular, circuit switching allows more control of the network and the circuits used, whereas individual packets are more difficult to trace and route. A consequence of this is the difficulty for a packet switching network to guarantee a defined QoS level. As minimum QoS was an unquestioned requirement for traditional manufacturers (whose monopolist users had to pay for any network failure) this made traditional manufacturers hostile to packet switching.

One of the trajectories identified in this paradigm deals with the above problem and relates to the development of hybrid forms between the two switching mode: the Connection-Oriented Packet-Switched Network. In this case, data are still chopped in packets but not individually routed as an end-to-end virtual circuit is established and all the packets are routed in the same path. This solution allows for a more efficient bandwidth allocation coupled with no repeated per-packet computation. An example of these switches is the Asynchronous Transfer Mode (ATM). Parallel to ATM switches, IP-based switches emerged within the computer data networking sector. As a result of the huge market for office switches, as well as fierce competition, the price/performance ratio of such IP-based switches decreased dramatically over the years. Their success was determined by the rapidly increasing demand for data communication and therefore the push towards broadband networking. Although, technically speaking, a traditional circuit-switched switch is more efficient at handling voice traffic, packet switches will also take over this function in public networks with the emergence of NGNs (Next Generation Networks). In fact. almost all the network operators have advertised their plans and strategies for their migration toward NGN (Fitchard, 2003).

Amplitude Modulation) instead of PCM (Pulse Code Modulation) was used. A famous unsuccessful example is the Highgate Wood Exchange produced in 1956 by British manufacturers in the JERC program. It is remembered as the *monstre sacreé* because of the high number of electronic components (around 180,000, including valves, diodes, and transistors) compared to the number of lines covered (only 600).

Before moving to the empirical part of this chapter it is important to notice that these paradigms to some extent overlap. They overlap for two reasons: first, as observed in the conclusion of the first chapter this sector is characterized by a slow innovation process, where engineers start developing new generations decades before they became economically viable. Secondly, switches are part of a network infrastructure where a considerable amount of legacy equipment is still in use at the same time. In particular, the adoption of new equipment (based on new technologies) was sometimes rather slow. It is interesting to notice that the recent announcements about the deployment of NGN network represent a novelty, because it implies the migration of the whole network (in same cases even of the *"last mile"*) to a new technology. This observation helps to clarify that competences in the industry became obsolete at a rather slow rate, in fact, as long as older piece of equipments were still in the network competences for upgrading or maintenance were always required.

5.5 Empirical analysis[25]

The empirical analysis is conducted in two stages: the first part looks at the general properties of the patent network in analysis and describes its structure over time. The second part will focus on the connectivity analysis and therefore the study of the network of "main paths" and "top main paths". In particular, subsection 5.5.2 will focus on the qualitative analysis of the technical contents of the patents in the technological trajectory.

5.5.1 Network analysis

The first aspect we examine is how the network evolves over time, focusing on the evolution of the number of nodes, the types of nodes, and the number of components. Figure 5.5 shows the time structure of the patent citation network used in this thesis.

The increase in the number of patents[26] coupled with the leveling off of the number of *isolates* brings about the development of an increasingly connected network. This is confirmed by the increasing trend of the number of components[27] (measured in the secondary axis), which shows some peaks and bottoms out. In order to better examine this trend the sample was divided into six subsamples and general descriptive indicators are reported in table 5.5. The network displays an increase in size, both in term of number of patents and of citations (the latter consistent with the general empirical evidence (Hall et al., 2001)) and the emergence of one large main component that finally contains 98% of all the patents.

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[25] The analysis is performed using the software Citpath developed by Menhir Software and used in Verspagen (2007)

[26] Notice that the sample contains patents granted since the 1924, however before 1950 these are only 15, so they are excluded from this figure.

[27] Following section 5.3.1, the network is directed and acyclical, therefore it does not have "strong components" but only "weak components".

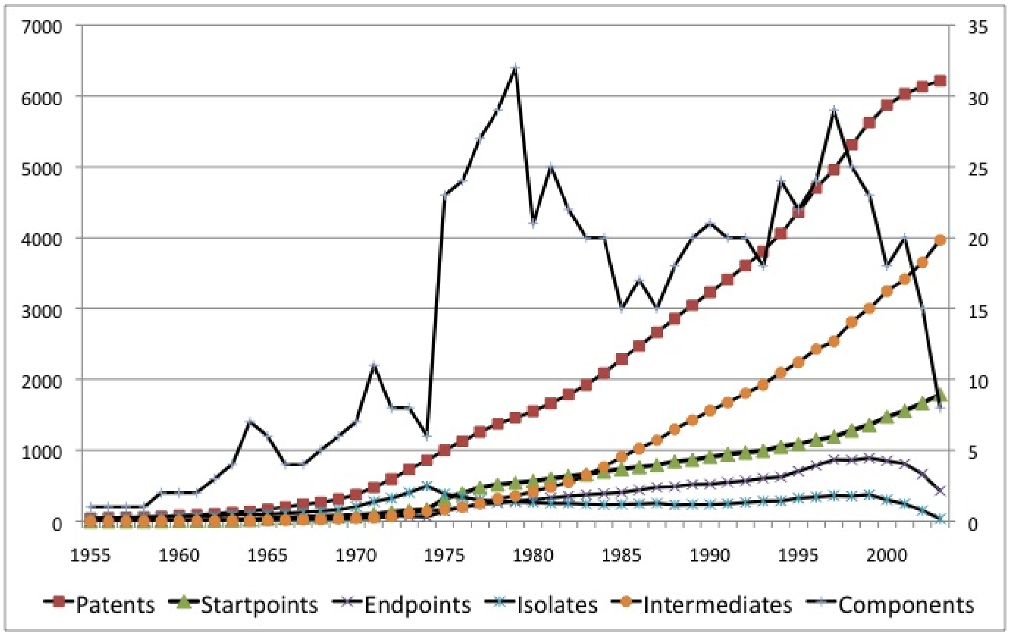

Figure 5.5: Timestructure of the patent citation network

Table 5.5: Size of the network

	Patents	Citations	Number of components	Larger than 3	Size main component
1924-1979	1459	2134	306	12	1095 (75%)
1924-1984	2089	4059	255	11	1784 (85%)
1924-1989	3046	7539	256	10	2749 (90%)
1924-1994	4060	10762	340	14	3662 (90%)
1924-1999	5623	16311	394	8	5180 (92%)
1924-2003	6214	20848	41	7	6120 (98%)

The fact that new patents are linked to the main component denotes a process of network integration consistent with the idea of the emergence of a dominant design. It is interesting to notice that the number of components reaches a minimum level in the late 1970s, middle 1980s, and at the end of the period considered. This is consistent with the idea of different generations of TDM digital switches and the emergence in this industry of packet switching[28].

Looking further at figure 5.5, we can notice an increase in the number of startpoints

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[28] It is worth to note that the years in table 5.5 refer to the grant year of the patents. Therefore there is a lag between those years and the one of invention. As approximation, for the patents in the sample here used, the average lag between application year and granting year is 2.4 year.

combined with a decrease in the endpoints. This indicates that new streams of research emerge, however they tend to converge to a limited set of *endpoints*, suggesting the presence of a rather sharp selection process.

A standard way to describe networks is looking at their centrality and therefore to the way center and periphery relate. Common centrality indicators are: degree, betweenness and closeness[29]; they were elaborated for undirected networks, however with some qualifications they can be also used for directed graphs (Wasserman and Faust, 1994). In fact, directionality implies that each node has two types of link: one that "is received" and one that "is made". These links are conceptually different, so it is important to distinguish them and to distinguish the way they structure the network. This applies to patents too, for which it is relevant to distinguish between citations made and received.

Centrality degree relates the idea of centrality with the number of connections each node has; in the case of a directed network it is possible to distinguish between indegrees and outdegrees indicating the incoming and outgoing arcs for each node. Furthermore, an overall indegree and outdegree centralization index can be calculated as the variation in the degrees of vertexes divided by the maximum degree variation that is possible in a network of the same size. It is worth noting again here that in a patent citation network the direction of the arcs follows the direction of the knowledge, therefore the outdegree is the number of received citations. It follows that node outdegree is a measure of the *importance* and *prestige* of the patent, which means that outdegrees might be regarded as a measure for patent value.

Centrality betweenness relates centrality to the number of times a node lies on the shortest path between all the nodes. In this case a node is central when it is connected by a short path to several other nodes. Also in this case it is possible to calculate an overall betweenness centralization index, which is the variation in the betweenness centrality of the vertexes divided by the maximum variation in betweenness centrality scores possible in a network of the same size.

Table 5.6 shows the evolution of network centrality measures and it points out opposed trends in the outdegree and indegree indexes. In particular, the decrease of the outdegree can be interpreted as the decrease of relative importance of the most cited patents, therefore, the general increase in the size of the network does not increase the *popularity*[30]of patents. Appendix C reports the most cited patents over time; these rankings are fairly stable over time and they show rather "old" patents. Indeed, the most cited patent of the entire sample is the famous Ethernet patent by Metcalfe issued in 1977. Looking at the betweenness we can notice an increase over time, indicating an increasing variation in node betweenness.

In a directed network it is also interesting to look at the distance among the nodes. Network theory uses several notions of distance, however here we are interested in the *shortest*

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[29] Closeness is not calculated here. In fact, given the unconnected (there is not a path between each node pair) nature of the network it is not possible to calculate an overall closeness indicator.

[30] Popularity refers to the number of vertex outdegrees.

Table 5.6: Centrality measures

	Outdegree Centralization Index	Indegree Centralization Index	Betweenness Centralization Index
1924-1979	2.51%	1.41%	0.08%
1924-1984	1.78%	0.96%	0.10%
1924-1989	1.56%	0.97%	0.10%
1924-1994	1.27%	0.75%	0.10%
1924-1999	0.93%	1.44%	0.16%
1924-2003	0.86%	2.49%	0.17%

distance between nodes, which is the geodesic distance. Table 5.7 summarizes the average distance and the maximum geodesic distance, which gives an idea of the diameter of the network[31].

Table 5.7: Summary of the geodesic distance.

	Average	Maximum
1924-1979	3.012	9
1924-1984	3.702	10
1924-1989	4.395	12
1924-1994	4.667	12
1924-1999	5.327	14
1924-2003	5.423	14

It appears that the average geodesic distance increases, just like the maximum length of the shortest path between two patents. Their increase is rather slow, meaning that the increasing size (especially in term of number of citations) does not determine a node departure. Therefore, despite the trend of knowledge integration a centre (and therefore an area where important patents might cluster) does not emerge.

5.5.2 Connectivity analysis

Section 5.3 introduces two connectivity measures, the *Search Path Link Count* ($SPLC$[32]) and the *Search Path Node Pairs* ($SPNP$). In this section we will use them for identifying the main flow of knowledge and therefore technological trajectories. As mentioned in section 5.3,

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[31] Note that in an acyclical directed network we cannot technically talk of "diameter" of the network as some distances cannot be computed.

[32] Notice that in this case $SPLC$ is always calculated for paths going from *startpoints* to *endpoints*.

these indicators tend to give similar results in the identification of the main paths, however, given the multiplicative effect, $SPNP$ tends to weight citations in the middle of the paths more .

Table 5.8: Summary statistics for $SPLC$ over time

	N	Mean	SD	Min	Max
1924-1979	2134	0.015	0.057	0.0002734	1
1924-1984	4059	0.01	0.045	0.0000338	1
1924-1989	7539	0.007	0.034	0.0000031	1
1924-1994	10762	0.006	0.031	0.0000003	1
1924-1999	16311	0.005	0.027	0	1
1924-2003	20848	0.004	0.025	0	1

Table 5.9: Summary statistics for $SPNP$ over time

	N	Mean	SD	Min	Max
1924-1979	2134	0.017	0.061	0.0001238	1
1924-1984	4059	0.011	0.049	0.0000159	1
1924-1989	7539	0.007	0.034	0.0000031	1
1924-1994	10762	0.007	0.035	0.0000001	1
1924-1999	16311	0.006	0.031	0	1
1924-2003	20848	0.005	0.029	0	1

Table 5.8 and 5.9 present some summary statistics for the two indicators over time and confirm the similarity between the two indicators. The indicators have been standardized using the maximum, so that it is possible to compare them. The decreasing mean suggests that each citation is connecting less patents over time. Furthermore, as the maximum is becoming rather big (in the case of the largest network for the $SPLC$ it is 139,643,996) the minimum becomes virtually indistinguishable form zero. Given the similarity, all the results presented in the following pages are obtained using $SPLC$. The analysis using $SPNP$ basically gives the same results, therefore it will not be reported.

The second step of the methodology previously presented is the identification of the network of main paths. The main component of the network of main paths for the telecommunication switching industry is displayed in figure 5.6.

Before analyzing it, some clarifications about the graphics are required in order to understand it:

1. Patents have different **colors**, which indicated the *endpoint* to which they converge. This means that patents with the same color converge to the same *endpoint*;

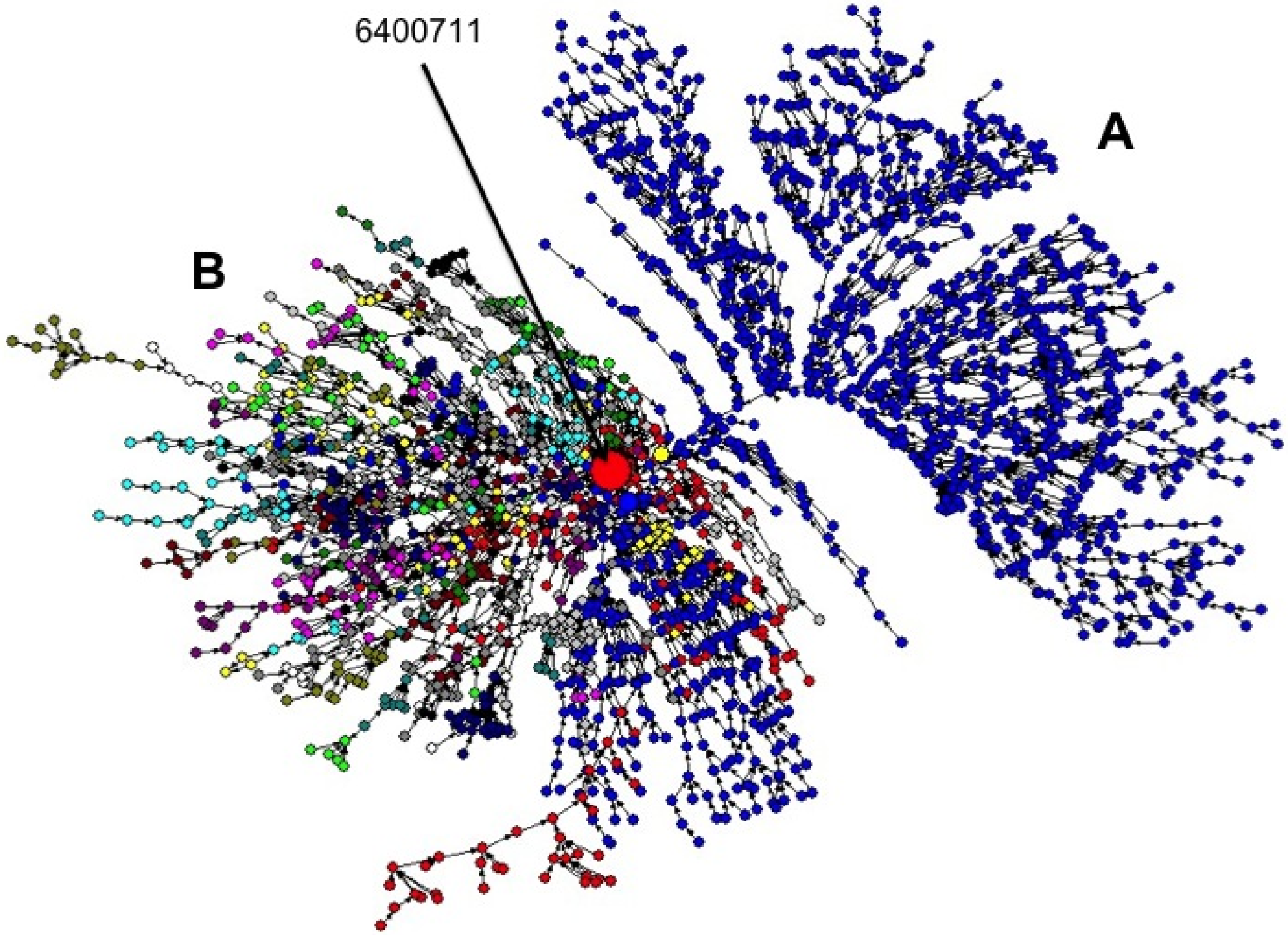

Figure 5.6: The largest component in the network of main paths

2. *Endpoints* have different **sizes**, which are proportional to the number of *startpoints* converging there. In this case the size is a proxy of the importance, or more precisely of the power of attraction of an *endpoint*.

A visual inspection of the network highlights the presence of two different environments (A and B). A is characterized by uniform convergence to the same patent (6400711), meaning that research starts rather fragmented as there are numerous independent paths, however, the selection process points to the same few patents. In particular, two *endpoints* (patents 6400711 and 6628629) are visible in the figure because of their size, attracting more than half of the patents in the sample, whose large majority is located in environment A. The B part of the network looks rather different: paths are rather "isolated", indicating independent or stand-alone chains of innovation.

Given this difference between the two areas in the network, we investigated whether these patents differ in some characteristics such as technological subclasses or the assignees, however no substantial differences appeared along these dimensions. In fact, frequency and ranks of assignees and technological classes greatly overlap. A substantial difference emerges when you look at the top main paths and their location in the network: all the top main paths are located in area A. As explained in Section 5.3 the identification of the top main path corresponds to the identification of the paths (from a *startpoint* to an *endpoint*) whose sum of $SPLC$ is the highest. This means that the top main path connects the largest number of patents, therefore cumulating all the technical knowledge there contained. This main flow of (technical) knowledge represents the technological trajectory over time, and its location in the A part of the network suggests that B represents a secondary and more explorative research, which finally does not emerge. Finally, the peculiar topology of the network in figure 5.6 calls for the analysis of central betweenness in order to point out the main junction. In this sense, the knowledge mediator is patent 5345446, whose importance (and technical contents) is discussed below.

The analysis is carried out looking at the top main path evolution. In the next pages, the top path for each period considered is calculated and discussed; however, their union is displayed in figure 6.5[33].

The validation of these trajectories is made by reading the patents with the purpose of analyzing the technical problems tackled and the solution proposed[34]. Briefly, this means examining the patents for the *engineering heuristics* applied.

Figure 5.8 displays the technological trajectory for the earliest period here considered. The two *startpoints* (2754367 and 2773934) disclose respectively an automatic and an electronic

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[33] For the complete list of the patents on these top paths, their issue year, and their assignees see Appendix A.

[34] Furthermore, the technical feature and the importance of the patents in the trajectories were discussed with an engineer who worked at Philips (and later at the AT&T and Philips joint venture) during the relevant period of time.

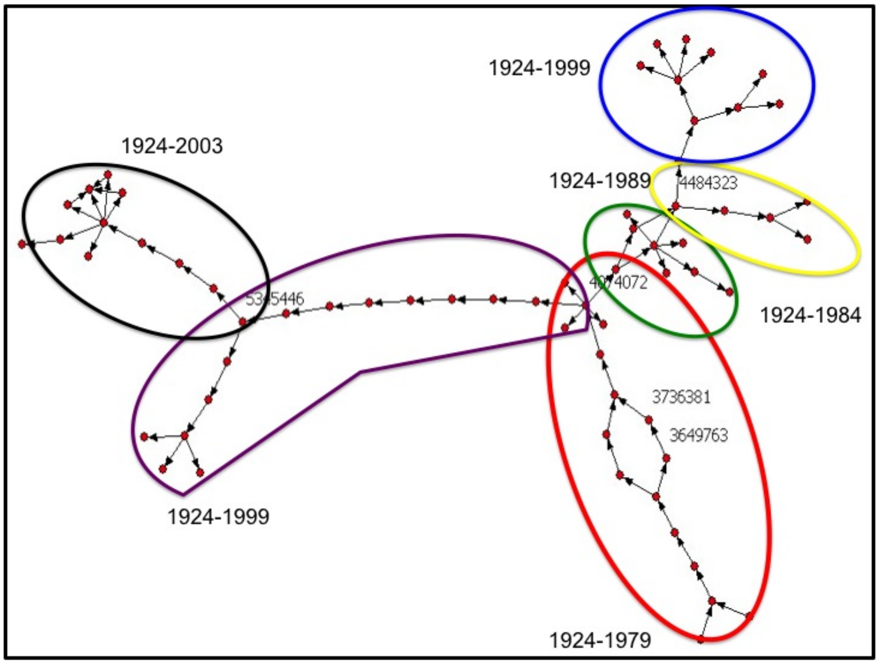

Figure 5.7: Union of the top main paths calculated at different points in time.

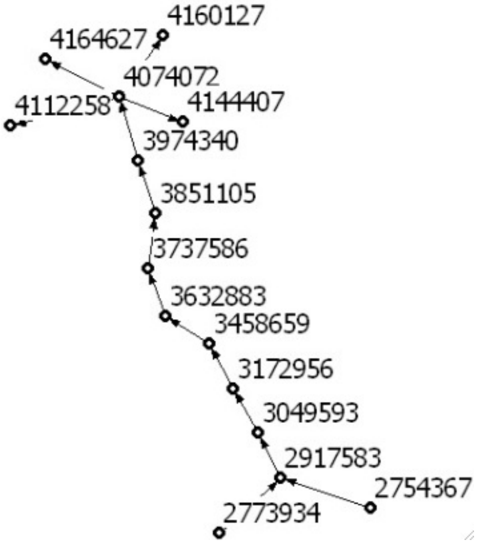

Figure 5.8: Top main path for 1924-1979

exchange. The subsequent patents focus on the emergence of a fully electronic switch and therefore the substitution of all the mechanical components still present in the network. The research covered by these patents already focuses on time division multiplexing (TDM) and they tackle a basic problem, which is the blocking of the system. Recalling what was said in chapter 1, TDM implies information is sliced into a sequence of time intervals (the timeslots) corresponding to a speech sample. Blocking occurs when a call attempt cannot be terminated and therefore there are delays in establishing the desired communication; it can be caused by the no availability of a channels and by idle timeslots. This blocking problem was hampering TDM switch reliability, so engineers were working at minimizing failures. In fact, in order to have TDM switches to succeed they should be able to guarantee similar level of reliability than the previous generations (however this is true for any generations).

Patent 3172956 proposed the use of the so-called *time-slot interchange*. This allows the displacement of a timeslot from one channel within a group to the timeslot of another channel, using a delay line adjusted to the code of the called line. It is interesting to note that this patent was granted to Bell Laboratories, and among the inventors there is Hiroshi Inose, considered one of the father of the *time-slot interchange*. This would constitute one of the basic elements of digital switching network, the T stage, whereas the second basic element, the S stage, is a device for the functioning of the switching matrix. This patent uses *time-slot interchange* for improving TDM reliability increasing the availability of timeslots and therefore reducing the risk of blocking. The following patents still focus on different solutions for designing a non-blocking system, ranging from the inclusion of buffering memories for providing delay (3632883) or suggesting an increase in the redundancy, knowing already that this is very costly in large systems (3737586).

Patent 3851105 introduces the problem of setting a switching network. As just mentioned above, TDM switches are built using both T and S stages. In chapter 3 we showed that several designs emerged, using different settings, such as S-T-S or T-S-T, and even more combining multiple stages. The purpose of including different stages is the possibility of increasing the capacity of a switch, which means being able to meet the increasing demand and also making TDM economically feasible. This is recognized in the patent, which states:

> it is purpose of the present invention to provide a new time division switching network having the advantage of being suitable for a large number of incoming and outgoing channels

Furthermore, the new setting proposed mitigating the blocking problem in a rather efficient way: the use of the S stage allows employing fewer crosspoints for redundancy, decreasing the cost per line.

In the patents just discussed a new problem is tackled, which is the control setting in the switch and, in particular, different solutions regarding distributed control are proposed. Finally the *endpoints* focused on some preliminary research about how to switch data on a TDM

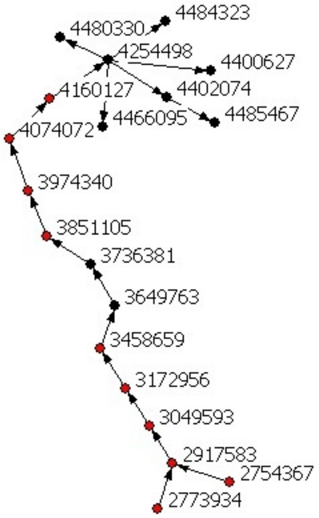

Figure 5.9: Top main path for 1924-1984

switched telephone network (3974340), how to improve existing services such as conference calls (4112258), and how to integrate multiprocessor into telegraphic network (4144407).

Figure 5.9 displays the trajectory for the period 1924-1984, where the new added patents are marked in red, in order to show the difference with the previous picture. First, we can notice that the new trajectory is nested on only one of the previous *endpoints*, which is patent 4160127. Furthermore, it is interesting to note a change in the series of patents in the lower part: patents 3737589 and 3632883 were substituted with patents 3736381 and 3649763. Undoubtedly, this change calls for an explanation that lies in the technical differences between the two groups of patents and in the content of patent 4160127. This patent, after reviewing the *prior art* and emphasizing the very high duplication costs for some switching network settings, discloses an improvement on the technique used in patent 3736381. In the summary of the invention, this earlier patent is explicitly mentioned as inefficient as,

> in real time communication switching systems since a significant loss of data may result during the time required to activate a spare [redundant] unit, particularly since control information which changes in time must be transferred to the spare unit

The improvement proposed regards a way to reduce the time needed (and also the data loss) for reverting the traffic in case of failures. Again, the main purpose is to make the switch more reliable and therefore with a more stable quality of service. Furthermore, patent 3649763 discloses another system for the management of the delay occurred in the TDM, which is responsible for service failure. The subsequent patents completing the trajectory, up to patent 4484323, cover two distinctive, however crucial, points for switch development, which are the use of software for flexibility and the controlling distributed processor. Patent 4254498, in fact, specifically states that the aim of the patents is to provide a system

> capable of economically and readily increasing or decreasing the switching network capacity [...] so that not only hardware but also software is utilized to control the speech path as modules

Following what was said in section 5.4, flexibility is a key feature for switches as it ensures the possibility of using the same technology and basically the same design for a large range of network size. Furthermore, flexibility is a characteristic highly valued by network operators. Given the investment for deploying such equipment in their infrastructure and the increasing demand at this time, flexibility was necessary in order to ensure the longevity of the investment. It is therefore not surprising that a network operator, the NTT, granted this patent.

Patent (4484323) covers the crucial issue of the control setting. In order to have an efficient time of execution, some switching systems separate routine functions from the main processing functions. However for the general reliability of the switch it is important how the communication among these separated controlling units takes place. In particular, this invention focuses on the disclosure of a remotely controlled distributed processor capacity in order to minimize system faults.

The top main path calculated on the sample up to 1989 is displayed in figure 5.10. This sequence is rather interesting because it explicitly focuses on data transmission. As pointed out previously, a rising demand for data transmission is characteristic of the telecommunication switching industry in the middle 1970s and early 1980s. At the time, the concept of packet switching was already known but not in use for telephony. What all these patents have in common is the attempt to adapt the existing circuit switching TDM technology for a different purpose that is data transmission. It is interesting to notice that this type of research was not finalized to the integration of packet switching but circuit switching was truly considered superior. For instance, patent 4521880 (filed in 1985) states:

> because of the complexity of known packet switching systems, circuit switching is sometimes a preferable alternative for use in many data communication applications

Manufacturers believed in the superiority of circuit switching even when they were expecting an increasing demand for data communication. In fact, patent 4644529 (filed in 1985) observes that:

> there will be even greater communications demands in the future, both as to diversity of services and traffic capacities

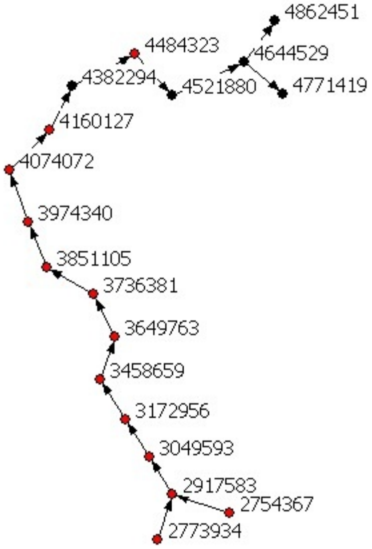

Figure 5.10: Top main path for 1924-1989

Moreover, the previous patent states:

> It is well settled that digital time-division multiplexed transmission is preferred for **both** voice and data communications [emphasis added]

In order to adapt TDM switches to data transmission some solutions were proposed, for instance inserting data transmission in the silence of voice communication. Furthermore, some patents looked at the integration of not only different equipment vintages but also different networks (for instance patent 4862451, *Method and apparatus for switching information between channels for synchronous information traffic and asynchronous data packets*).

Figure 5.11 shows the technological trajectory including patents granted until 1994. Patent 4644535 covers multiplexing/demultiplexing (MUX/DMUX) techniques in order to exchange digital samples of voice, data, and control information. This invention has important consequences for the implementation of the so-called ISDN (Integrated Service Digital Network), which constituted the first attempt to integrate speech and data on the same lines, adding features that were not available in the classic telephone network. The following patents deal with similar issues, in particular, the integration of fast transmission and therefore of protocols such as SONET (Synchronous optical networking) and SDH (Synchronous Digital Hierarchy). These protocols allow the transportation of a large amount of telephone calls and data traffic over the same fiber wire without synchronization problems. In particular, this gives the possibility of cross-connecting high speed digital signals. Furthermore, patents in this trajectory looks at the problem of connecting different vintage of transmission systems to the switching

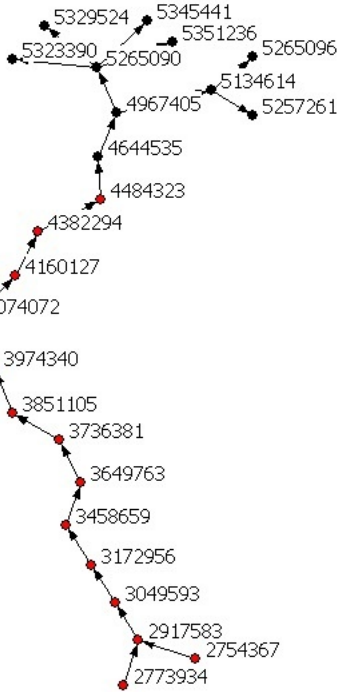

Figure 5.11: Top main path for 1924-1994

system. For instance patent 4967405 recognizes that optical cable are the future and they will substitute the copper wire, however, the replacement cannot be instantaneous and therefore different technologies have to co-exist.

Adding the data up to 1999 completely changes the structure of the network. In fact, looking at figure 5.12 and 6.5 we can notice a change in the direction of technology: the established trajectory is discarded in favor of a new one. In fact, the new top main path shares only the very first part, up to patent 4074072 granted in 1978, with its antecedents. Given the special position of this patent it is interesting to look at its technical contents and to understand why that patent *became* important. This patent proposes to divide the switch network in partitions individually controlled by a single processor. The consequence of this setting is a simultaneous increase in reliability and flexibility with regards to the growth of the network.

Patent 4201891 focuses on an issue already explored in the previous pages, which is the distributed control, with the addition of both speech and control information on the same circuit.

Moving to the subsequent patents we should notice that all them are contemporary to the ones discussed in the previous pages (for instance, patent 4451827 was granted in 1984, just like patent 4485467 in figure 5.9), however they become "relevant" (belonging to the network of top paths) only when patents up to 1999 are considered in the calculations. This means these patents focus on different technical problems and propose different solutions that would become relevant only later. In particular, differently from the patents on the other side of the thick line in figure 6.5, they do not focus on TDM switches and they do not focus on how to use existing technology for data communication. New solutions are explored and in particular packet switching (or more generically, cell switching[35]) starts emerging. For instance, patent 4451827 is the first patent on computer networking, therefore only covering data transmission and not telephony. From this point on, patents recognize the efficiency of cell-switching and individual packets routing. However, as TDM switches are still present in the network there is a need to develop techniques for integrating them in a packet switching network. As just mentioned, the difference is that here the superiority of packet switching is recognized. In this line, patents 4603416 and 4782478 look at how to switch packets on the TDM and the solution proposed is to use the analogy between a packet and a timeslot. More important, in the latter patent the concept of "virtual circuit" is used. As summarized in section 5.4, engineers were working at hybrid forms of packet switching (such as Connection-Oriented Packet-Switched Network) where the use of a "virtual network" allowed for a predetermination of the bandwidth available. The benefit of this "virtual network" is twofold: on the one hand, it allows more control of network usage (as the connection is established in advance and it will last for all the duration of the transmission), and on the other hand it reduces calculations for the routing (in fact the routing algorithm is used only once for each "virtual circuit" and not for each

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[35] Cell switching generically refers to the practice of splitting the transmitted information in packets (or cells).

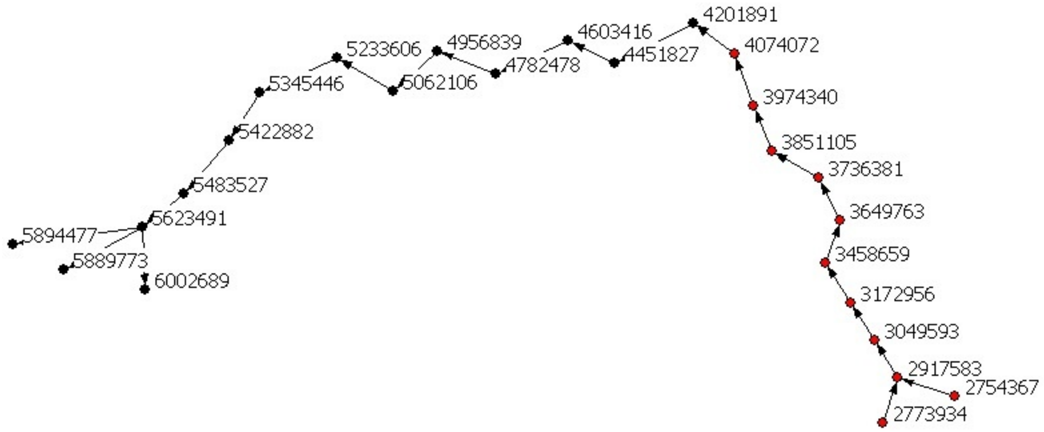

Figure 5.12: Top main path for 1924-1999

packets). Patent 4956839 clearly reports what was just explained:

> Although the time division speech path system is suited for the line or call switching, it can not always be said that this system is suited for communications of different rates for which demand is expected to increase in the future. Further, the digital time division speech path is not necessarily suited as multi-media having a variety of properties. On the other hand, a packet switching system which seems capable of coping with more flexibly the requirements mentioned above encounters difficulty in application to the communications of different rates and among others a high-speed broad band communication at the present state of the art

The introduction of this “virtual circuit” is a distinguishing feature of Asynchronous Transfer Mode (ATM) switches and it constitutes the main difference with IP-based switches.

From this point on patents address problems related to switching mode, indicating a transition to packet switching. Patents before 5345446 describe the transition from “adapted” TDM switches for the transmission of packets (either exploiting the analogy between timeslot and packets or introducing self-routing packets just attaching a header to a slot) to the introduction, improvement, and integration of ATM switches in the networks. Interestingly, the technical problems tackled also changed, moving from the blocking problem to the loss of cells problem (506210), or the possibility of prioritize the switching of cells in order to ensure different minimum QoS level to different users (5233606). Finally, all the patents up to the end of the trajectory focus on the adaptation of ATM switches, designed for broadband data communication, for narrowband communications, in particular voice.

Figure 5.13 represents the top main path for the whole sample and also in this case there is a change in the direction of the technology, however, less dramatic than the previous one.

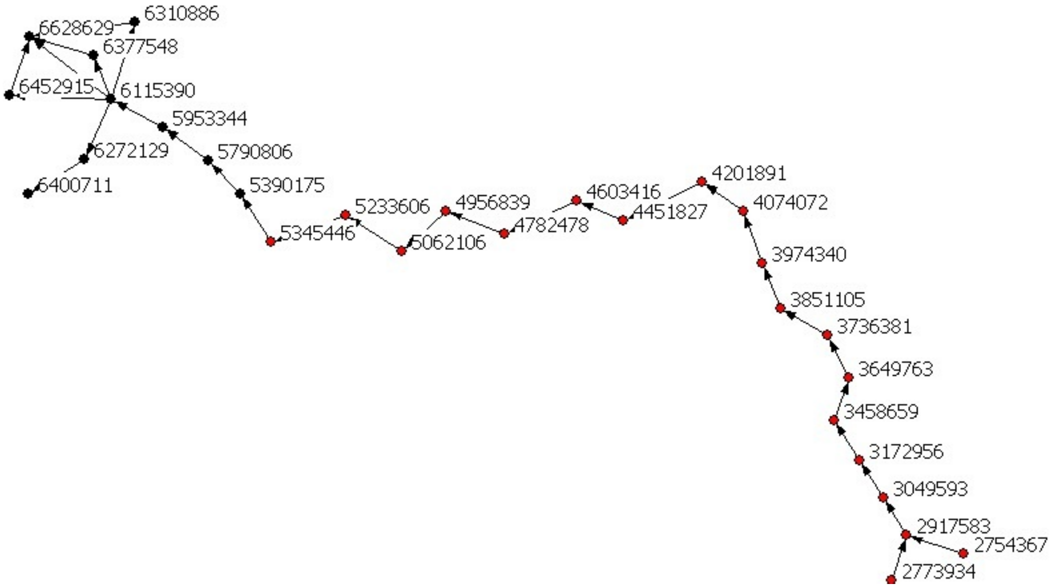

Figure 5.13: Top main path for 1924-2003

Patents along this path depart from the use of ATM switches, although patent 5390175 is still related to this generation. In particular that patent points out how ATM is not efficient in handling simultaneous low and high speed traffic. This inefficiency is partially solved using systems for "separating" these traffics, for instance patent 5790806 proposed an efficient way to manage an integrated cable network through its segmentation. This solution again allows for prioritizing users and allowing for diversified levels of QoS. The last patents (after 5345446) in the trajectory confirm the transition to IP-based switches. Again the technical problem relates to packet losses and the provision of minimal QoS. The solutions proposed are rather similar to ATM as they regard ways to prioritize packets in order to ensure different minimum QoS. Finally, there is a semicircle at the end of the trajectory involving several patents. As in section 5.3, this happens because all those edges have exactly the same connectivity measure.

From a visual analysis of trajectories evolution we see that patent 5345446 occupies a pivotal position; indeed it has the highest betweenness in the network of main paths (figure 5.6). This patent is a crucial junction between two trajectories: the ATM and IP-based ones. The discarding of the ATM trajectory is not surprising, as ATM was not a very successful switching platform, mainly developed by telecom manufacturers as a compromise between circuit and packet switching. The new emerging trajectory points directly to LAN technology first and wireless IP access technology. This is consistent with the increasing demand for IP equipment followed by the transition from the PSTN (Public Switched Telecom Network) to NGN. It clearly shows that a change of direction occurred in the late 1990s, when the established trajectory toward the upper right is discarded in favor of the trajectory toward the left. Technical contents of these patents shed some light on the differences between these two trends.

5.6 From technology to industrial dynamics

The aim of this short section is to change the focus of the analysis and to look at the results obtained in the previous sections from the firm perspective. Therefore, following the account in section 4.3, we can now look at the co-evolution of technology and industry by looking at firm's innovative performance over time.

The analysis of the technical contents of the patents belonging to the technological trajectories confirms a paradigmatic shift. Furthermore, the structure of the network displayed in figure 6.5 suggests a transition from a "creative accumulation" to a "creative destruction" regime. In fact, for almost 50 years, from the middle 1950s to the middle 1990s, the process was very cumulative whereas in the late 1990s, in only 5 years two different trajectories are explored. According to the theory, a paradigmatic change should have two effects: (i) to provide a window of opportunity to newcomers, and (ii) to jeopardize or even displace the leadership of incumbents. Following the analysis of the previous section, we can assess these effects by looking at the stability of the assignee in the technological trajectories and at the evolution of number of patents and citations for some (leading) incumbents.

5.6.1 Who owns the patents in the technological trajectories?

Table 5.10 summarizes the information available in appendix B. Following the jargon introduced before we can look at to what extent "Bellheads" were able to maintain their technological leadership and how many "Netheads" were able to tap into the technology.

Table 5.10: Patent assignees in the technological trajectories

Time	Number of patents on the trajectory[1]	Number of new patents in the trajectory	Number of "Bellheads[2]" assignees	Number of "Netheads" assignees
1924-1979	9		5	0
1924-1984	11	5	7	0
1924-1989	14	3	8	0
1924-1994	16	4	8	2
1924-1999	20	11	10	0
1924-2003	22	8	10	6

[1] With exclusion of *startpoints* and *endpoints*.

[2] "Bellheads" are companies discussed in chapter 4 and in two cases Japanese network operators.

The first column shows the number of patents in each trajectories; no *startpoints* or *endpoints* are included given the high level of arbitrariness in their choice[36]. The second column indicates how may new patents (respect the previous time interval) are included; the high number in the period 1924-1999 indicates that with the paradigmatic change several previous patents became obsolete.

The last two columns are the one of main interest in this section, in fact they show the distribution of the number of assignees between "Bellheads" and "Netheads" over time. This distinction is rather rough, however still meaningful in the period under consideration. In fact, only two patents could not be assigned to any of this category[37]. Figures in table 5.10 show a change in the distribution with a stabilization of the number of "Bellheads" and an acceleration of the number of "Netheads". In particular, the latter are responsible for six out of the eight patents added in the last part of the trajectory.

Following the history in chapter 4, new companies enter the market (see table 4.6) and their presence on the top main path shows also their success in being close to the most relevant knowledge.

5.6.2 Innovative performance of selected incumbents

The paradigmatic change (together with the national context discussed in section 4.3) should not only affect the probability of observing new entrants but also the "fate of the small club of companies". Therefore in this section we are going to focus on the innovative performance of few incumbents ("Bellheads").

If we consider the technological trajectories identified in the previous section as the "relevant knowledge", we can compare the distance of individual firms' patent portfolio to technological trajectories over time. This distance is calculated in two step: (i) by measuring the distance between each patent and the closest path belonging to the trajectory as the reciprocal of the geodesic distance[38] and (ii) by summing all those weighted distances by company[39]. Table 5.11 reports the ranking of closeness to the trajectory and the difference with the previous period.

Looking at the evolution of the ranking it is interesting to have a close look at few leading incumbents: Alcatel, Lucent, ITT, NEC, and Fujitsu. Figure 5.14 reports five indicators: (i) number of patents granted, (ii) number of received citations (Forward citations), (iii) number of citations made (Backward citations), (iv) net count of citation received (Forward

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[36] See section 6.3 for a discussion about this point.

[37] The assignees not classified are: Johns Hopkins University and an individual inventor. However, the latter is an active inventor involved in other 15 USPTO patents assigned to the Centre National D'Etude des Telecommunications (CNET) (a R&D facility created by the French Government).

[38] The use of reciprocal help to correct for the skewness of distance distribution among firm's portfolio

[39] Note that subsidiaries were aggregated in groups. In case of acquisitions, patents go to the acquiring firm's patent portfolio since the year of acquisition.

Table 5.11: Distance from the Top path

	1924-1979	1924-1984	1924-1989	1924-1994	1924-1999	1924-2003
Lucent	1	1	1	1	1	1
ITT	2	2	2	2	12 (+10)	12
Ericsson	3	5 (+2)	6 (+1)	6	6	4 (-2)
Siemens	4	4	4	3 (-1)	7 (+4)	8 (+1)
GTE	5	3 (-2)	5 (+2)	5	11 (+6)	11
Alcatel	7	9 (+2)	9	8 (-1)	3 (-5)	2 (-1)
GEC-Plessey	9	10 (+1)	7 (-3)	10 (+3)	15 (+5)	16 (+1)
Phillips	10	13 (+3)	11 (-2)	11	13 (+2)	13
NEC	13	22 (+9)	15 (-7)	7 (-8)	2 (-5)	3 (+1)
Motorola	15	19 (+4)	43 (+24)	32 (-11)	8 (-24)	7 (-1)
Northern	20	11 (-9)	13 (+2)	13	10 (-3)	9 (-1)
Fujitsu	23	17 (-6)	27 (+10)	19 (-8)	5 (-14)	5

citations minus Backwards citations), and (v) the weighted patent count (WPC) (Jaffe and Trajtenberg, 2005).

Table 5.11 points out Lucent's leadership and Figure 4.3 highlights its extent. Lucent has been a leader in term of patents issued and also in term of the net citations received (the series Difference is always above zero) but this leadership is not constant over time. In particular, there is a decline in the early 1980s. Following the account in chapter 4, this decline corresponds to a delicate phase for this firm preceding the voluntary divestiture and the end of AT&T monopoly. The transition toward a less integrated relation with network operators appeared to level off its technological advantages; but after this a new phase of increasing received citations started again.

Unsuccessful firms (i.e. ITT, GTE, GEC-Plessey and Philips, which exit the market) fell in the ranking. The ITT case is particularly interesting: despite its granted patents become almost zero in the 1990s, the number of net citations is sharply growing. According to section 4.3.1.4 ITT's withdrawing was driven by strategic and financial reasons and the graph seems to support this. ITT made a substantial investment [40] for the development of its System 12 that according to technicians was brilliant (Fransman, 1995), however, management was disappointed by the early sale figures.

The company that benefitted the most from the exit of ITT was Alcatel, which acquired

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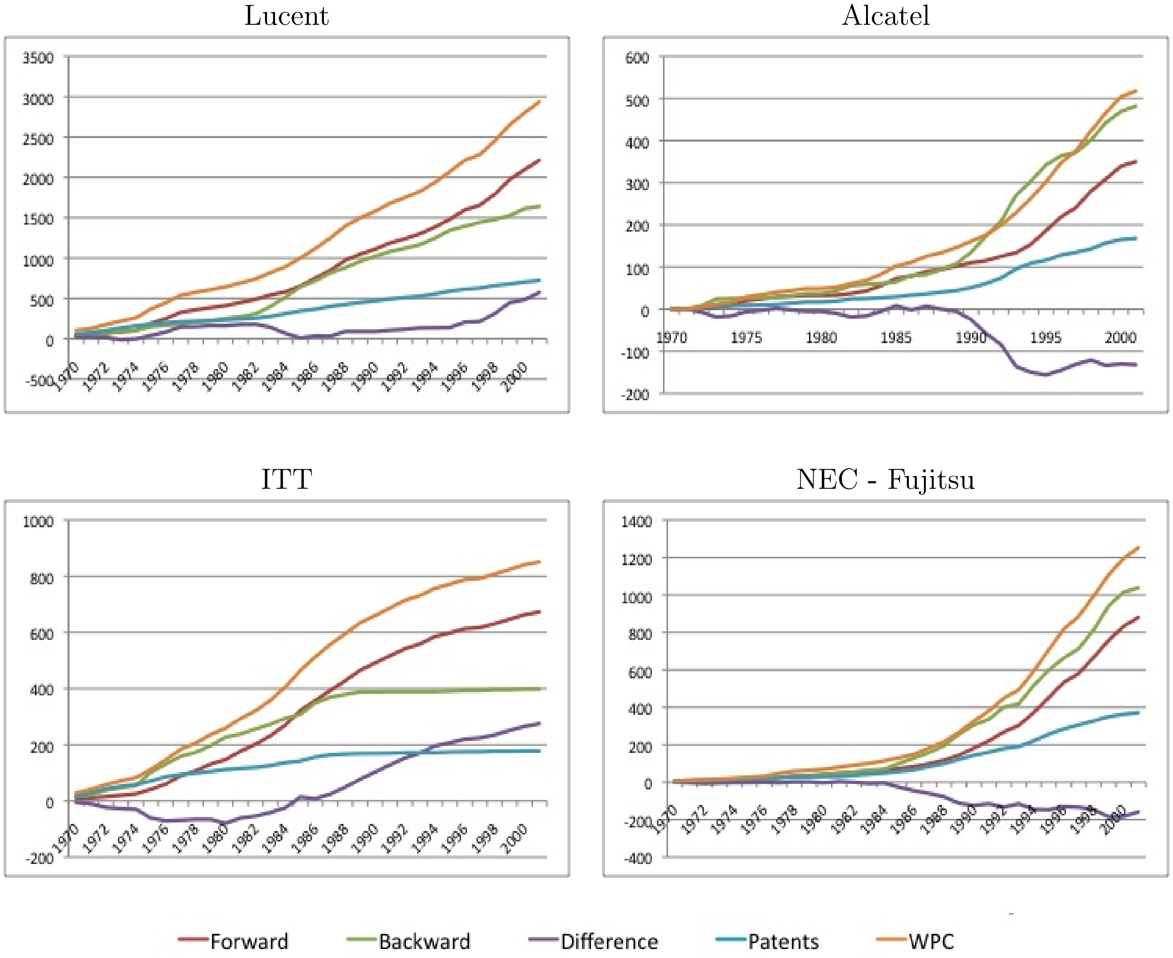
[40] By March 1985 the company had spent $1.1 billion (Fransman, 1995)


Lucent

Alcatel

ITT

NEC - Fujitsu

Figure 5.14: Innovative performance of selected incumbents

ITT telecom interests (and also its digital switching platform, the System12). In fact, table 5.11 shows the catching up of this company in term of distance from the technological trajectory. Figure 4.3 reveals Alcatel very limited patent activity until the early 1990. This graph is consistent with the story of this company that was able to flourish because of the effort placed by the French government, and the ITT acquisition. In this respect we can compare the market share between E10, the switching platform entirely developed by Alcatel and System12, developed by ITT and later sold by Alcatel.

Table 5.12: Market share digital switching platform (2001)

Company	Platform	World Market Share
AT&T Lucent	ESS	0.19
Nortel	DMS	0.12
Siemens	EWSD	0.12
ITT-Alcatel	S12	0.11
Ericsson	AXE	0.07
Alcatel	E10	0.04

Source: Dittberner Associates Inc. (2003)

Table 5.12 shows that up to 2001, System12 is the 4th most sold system, well above the E10. Therefore, it appears that Alcatel market leading position is achieved by selling the System12 rather than the E10. This suggests that if on the one hand market is able to recognise good products this does not ensure sales and market performance. Unfortunately, it is difficult to systematically test because following what said in chapter 3 telecommunication switching performance can not be easily evaluated and compared.

The final graph is about two Japanese manufacturers: NEC and Fujitsu. They are jointly considered because they show similar trends and, since the 1960s they were in a "collaborative competition" regime coordinated by NTT. NTT played a central role in developing a Japanese digital switching platform. In fact, through the ECL (Electrical Communication Laboratories), it coordinated the division of labour of four manufacturers (Fujitsu, Hitachi, OKI, and NEC). The aim was to avoid wasteful duplications, to exploit individual's suppliers' relative strengths, and to create the right incentive to the suppliers (i.e. fixing a generous rate of return in the domestic public procurement) for further innovations. Therefore, it is not surprising that the examined firms are systematically knowledge "importer" (DIfference always minor than zero), also when the number of patents. Moreover, further analysis on their preferred cited companies it emergences that around the 13% of NEC and Fujitsu outgoing citations are directed to the Japanese partners[41].

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[41] This percentage excludes self-citations and its magnitude is comparable to citations to Lucent, the industry "knowledge exporter" (Difference always major than zero).

5.7 Conclusions

The aim of this chapter is to provide an empirical representation of technological change in the telecommunication switching industry. In section 2.3 we reviewed the literature (both theoretical and empirical) about technological paradigms and trajectories in order to highlight their advantages over the neoclassical approach. In particular, we stress the pitfall of assuming instantaneous adjustments of artifacts features and engineering competences to market forces. The technological paradigms and trajectories approach, elaborated by Dosi (1982) contends that a technological paradigm is established by engineering knowledge and that it determines the technological and search space; and on the other, the technological trajectories indicate the selected advances. This corresponds to identify new drivers of the technology *inner dynamics* focusing on the engineering activities, who are central actors as it is them that are primarily involved in R&D activities.

It has been argued this approach "reconciles" the pure *demand pull* and *technology push* approach to technological change. In fact, it provides new theoretical concepts for tackling the tension between *inner dynamics* and market forces. This new approach does not seek to neglect the role of the market in steering technological change entirely, but aims to limit its extent by complementing it with other determining factors. The selection of viable solutions to technical problems depends both on engineering heuristics, which represent the search strategies applied by engineers depending on their bulk of knowledge, and on economic considerations.

The empirical analysis presented in this chapter is carried out using patent and citation data. Network analysis (in particular connectivity measures) are used for identifying the main flow of knowledge, and therefore the technological trajectory whiten the network. In this representation, a patent citation network represents the industry knowledge base, therefore, major shifts in the main flows of knowledge imply changes in the engineering heuristics, and therefore paradigmatic technological changes.

Moving to the conclusions; *From a paradigm and trajectory perspective, how can we characterize technological change in the telecommunication switching industry?*

1. Our use of patents goes beyond the simple patent (or citations) counts; in fact, the methodology presented combines quantitative and qualitative research. Citations are used for calculating connectivity measures, which allow identifying a subset of "important patents" representing the technological trajectory. However, this limited set of patents needs to be validated through the analysis of their technical problems and the engineer heuristics applied by researchers.

2. Given the definition of paradigms and trajectories, we clustered the switch generations as they were introduced in chapter one. This aggregation process was carried out by comparing the generations along three specific aspects. These are: (1) the technical skills and competences needed in each generation (which depend on the differences in

the artifact technical characteristics, listed in table 5.1), (2) the perceived barriers and the bottlenecks on which engineers were working, and (3) the dominant *engineering heuristics* as applied by the engineers. Analyzing the data on the basis of these three aspects, four distinct technological paradigms can be identified. These are summarized in table 5.3, together with their corresponding trajectories.

3. The necessary patent data is available from approximately 1950 on, allowing us to perform empirical testing on the last two paradigms. The driver for the emergence of the "electronic circuit switching" paradigm is the new opportunities that are offered by electronic (semiconductor) components. These new components were used at the technical crosspoints (i.e. literally switching the data) as well as in the control functions of switches (being used in SPC and electronic memories). In contrast, the last paradigm (the "packet switches") emerged as a result of a market force, in particular, from the continuously increasing demand for data communication. As already mentioned in chapter one it is interesting to notice the different origin of these two shifts: the first one being internal[42](transistors were invented and developed at the Bell Laboratories) and the second one being external (with technologies developed in the data networking industry).

4. The qualitative patent analysis validates the paradigmatic shift from "electronic circuit switching" to "packet switching". In particular, network analysis highlights a sudden change in the direction of technological change occurring in the middle 1990s. Patents display a change in the technical problems tackled and differences in the solutions and components proposed. This is evident looking at the evolution of expectations about data communication and packet switching. The established parties did forecast the upward trend in data communication demand, however, they rejected "pure" packet switching technologies for a perceived lack of efficiency and lack of quality-of-service features. Instead, they focused on the development of a technology that was closer to their own, circuit-switched technologies while adapting some selected features of a 'real' packet switching technology.

5. This is related not only to the high switching cost but also in the "conceptual" difference about network infrastructure management implied in the two paradigms. Finally, these cases seems to support Constant's view (1973) about the dynamics of technological paradigms. Shifts take place when an alternative (and better) paradigm exists and it is therefore possible to test its superiority.

6. Chapter 3 discussed the difficulty of elaborating technological performance measures for telecommunication switches because of their "tailor-made" nature and the large variety

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[42] From the history, it emerges that also previous paradigms were originated inside the industry, specifically most of the innovations took places in the R&D laboratories of the network operators (for details see chapter two).

of users needed. This is confirmed in the patents, which do not express "output" quantification. In the description of the invention they mention what service characteristics are going to be affected, however these are rather general, referring to improvement for *large switches*, *reliability*, or *flexibility*. Advances are never precisely quantified or compared them with previous levels.

7. The analysis of the technological trajectories from the firm perspective allows to link technological change and industrial dynamics. In fact, paradigmatic changes affect industry structure and its technological regime. In particular, figure 6.5 displays the transition from a "creative accumulation" to a "creative destruction" regime. It shows a rather cumulative process for a period almost as long as 50 years (from the middle 1950s to the middle 1990s) and then rather suddenly, in the late 1990s, two different trajectories are explored in no more than five years. The movement towards a more entrepreneurial regime (with new smaller entrants) is confirmed also from the analysis of patents' assignees showing the presence of new entrants in the last part of the technological trajectory. These firms belong to the data communication industry (for instance Malibu Networks, 3M Communications[43]) showing their success in being central to the most relevant knowledge. The concentration of new entrants on the latest technology confirms something that already emerged from the patent analysis, which is the presence of differences in incumbents and new entrants' technological preferences (Antonelli, 1995). Incumbents that want to fully exploit their legacy and capabilities tend to favor centripetal technologies that enhance the relevance of existing economies of scale, scope and density. Furthermore they simply try to adapt existing technologies to new developments. Instead, new entrants call for centrifugal technologies where specialized technologies reduce the role of inter-functional economies of scope and segmental technologies that reduce the role of network externalities (Antonelli, 1999).

8. The innovative performance of incumbents is rather heterogeneous. Some firms (i.e. Lucent and ITT) lead both in terms of the relevance of their knowledge base and in term of their "net contribution" to the knowledge network. Alcatel and the Japanese manufacturers show the tendency to get closer to the relevant knowledge (i.e. the technological trajectory) but this happens because the acquisition of external knowledge. The major implication is that technological advantage does not secure survival in the telecom switching industry. Other factors, such as strong political intervention (like in France) or a committed network operator (like in Japan) are of pivotal importance for the long run success.

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[43] See Appendix A for the complete list.

Chapter 6

Knowledge persistence: A genetic approach to patent citation networks[1]

6.1 Introduction

Populations' phenotypical differences can be evident; for instance, dark hair, skin, and eyes are more diffused in warm areas, whereas lighter color dominates in the "Nordic" ones. Nowadays we know that these differences are the result of the evolutionary process of adaptation to different environments. Given these observed differences and the mechanism of genetic inheritance it is possible to postulate that genes of modern populations contain an (inherited) historical record of the human species. Therefore, it becomes interesting to look at to what extent these differences appear at genotypical level. A branch of genetics, so-called population genetics, studies population genetic variations (in particular, populations' allele frequency distributions and change) under the influence of evolutionary processes and population subdivisions and structure in space. A result of this discipline has been the establishment of a connection between migration patterns and genetic variation (Cavalli-Sforza, Menozzi and Piazza, 1994). In a nutshell, the aim of population geneticists has been to investigate (genetic) differences among populations and to infer migration patterns. As a result, we now know more about how and when regions became populated through migration streams from Africa.

These research topics, and in particular the interest in searching for common ancestors, can be rephrased in the context of knowledge and technology evolution: *What are the origins of current knowledge? How did different strands of research develop? How did they fertilize each other?* These questions are relevant for understanding how technological advances differ across technologies and the underpinning knowledge base. The aim of this chapter is to answer these questions by proposing a genetic approach (GA) for the study of technological

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[1] This chapter draws on A. Martinelli and Ö. Nomaler *"Detecting Patterns of Technological Rupture in a Patent Citation Network"*, DIME Grand Conference, Strasbourg (7-9 April 2008).

change and the emergence of new technologies. In particular, we will introduce the concept of persistence of knowledge and the concept of "thickness" in order to detect patterns of cumulativeness in a patent citation network. Furthermore, in this chapter we compare the results obtained with the GA and Hummon's and Doreian's approach (HDA) used in the previous chapter.

The chapter is structured as follows: section 6.2 introduces the notion of genetic decomposition in innovation studies. Section 6.3 compares the persistence index to other methodologies. Section 6.4 discusses the results and is followed by a section presenting the conclusions.

6.2 A genetic approach to patent citation networks

Just as population geneticists trace our (geographical) origins, we can investigate the origin and development of the current bulk of knowledge. Following again the parallel to population genetics, the main idea is: given a set of contemporary patents, representing the state of the art technology, which are their origins? Which patents had better fitness and therefore their technological contribution persisted the most? How are different technological lineages linked? Using again the genetic jargon, we can answer these questions studying contemporary patent descendants. In the previous pages we argue that genetics provided a good parallel, however it can also be misleading; at different stages of this section we will further discuss "deviations" and differences from population genetics methods. A major difference already emerges looking at the type of data used: geneticists work with genes of living populations and DNA samples from fossils, meaning they have few observation points in time. By contrast, we observe the whole population (we have an almost complete historical patent dataset) and all the reciprocal links (the citations). Nevertheless, simply mapping all the lineages of patents is different from quantifying (i) patents' individual contribution to future knowledge, (ii) patents' knowledge content persistence into future patents (i.e. their descendants), and (iii) patent inventive step. In this section we first describe the technical details of the persistence and thickness indexes and then link them to innovation studies. Being acquainted with the technical details of the calculation will make it easier to discuss their use in the context of innovation.

6.2.1 Knowledge persistence and genetic decomposition

As already mentioned in the previous chapter, a patent discloses (and therefore embeds) information about a solution to a specific technical problem. Furthermore, it includes *prior art*, which is information made available to the public that might be relevant to assess a patent's claims of originality. In a nutshell, this *prior art* indicates the previous knowledge upon which new knowledge is built; therefore, a citation constitutes a knowledge spillover between a cited and citing patent (Marco, 2007). This means that a citing patent uses pieces of knowledge of the cited patents and this can be re-phrased by saying that a patent *inherits* (part of) its cited patents' knowledge. We can conclude that some piece of knowledge persists within the network; therefore, identifying "persistent patents" corresponds to pinpointing those patents whose knowledge is found most often throughout subsequent patents. This is operationalized using the Mendelian notion of genetic inheritance, and therefore thinking about citations as links through which a "parent" patent transmits its genes (part of its knowledge) to its "descendants".

In a patent citation network there are three types of patents: *startpoints*[2], *endpoints*[3], and *intermediates*. *Endpoints* are generally recent patents representing contemporary technologies. Following the parallel with genetics, they represent the observed population, and therefore the aim of genetic decomposition is to quantify the contribution of earlier patents to *endpoints*. This exercise conceptually corresponds to the work of population geneticists decomposing population genes and tracing changes. However, it is important to stress that, if on the one hand, the conceptual similarity with genetics can be evident, on the other, the employment of the same methodologies and statistical tools for the analysis is problematic. In fact, geneticists often use allele frequencies for clustering, which cannot be straightforwardly translated in the context of patents.

The quantity of knowledge a patent is able to spread depends on the pattern of its forward direct and indirect citations. In fact, we can already contend that a persistence index is a way to "globally" evaluate the patent citation structure. The word globally refers to the fact that we do not limit ourselves to the first level of ties/citations; this indicator is able to account for any citation structure between any patent and recent patents[4].

Figure 6.1 represents a very simple patent citation network structure with five *startpoints* and two *endpoints*. The calculation of the persistence index corresponds to quantifying the degree in which the *startpoints'* prospective knowledge is retained in the *endpoints* and looking at how much knowledge the two *endpoints* actually share. Clearly, both these aspects depend on the structure of the forward citations and on the number of *intermediates* and their citations. This means that to calculate the persistence index we should not focus only on *startpoints*, but should also account for *intermediates*' contributions which represents the "new" knowledge injected into the system. In fact, in the framework of genetic decomposition in a patent citation network, both knowledge persistence and knowledge creation coexist. Summarizing, figure 6.1 represents a process of knowledge creation, transmission, and transformation. After the explanation of the technical details the next section will further discuss the aspects of knowledge dynamics captured by the indicator proposed.

Following what has been said before, the simple network displayed in figure 6.1 is composed of three layers of patents indicated with TR0, TR1, and TR2. Patents in the figure are genetically decomposed using the following heuristics:

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[2] Startpoints are patents that, within a specific dataset, do not cite any previous patents but they are cited by forward patents. Clearly this makes them appear as pure and independent knowledge sources.

[3] *Endpoints* are patents which cite but they are not cited by forward patents.

[4] As it will be clear from section 6.2.1, recent patents refer to the set of *endpoints*.

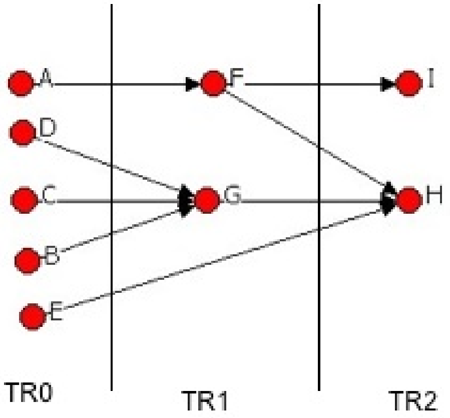

Figure 6.1: Simple patent citation network structure

1. *Endpoints* are identified and working backwards each patent is assigned to a layer;
2. For each *startpoint* belonging to the first layer (TR0 in figure 6.1) the persistence index is calculated. This is going to quantify how much of their knowledge is retained in the *endpoints* (TR2 in figure 6.1);
3. The *startpoints* are deleted (the network is truncated) and therefore a new layer of *startpoints* is created (TR1 in figure 6.1);
4. Calculation of the persistence index for the new group of *startpoints*;
5. Deletion of the layer and repetition of step 2 and 3 up to the last layer.

This procedure is repeated for each layer and the number of layers depends on the length of the largest geodesic distance in the network.

Step 2 and (recursively) 4 represent the core of the new indicator, which corresponds to the application of the Mendelian law of genetic inheritance to citations.

Looking at the first layer (TR0) in figure 6.1 we can see that the only patent cited by patent **F** is patent **A**, thus 100% of the inherited knowledge embodied in patent **F** is the knowledge of patent **A**. Instead, patent **G** makes three citations to patents **B**, **C**, and **D**, thus the inherited knowledge embodied in patent **G** consists 33.3% of patent **B**, 33.3% of patent **C** and 33.3% of patent **D**.

In the second layer (TR1), the endpoint **I** makes only one citation and that is directed to patent **F**. Since the embodied knowledge in patent **F** is 100% that of patent **A**, the inherited knowledge embodied in patent **I** is again 100% that of patent **A**. The endpoint **H** makes 3 citations. The first is to patent **F** that has 100% patent **A** knowledge, thus $\frac{1}{3}100\% = 33.3\%$

of the inherited knowledge embodied in patent **H** is the knowledge of patent **A**. The second citation of patent **H** is to patent **G** that embodies 33.3% of each of the respective knowledge of patents **B**, **C**, and **D**. Since patent **H** inherits only $\frac{1}{3}$ of its knowledge from patent **G**, it inherits indirectly $\frac{1}{3}33.3\% = 11.1\%$ of each of the knowledge of the *startpoints* **B**, **C**, and **D**. Finally 33.3% of the inherited knowledge in patent **H** comes directly from *startpoint* **E**.

Focusing on the TR0 level: *How much knowledge of (startpoints) **A**, **D**, **C**, **B**, and **E** is retained in (*endpoints*) **H** and **I**?* The answer is displayed in last row of table 6.1, which gives the column sums of the contribution of each *startpoint*.

Table 6.1: Persistence of knowledge for Truncation 0

		Startpoints				
		A	B	C	D	E
Endpoints	I	1	0	0	0	0
	H	0.33	0.11	0.11	0.11	0.33
Sum		1.33	0.11	0.11	0.11	0.33

It is worth observing that each row represents a genetic decomposition of the *endpoint* and therefore adds up to 1, and the last row sum adds up to the number of *endpoints*. This last row supplies a fractional count that is the basis of the "persistence" index: effectively, 1.33 out of the 2 *endpoints* are the pure descendants of the *startpoint* **A**, 0.33 out of 2 are the pure descendants of the startpoint **E**, and each of the *startpoints* **B**, **C**, and **D** has 0.11 pure descendants. Clearly, *startpoint* **A** is the most important *startpoint* since it is $\frac{1.33}{0.33} = 4$ times as important as patent **E** and $\frac{1.33}{0.11} = 12$ times as important as patents **B**, **C**, and **D**. Patent **E** is the second most important *startpoint* and *startpoints* **B**, **C**, and **D** look not so important on their own.

As explained in the step list before, the decomposition algorithm puts only the *startpoints* into competition. In other words, the intermediate patents **F** and **G** do not show up in table 6.1 as knowledge suppliers as they just transmit the knowledge from the *startpoints* to the *endpoints*. Therefore, after step 2, *startpoints* in layer TR0 are removed from the network (i.e., truncate the network from the left), and a new set of *startpoints* is created. In the example of Figure 6.1, one left truncation (i.e., removal of patents **A** , **B** ,**C**, **D**, and **E**) brings patents **F** and **G** forward as *startpoints*. Again the question is *How much knowledge of **F** and **G** is retained in **H** and **I**?* Last row in table 6.2 contains the answer.

Patent **F** appears to have 1.5 pure descendants and patent **G** has 0.5 pure descendants; thus patent **F** is $\frac{1.5}{0.5} = 3$ times as important as patent **G**.

In the simple network displayed in figure 6.1 only three layers are present since another step of truncation leaves us only with the *endpoints*. In real samples the network is left truncated and analyzed as long as it is possible to truncate further. For each layer matrices like table 6.1 and 6.2 are calculated and the persistence index is calculated as the sum of each

Table 6.2: Persistence of knowledge for Truncation 1

		Startpoints	
		F	G
Endpoints	I	1	0
	H	0.5	0.5
Sum		1.5	0.5

contribution (the last row in tables 6.1 and 6.2). The persistence index is then normalized using the maximum, meaning that for each truncation the persistence index takes a value between 0 and 1[5].

The persistence index just presented represents a measure of a patents' importance. In this framework importance is associated with the capacity of a patent to spread its knowledge to recent patents (*endpoints*) and therefore throughout the network. In the empirical section, this index will be used not only for evaluating patents but also citations. In particular, a binary patent citation network will be weighted using the product of the persistence index of the connected patents. In this way, citations will be ranked depending on the persistence of the knowledge they transmit.

Before moving to the next section it is worth to discussing the assumptions underlying the calculation of the persistence index. This corresponds to address critiques emerging from the fact that the parallel between knowledge and population genetics is just conceptual, and that genetic inheritance has features that do not apply to knowledge inheritance and persistence.

In the previous pages we suggested that *intermediates* are patents that inject new knowledge in the system. However, what is the nature of this new knowledge? According to way the genetic decomposition is calculated the inventive step of a patent is the recombination of the inherited knowledge. However in a second step (through truncations) this new knowledge also becomes part of the system and contributes to the *endpoints*. Following this it appears that a building block of the evolutionary process, which is random mutation, is missing. In this respect, the genetic patent decomposition might look like a deterministic representation of technology evolution, where nothing genuinely new is created. However, knowledge is recombined and therefore by definition it is transformed into something different and therefore new. In the genetic decomposition approach, novelty is created through recombination, therefore the patent citation network represents a system accounting for both knowledge persistence and generation. This concept of innovation is rather similar to the concept of "recombining knowledge" put forward by Weitzman (1998; 1996), according to which *. . . new ideas arise out of existing ideas in some kind of cumulative interactive process . . . "* (Weitzman, 1996, page 209).

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[5] It is worth noting that by construction the persistence index can be calculated only for *startpoints* and *intermediates*.

The second point follows from the previous one and relates to the assumption of "rivalry" in the use of knowledge. This is not explicitly mentioned but it derives from the way *endpoints* are decomposed. In fact, we know that patents inherit an amount of knowledge depending on the number of backward citations, and it appears as if each forward patent incorporates a distinct piece of knowledge (as the genetic decomposition adds up to 1). However, this computation can be seen from a different perspective: all the subsequent patents are receiving the same piece of knowledge, the "valuable" one. Let's consider a highly cited patent. According to the calculation the knowledge it will transmit to the next layer is very little. However, what really matters is the global citation pattern, and therefore how much that little piece of knowledge can persist through transformation in subsequent layers and finally in the *endpoints*. In this way, a piece of valuable knowledge is spread in several descendant patents, which may or may not blossom into a promising chains of invention. This means that the rivalry assumption it is just a computational assumption that do not affect the whole validity and meaning of the genetic decomposition approach.

Finally, it is worth spending some words on the selection mechanism. From evolutionary theory we know that species retain some features (which derive from genetic mutation) if these provide a better adaptation (fitness) to the environment. In this sense, the selection process is operated by the environment. How does this selection take place in a genetic decomposition of a patent citation network? In this case, selection is operated by the engineers (or eventually by patent examiners), who place citations, determining the citations structure of the network. As it will appear from the methodological section, the important patents (containing the "best" knowledge[6]) emerge not only from the number of citations itself, but from the number (and distribution) of the citations along all their descendants.

6.2.2 The thickness measure

The previous section presented a method for evaluating patents according to their capacity to persist in the network. However, this index does not explain how these important patents are connected, and therefore whether and how knowledge is transmitted among them. In fact, different connection structures correspond to different patters of technological change; in extreme cases we can confront long and thin paths with short and thick paths, such as the ones represented in 6.2.

Following the discussion at the end of section 6.2.1 we highlighted that within the genetic approach (GA), novelty is determined by knowledge recombination, and the aim of the thickness measure is to assess the scope of the recombined knowledge. In the top part of figure 6.2 (a), important patents (1 and 8) are connected through an unique long chain, whereas in the case at the bottom (b) important patents are connected through thick (and relatively shorter) chains. As we will discuss in section 6.2.3 these two settings can be associated with

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[6] Note that best is an approximation for *high fit*, which in term of knowledge might refer to its usefulness, its value, its coherence, etc. etc.

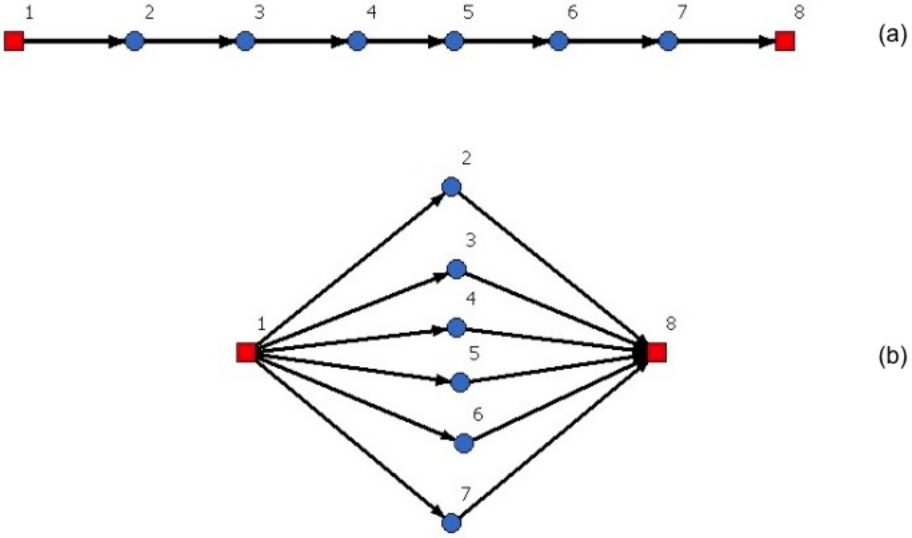

Figure 6.2: Example of connective structure between important patents

two completely different ways through which technology advances. In the first case, the structure suggests an incremental advance, coupled with a limited genetic variety and therefore a limited extent of the recombined knowledge. On the other hand, the thickness of the relation between patent 1 and 8 in (b) represents the diversification of the technological research involved with the invention of patent 8 and therefore the large scope of the knowledge involved with that patent. In this framework the thickness measure refers to the "width"[7] of the connection between persistent patent pairs, and it will be used for discriminating between situations like (a) and (b). In the next section we will further develop the implication of the thickness measure for the study of technological change, whereas in the following paragraphs we will focus on the computational details. Again, knowledge of the technicalities will facilitate the discussion about what this indicator is capturing (and what it is not).

The thickness measure is calculated for each (reachable[8]) pair of persistent patents and it regards all the possible paths (therefore not only directed links) between them. This means that, for all patent pairs, an exhaustive search algorithm can enumerate all possible citation chains that connect them and build the sub-network of all citations and all patents lying in between. Length and width (i.e. thickness) are concepts defined to understand the properties of these sub-networks. In particular, given persistent patents A and B, let $N^P_{A,B}$ denote the

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[7] Please note that in the rest of this chapter thickness and width are used as synonyms.

[8] Reachable means that there is at least one path between the two patents under consideration.

number of all possible paths (i.e. citation chains) that connect them, and let $L^i_{A,B}$ denote the chain length of the i^{th} path (of the $N^P_{A,B}$ possible paths). Thus the average citation chain length between patents A and B is defined as

$$L^{Avg}_{A,B} = \frac{\sum_{i=1}^{N^P_{A,B}} L^i_{A,B}}{N^P_{A,B}}$$

Further let $N^{Cit}_{A,B}$ denote the number of all (direct) citations that show up on any of the $N^P_{A,B}$ possible paths that connect patents A and B. Accordingly we define the thickness (width) of the sub-network that connect patents A and B as

$$W_{A,B} = \frac{N^{Cit}_{A,B}}{L^{Avg}_{A,B}}$$

In order to show the rationale behind this indicator we can look at the two alternative sub-networks depicted on figures 6.2(a) and 6.2(b). For the long and thin sub-network on figures 6.2(a), one counts $N^P_{1,8} = 1$, $L^{Avg}_{1,8} = 7$, $N^{Cit}_{1,8} = 7$ and thus $W_{A,B} = 1$. However, for the short and thick sub-network depicted on figure 6.2(b) $N^P_{1,8} = 6$, $L^{Avg}_{1,8} = 2$, $N^{Cit}_{1,8} = 12$ and thus $W_{A,B} = 6$. Clearly, the average length and thickness measures capture the fact that the former sub-network is a serial connection with 7 citations, whereas the latter sub-network provides 6 parallel connections between patents 1 and 8, where each parallel connection is a short chain of only 2 serial citations.

In a nutshell, the width/thickness measure characterizes the connection between important patents and helps to discriminate between situations (a) and (b) in figure 6.2. In particular, it "encapsulates" all the possible paths (direct and indirect) connecting any important dyads, quantifying the scope of the knowledge flow and therefore the knowledge diversification between two patents.

6.2.3 Knowledge persistence, thickness, and patterns of technological change

In the previous section we tried to convince the reader that it is meaningful to apply a genetic framework of analysis based on inheritance to citations and we introduced two indicators (knowledge persistence and thickness) for the analysis of patent citation networks. In this section we are going to point out what we can learn about patterns of technological change through the use of such indexes. In other words, we move away from considering these indicators simply as network reduction methods, and link them to innovation studies. This can be expressed in two simple questions: *What can we learn, using the persistence and the thickness indexes, about patterns of knowledge creation? What is the relation between the two indicators?*

In the first place we can note that the idea of genetic inheritance is strictly linked to the concept of cumulativeness. Therefore, the study of knowledge persistence can be seen as a way to study the extent of cumulativeness observed in the process of technological change. In this respect, the HDA, used in the previous chapter, also deals with cumulativeness, and section 6.3 will explore similarities and differences between the two approaches.

At the technological level, cumulativeness means that innovations developed today constitute the building blocks for future ones[9]. It also means that an innovation not only generates a subsequent stream of incremental innovations, but can also be used in other fields and generate new knowledge. The degree of cumulativeness is endogenous to the technology (Breschi et al., 2000), at the very micro level (such as at patent level): even the most disruptive technological breakthrough is rooted in previous knowledge. For instance, in the NBER patent dataset more than 99% of the patents are included in the largest (weak) component (Batagelj, 2003): therefore a large number of technological classes (representing the possible technologies) are connected. In this sense the persistence index can be used to characterize and measure the degree of cumulativeness of a specific technological development, and, as it investigates "ancestors" (the relation between early *startpoints* and *endpoints*), it focuses on long-run cumulativeness. Following this reasoning, it becomes clear how the persistence index can be related to fundamental characteristics of technological change, technological regimes, and ultimately to industrial dynamics.

A second relevant aspect relates to the recombination and scope of knowledge. As already observed in the previous section, novelty in the GA is generated through the recombination of existing knowledge. It follows that recombination can entail a more or less broad knowledge base, and therefore the scope of the building blocks can vary.

Looking at figure 6.2 we can observe two different patterns of citations, where the transition from patents 1 to 8 is differently configured. Part (b) of figure 6.2 has a higher thickness than part (a). In fact, it recombines different strands of (in this case independent) research. In case (a) the path is unique, showing a clearly established trajectory and technology inner dynamics (to use the jargon presented in chapter 2); whereas, in case (b) alternative trajectories connect the two patents. In the previous chapter we suggest that the patent citation network represents a portion of an industry knowledge base; in the same framework, the two network structures in figure 6.2 refer to two different search strategies as they show two ways to explore the technological space. Constant points out that technology is *"... intrinsically imperfect..."* (Constant, 1973, page 554); therefore technological progression is normal, however we can contend that it takes place differently depending on the uncertainty faced by the actors. In particular, the situation displayed in figure 6.2 part (b) represents a case of "search around", where several possibilities are explored to arrive at patent 8. This setting is consistent with a paradigmatic shift, characterized by the absence of established heuristics that implies the exploration of a larger portion of technological space and makes the research

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[9] Note that concepts such as technological paradigm and trajectories (tackled in chapter 2) exactly stress the cumulative nature of technological change (Dosi, 1982; Dosi, 1988*b*).

more uncertain. Using concepts taken from a different field, which is organizational learning, we can say that case (a) looks like a case of exploitation of existing heuristics and shared knowledge within the current paradigm, whereas case (b) looks like a case of exploration of different routes (March, 1991). In a nutshell, the "width measure" highlights the extent of exploration of the technological space and the search for new heuristics. It follows that through this indicator we can point out the emergence of radical technologies and new paradigms.

It is worth to pointing out that recent studies measure the scope of the patent by using the number of claims (Guellec and van Pottelsberghe, 2007). The method here proposed it is not comparable in a straightforward way as the "width" measure is assigned to a dyad and not to a patent.

Before moving to the next section, where the GA is compared to the HDA, it is fair to observe that paradigmatic change and radical innovation are not synonyms. In particular, the former is a subset of the latter, as it is possible to have a radical change without a paradigmatic change, but not the other way round (Christensen, 1993). In particular, a radical innovation can be classified as a paradigmatic change by a qualitative analysis aimed at searching both for heuristics shifts and changes in perceived technological bottlenecks.

6.3 The genetic approach vs. other approaches

In the review of the literature on patent citation networks in chapter 5, we highlight the paucity of indicators rooted in innovation studies for the analysis of patent citation networks. Before moving to the empirical part and the results we are going to compare the genetic approach (GA) with alternative approaches.

As already mentioned at several points, the literature on patent and citation counts tends to have a "local" view, as it focuses on the first round of citations. Looking at the "technological" characteristics of a patents, some attempts have been made to characterize the knowledge content of a patent. Examples of this include the "originality" and "generality" indexes elaborated by Trajtenberg, Henderson, and Jaffe (1997). These indicators compare the technological class of a patent and the technological classes of cited and citing patents. In particular, the more technologically widespread are forward citations, the more general is the patent; while, the more widespread are backwards citations, the more original is the patent. In this logic, a patent that cites previous patents belonging to a narrow set of technologies has a lower level of originality. It is already clear that this type of methodology is rather different from a network approach. However, these indicators (which are included in the famous NBER patent database (Hall et al., 2001)) go in the direction of assessing patent knowledge content through the use of technological classes .

Looking at the network approach the only comparable methodology is the Hummon and Doreian approach (HDA) used in the previous chapter. The HDA approach builds on the work by Hummon and Doreian (1989), who proposed the use of connectivity measures in order to identify the main flow of knowledge within a publication network. Recently, an emerging strand of literature applied this to patent citation networks in order to identify technological trajectories (Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009). The two indicators used for weighting citations, and therefore to evaluate their importance, are the *Search Path Link Count* (SPLC) and the *Search Path Node Pair* (SPNP). The former assigns to each connection (i.e., edge) the number of times the given edge lies in all the possible search paths; whereas the latter assigns the product of the number of all downstream and upstream connected nodes.

Ultimately both GA and HDA have the same aim which is to trace "important" technological advances. However they deeply differ in the underlying rationale and definitions. Before systematically describing these differences (summarized in table 6.3), an example from population genetics can be helpful. Summarizing, we can say that the work of geneticists is: given the observed population genetic differences with ancestors[10], to highlight streams of migration. The application of the GA to *endpoints* follows exactly the same rationale and therefore it can be considered a backward mapping of successful (persistent) technologies. The application of the HDA to populations would work in a complete different way, that is: starting from the ancestors at each (population) bifurcation, to follow the future development of the largest stream. This would correspond to tracing just the largest population and to ignore the remainders and their future development. Of course, the application of the HDA by geneticists would be a nonsense, however this example clarifies the basic differences between the two approach that is the direction of mapping: backwards for the GA and forward for the HDA. As a consequence, the HDA might be very sensible to "local" peaks, and therefore discard chains of innovations which from an ex-post perspective (the importance of the *endpoints*) are relevant.

Table 6.3: Comparison between genetic approach and Hummon and Doreian approach

Dimension	**Connectivity approach (HDA)**	**Genetic approach (GA)**
Type of cumulativeness	Aggregation/Integration	Inheritance
Important patents	*A priori*	Persistence
Type of links	Only direct	Both direct and indirect

Table 6.3 systematically list the differences between the two approaches, however, it is worth noting that those dimensions are tightly related and for this reason it is difficult to

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[10] Please note that this is a rough simplification of the principles and statistical methods used by geneticists. However it would not be of any help to discuss these in further details, given the impossibility of using them in the context of patent genetic decomposition.

neatly separate them.

According to the HDA cumulativeness is a concept associated with the idea of "aggregating knowledge": links with high SPLC or SPNP correspond to citations connecting the largest number of patents. Using the metaphor of a river, the identification of the top main path corresponds to identifying the stream with the largest capacity. Furthermore, the search algorithm for top main paths "forces" one to detect trajectories that emphasize incremental direct progress. On the contrary, in the GA, cumulativeness is related to the idea of inheritance of knowledge. In fact, we are interested in looking at the knowledge composition of recent patents, in order to see which previous patents were effective in spreading their knowledge.

The second point of difference relates to the way important network elements are identified. This point is ancillary to the previous one, as assumptions about importance are built on the definition of cumulativeness. The most evident difference is that HDA evaluates links, whereas GA looks primarily to nodes (i.e. patents). In the HDA, it is possible to distinguish between three types of important patents: *startpoints*, *endpoints*, and junctions. Both *startpoints* and *endpoints* are determined *a priori* as it often depends on the way the sample is built[11]. For this reasons, *startpoints* and *endpoints* are rather arbitrary and cannot be considered genuinely "important". On the contrary, *junctions* are identified according to their position in the network of main paths and their role is pivotal in connecting and aggregating independent streams of research. It is worth noting that following the work by Fontana, Nuvolari, and Verspagen (2009), having a large number of citations is not a sufficient condition for becoming an important *junction* in the top main path. Within the HDA these patents are closely investigated in order to understand what type of technical issue (and solution) they disclosed. In the GA approach, patents (except *endpoints*) are directly evaluated according to their persistence and therefore their importance does not directly emerges from the sampling.

The third point of difference between the two approaches is the type of algorithm used and the emphasis on the type of links examined. The search algorithm used in the HDA selects highly valuable subsequent (i.e. direct) links, which introduces a certain bias towards a particular definition of cumulativeness and over-emphasizes the notion of incremental progress. From this emerges a point of weakness of this methodology, derived from the local evaluation of each citation for including in the network of main paths. It follows that in the network of main paths some of the citations might be included as simple connectors without having a very high global connectivity power. On the other hand, as will be discussed in section 6.4.2.2, the GA considers both direct and indirect links as they disclose different types of information about degree of cumulativeness. In particular, a different way to reduce links is undertaken: in the HDA, network complexity is reduced by dropping weak direct links, in the GA, by aggregating them. In fact, in the GA all the possible paths between persistent patents are "encapsulated" in a single tie weighted using the thickness measure introduced before, and therefore accounting for the knowledge scope of the inventive step. In the next pages we will

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[11] As explained in the previous chapter, only internal citations are considered, excluding all the citations directed outside the initial patent sample.

discuss the relation between the two methods, by looking at the results obtained.

6.4 Empirical Analysis

In this section the results obtained using the genetic decomposition and the persistence index are discussed. Furthermore, these results will be compared with the ones obtained in the previous chapter using the HDA.

The dataset used is the same as the previous chapter; it includes 6214 patents granted between 1924 and 2003, and 20,848 citations[12]. The longest geodesic in the network is 25, so the network here analyzed has 25 levels of truncation.

Following the computational details in the previous section, the persistence index is calculated only for the *startpoints* generated after each truncation. Therefore, the persistence index can be calculated only for a subsample of the patents. Table 6.6 shows the number of *startpoints* evaluated in each of the 25 truncation levels.

The persistence index calculated at each truncation presents a very skewed distribution displayed in appendix F. Even if the graphs are small, they clearly show high left skewness, meaning that only a handful of patents are successful in spreading their knowledge, whereas the contribution of the great majority is diluted over time. This is consistent with the evidence on strongly skewed distribution of other indexes for patent importance and value (e.g. forward citations, license fees, etc. etc.) indicating that, generally, only few patents are important. From this perspective, the persistence index can be used for ranking patents and identifying "important" ones. In particular the index can be used in two complementary ways: (i) to study a persistent weighted network in section 6.4.1, and (ii) to study the properties of a subsample of important patents in section 6.4.2. In this chapter we will apply both and we will discuss the complementarities.

6.4.1 The *"persistence weighted network"*

The persistence index is associated to patents (as it measures the contribution of each patent to future patents), so it can be used to directly compare and rank their importance. However, the same indicator can be used to weight citations just by assigning to each link the product of the normalized (by the maximum) persistence index of the citing and cited patent. In this way the binary patent citation network is weighted according to the persistence of the knowledge transferred by that citation. Given the fact that the persistence index is available for a subsample of patents, it is not possible to weight all the citations. Therefore, the weighted network include 16,747 citations, corresponding to 80.3% of the full sample.

Figure 6.3 shows the distribution of the logarithm of the citation weights. It highlights

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[12] For the details about how the sample is built see section 5.3.4.

Table 6.4: Number of *startpoints* per truncation

Truncation	Number of *startpoints*
0	1787
1	485
2	239
3	160
4	131
5	127
6	120
7	139
8	148
9	135
10	144
11	178
12	2194
13	219
14	225
15	244
16	231
17	242
18	217
19	157
20	102
21	52
22	33
23	14
24	6
TOTAL	5754

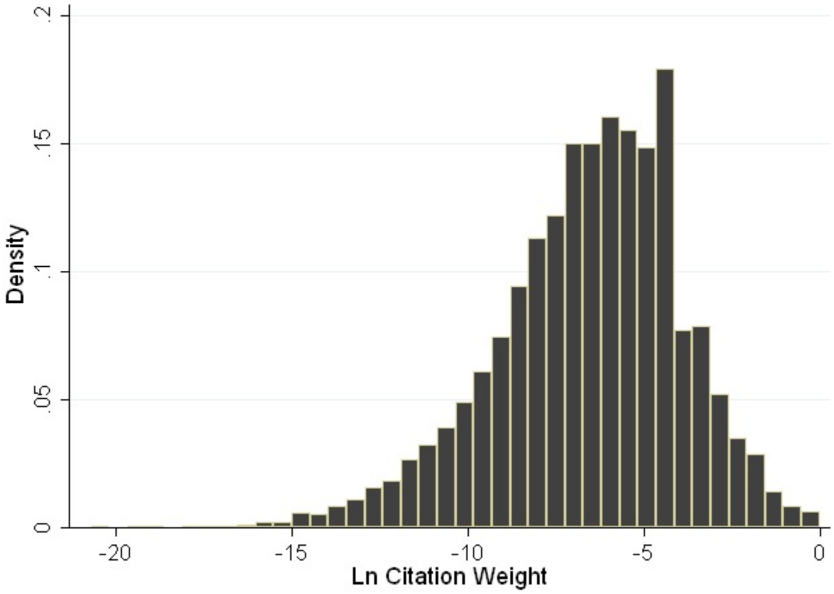

Figure 6.3: Distribution of citation weights

that very few links persistently transmit knowledge[13]. In fact, in this graph, the last column represents the number of citations with the highest weight, directly connecting the patents with the highest persistence index[14].

In the following pages the new network, the "persistence weighted network" is analyzed, looking at how its structure evolves considering different cutoff points. This corresponds to deleting unimportant links and considering only citations with a (relative) high persistence measure. In this logic the first step is to set a very high threshold such as 0.9 and to look at citations transmitting the most persistent knowledge within the network.

The resulting network is represented in figure 6.4, which presents two separate components. Undoubtedly, the fragmentation is dependent on the chosen threshold. However, this two component structure is stable down to a 0.75 threshold.

This reduced form of the original network has some overlap with the network of top main paths obtained using the HDA, shown in figure 6.5; these common patents are indicated as (red) squares in both figures 6.4 and 6.5. Following the conclusion of the previous chapter, figure 6.5 depicts a paradigmatic change from circuit switching to packet switching occurring in the late 1990s, when the established trajectory toward the upper right is discarded in favor

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[13] The summary statistics for the weights are: mean 0.0169, standard deviation 0.0655, minimum 1.05e-09, and maximum 1.

[14] Because of the normalization by the maximum the maximum weight is 1, which becomes 0 using the logarithmic transformation.

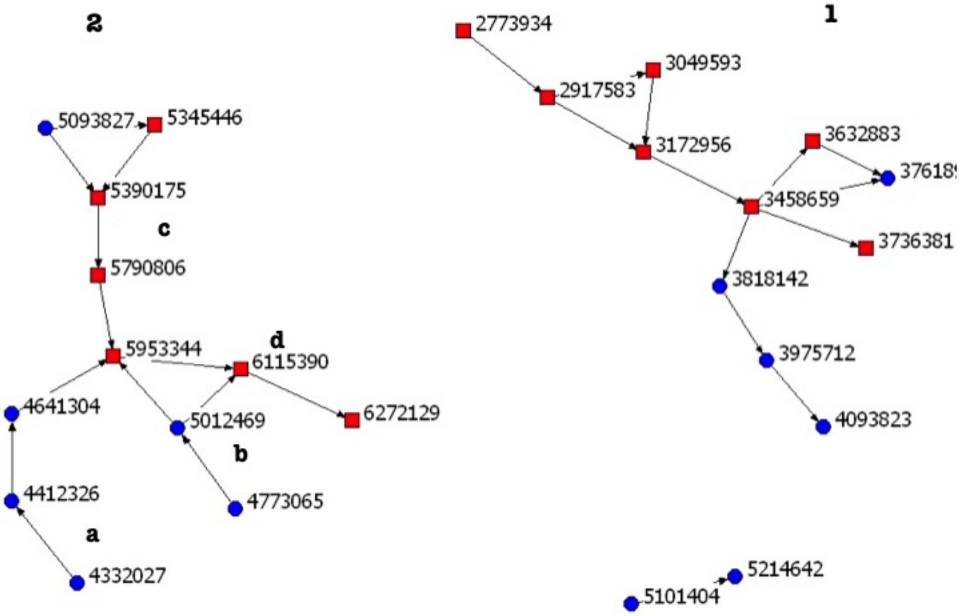

Figure 6.4: GA Network with cut off point 0.90

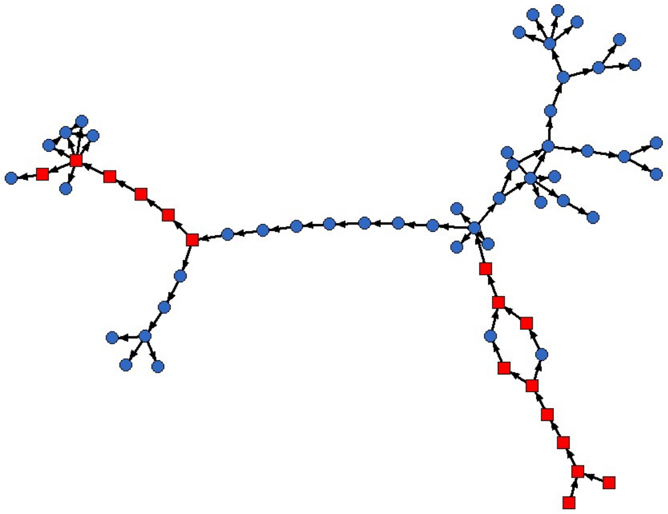

Figure 6.5: Network of top main paths obtained using the HDA

of the trajectory toward the left. The qualitative analysis supports the idea of a paradigmatic change because of a change in the engineering heuristics, in the competences needed, and in the perceived technical bottlenecks. Summarizing, figure 6.5 represents a chain of patents displaying the transition from circuit switching to packet switching.

From a visual comparison between figure 6.4 and 6.5 it appears that the two components displayed in figure 6.4 belongs to different paradigms. However this statement needs to be corroborated by the analysis of the technical contents of the patents belonging to the two components. At first, components 1 and 2 differs in their vintage: component 1 comprises patents granted between 1949 and 1977, component 2, patent granted between 1980 and 1999. Beyond the years of grant, substantial differences emerge looking at their technical contents. Components 1 deals with the development of a reliable time-division multiplexing (TDM) switching. Content-wise these patents show high similarity with the early ones in figure 6.5, looking at switch reliability, switch control, and introducing the *time slot interchange*.

Component 2 is composed of three branches (**a**, **b**, and **c**) converging to patent 5953344 and finally to the endpoint 6272129. These patents address technical solutions responding to increasing demand for data communication. Nevertheless, each branch proposes and implements different technical solutions. Strand **a** includes early patents focusing on packet switching. As already mentioned in chapter 2, this technology was developed for military and security purposes in the early 1960s; later it would become a standard technology in computer networking, but it is only in recent time that its use has expanded to telephone network. Patents in strand **b** resemble some patents located in the upper-right part of figure 6.5, as they try to adapt existing TDM technologies for data transmission. This solution was chosen by telecommunication manufacturers in order to use their TDM competences. However it was not sustainable in the long run and therefore abandoned. Finally, patents in strand **c** cover the Asynchronous Transfer Mode (ATM) switching platform. Recalling the previous chapter, this technology was proposed as an hybrid solution between two different paradigms (circuit and packet switching). As explained in the previous chapter, a characteristic feature of packet switching is the fact that transmitted information is chopped into packets that are individually routed in the network. This implies that each packet can take a different route between the same sender and receiver. In the case of connection-oriented packet switching, data are still divided into packets but the path is conceived at the outset, and all the packets are then sent through the same path. Despite its potential to mitigate some problems of packet switching (such as the decrease in the Quality of Service) it was still not optimal for quick demand increase for data communication. Finally, patents 6115390 and 6272129 deal with the transition to packet switches using the Internet Protocol and wireless technologies. From what was said above we can conclude that the two distinct components relate to different technologies, and looking at the overlap with the HDA, they do belong to two different technological paradigms.

Using a visual metaphor, we can conceive the persistent weighted network as a landscape where patent height depends on the persistence index. Using a very high cut off point corresponds to considering the emerging peaks and in figure 6.4 we can identify two areas of high persistence in the network of diluted knowledge; in this case, peaks correspond to two different technological paradigms.

Given these two peaks it is interesting to look at how they are connected, which means to looking at how the network structure (or the knowledge base landscape) changes when one lows the cutoff points. For instance, we can imagine two opposite scenarios: on the one hand these two peaks may be connected by several links or they may be connected by an unique link. Both examples correspond to different way through which persistent knowledge is transmitted and a new paradigm emerges.

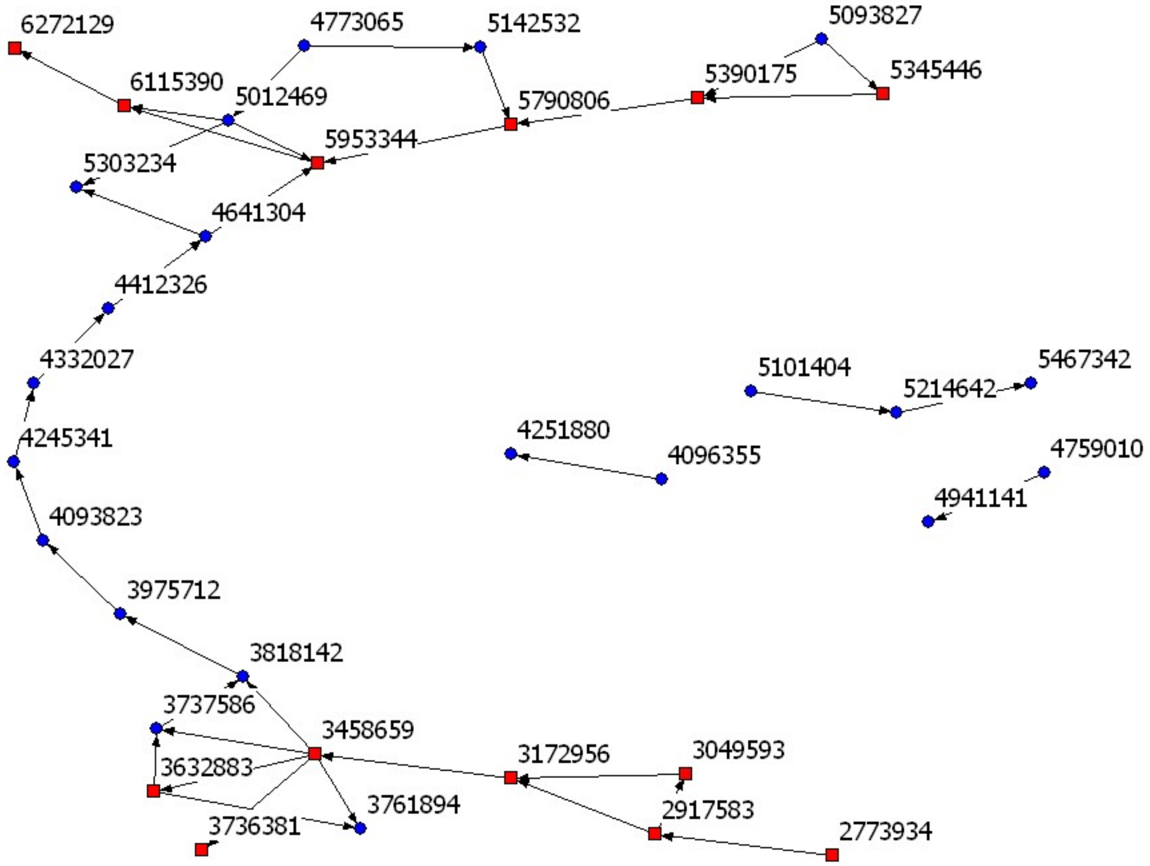

Figure 6.6: Network with cut off point 0.75

Figure 6.6 shows citations with a weight larger than 0.75, which allows more patents and citations to be included in the structure. Looking at the structure we can observe that most of the citations newly included are in the area of the two separate components (where some triads are closed). This means that, in this case, persistent (and therefore important) knowledge links tend to cluster around the peaks rather than connecting them. Second, the citation network is by no means broken anywhere between the earlier and the latest patents and a single semipath connects the two components. More on this point it is interesting to note that the connection between the two components takes place through one single patent (patent 4245341). Third, comparing this figure with the results obtained using the HDA, the two methods give different results concerning the patents that establish the connection between the earlier and the later ones.

As the structure is dependent on the choice of cut off points, it is interesting to look at the network structure when the threshold is lowered to 0.5. Figure 6.7 shows the resulting network.

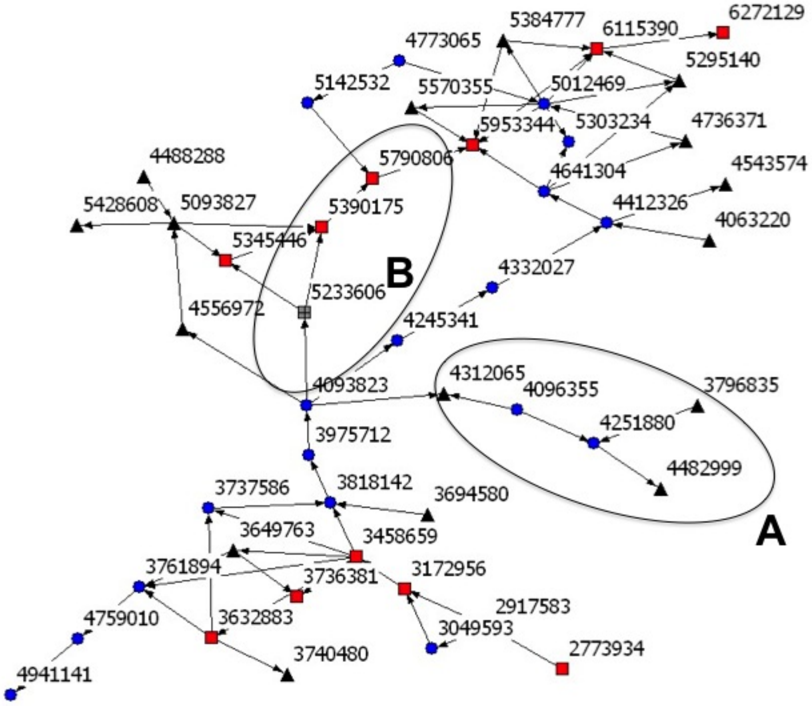

Figure 6.7: Network with cut off point 0.5

The two structures are different but still comparable, despite the increase in number of nodes and edges. The figure might be confusing, and therefore nodes are indicated with different shapes depending on their presence in previous truncations or in figure 6.5. In particular, black triangles indicate the newly added patents, whereas the grey box (patent 5233606) is a newly added patent that is found also using the HDA (i.e. it is present in figure 6.5). Looking at the whole structure, we can notice: (i) the emergence of a few short paths (indicated with A in figure 6.7), and (ii) the emergence of a shortest path connecting the two isolated components of figure 6.4 (indicated with B in figure 6.7). Following the analysis of the previous figures, it is interesting to look at the technical contents of these patents.

Patents in the circle indicated with A are relatively old patents granted between 1982 (3796835) and 1984 (4482999). Those patents cover early development of data transmission over a telephone network. In particular, some of them (i.e. patent 4312065) already put forward the idea of packets, but still in a "connection-oriented" framework. Patents in group B include later patents related to the early generations of ATM (i.e. X.25 and Frame Relay). In fact they connect to branch **a** in figure 6.4. In this case, lowering the level of the threshold sheds some light on chains of less-and-less persistent innovation, detecting ways through which the technological space was explored. In this respect, this corresponds to highlighting abandoned technologies, and in particular, patents that contained relatively persistent knowledge but that are made obsolete by the emergence of new knowledge.

This analysis shares with the HDA the focus on direct citations among patents. However, differently from the HDA, the pattern emerging from this exercise is not predetermined, meaning that there is no reason to assume that technology develops only along one path, especially in case of a paradigmatic change where a lot of "search around" is performed. In figure 6.5 the trajectory is sequentially built; from each *startpoint* edges with the highest connectivity measure are sequentially selected up to an *endpoints*. It follows that in the case of the HDA, the single ridge connecting the two peaks is endogenous in the search algorithm which does not allow for the emergence of multiple paths. On the contrary, in the analysis so far performed using the GA approach no "greedy" algorithm is used and multiple connecting semipaths might emerge. From these different algorithms different considerations about the time structure emerge. If on the one hand in both cases we have the representation of technology evolution, on the other hand in the GA the time dimension is less constraining, however it is still present in the direction of the arcs and in the numbering of patents. In this respect, figure 6.4 and 6.5 show two ways of representing "technological discontinuities".

6.4.2 Subnetworks of persistent patents

In the previous section we focused on the analysis of the *persistence weighted network* and the direct links transmitting persistent knowledge between two paradigms. In this section we use a different perspective departing from the focus on direct links. This is done in two steps: (i) the identification of important patents, and (ii) the analysis of their direct and indirect links.

6.4.2.1 Reducing the number of nodes

We anticipated that the persistence index can be used for ranking patents and for identifying important patents. Therefore, from this perspective, this method can be seen as a way to reduce network complexity. Given a patent rank built on their persistence, we can expect a certain amount of arbitrariness in deciding which patents are important, that corresponds to set a minimum threshold.

However, in the case of the telecommunication switching industry it appears that the arbitrariness is very low as the importance index shows an extremely skewed distribution and, for each truncation, no more than a handful of patents have a quite high importance indexes. Appendix F reports the distribution of the frequency of the persistence index for the first 20 truncations; even if the graphs are in small print, they clearly show high positive skewness. Using a rather conservative cutoff point, 0.5, we extract 79 "important patents". These, together with some relevant information, are reported in appendix D.

The rationale for using a method for reducing network complexity is the possibility of inferring some properties on the whole network just using that subsample. In this case it is hard to test whether this subsample (representing 1.27% of the full sample) is a representative one; in fact, testing its representativeness is not straightforward because of the difficulty of expressing a baseline (i.e. *a priori* what properties the subsample should retain). As a bottom line we are going to compare some descriptive statistics and to test the subsample against a random one from the full population. The rationale of comparing the patent sample extracted using the GA to a random generated sample, is exactly to show that the subsample we are going to work with is not randomly drawn from the initial sample. The random sample was extracted in a simple way, assigning to each observation a random number and taking the lowest 79th observations. In this comparison we focus on four citation indicators that are:

1. the weighted citations count, where the number of forward citations received by the patent is normalized by the average number of citations received by patents in the same age cohort;
2. the patent citation count proposed by Jaffe et al. (2005), which consists in the number of forward citations plus 1;

The two other indicators are based on the SPLC indicator introduced by Hummond and Dorein (1989). Recalling what said in section 6.3, SPLC represents the extent of knowledge cumulativess associated with a citation. Note that these indicators are evaluating citations and not patents; therefore they can be assigned to either the cited or the citing patent of each citation[15]. The interpretation does not vary much and in this case the citation weight is assigned to the cited patent. Following this, the last two indicators considered for the comparison are:

1. the SPLC by row, which consists in the row sum of the matrix where each citation is evaluated using SPLC. This means assigning the value to the "cited" patent;

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[15] Technically, this corresponds to make either a column or row sum in the SPLC weighted citation matrix.

2. the SPLC by column, which consists in the column sum of the matrix where each citation is evaluated using SPLC. This means assigning the value to the "citing" patent.

Table 6.5 reports the summary statistics for the above mentioned indicators for two samples: the full sample on which it was possible to calculate the genetic decomposition (5754) and the subsample extracted using the genetic decomposition (79). As already mentioned at the beginning of section 6.2.1, the size of the two samples do not coincide[16] because the genetic decomposition is possible only for the *startpoints* at each truncation level and therefore not for the whole starting sample. The calculation involving SPLC has one observation less because it was calculated for patents issued after 1950. In this way 16 patents are missed, of which only one actually has citations[17].

Table 6.5: Summary statistics for citation indicators

Variable	N	Mean	Median	SD	Min	Max
Weighted count	5675	0.9631	0.651	0.970	0.217	8.242
	79	3.239	2.955	2.182	0.217	15.08
Weighted patent count	5675	4.502	3	3.623	2	39
	79	13.303	11	8.385	2	58
SPLC Row	5674	0.0101	0.000	.0.455	0.000	0.955
	79	0.318	0.12	0.438	0.003	2
SPLC Column	5674	0.009	0.000	0.0450	0.000	0.955
	79	0.288	0.984	0.420	0	2

Table 6.5 shows that the patents extracted using genetic decomposition received more citations and have higher connectivity. This holds both for the mean and the median.

Table 6.6: Results of the Wilcoxon-Mann-Whitney test on the median

Variables	z	P-value
Weighted patent count	8.601	0.000
Weighted count	8.645	0.000
SPLC Column	9.958	0.000
SPLC Row	9.087	0.000

Table 6.6 shows the results of the comparison between the random sample and the one extracted using the genetic decomposition. The non-parametric Wilcoxon-Mann-Whitney

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[16] The patent sample includes 6214 patents.

[17] This means that patent 2406165 is included in the genetic decomposition as start point but not in the SPLC matrix.

test used to account for the high skewness of the variables, rejects the hypothesis that the samples are extracted from the same distribution.

Before moving to the analysis of the links between important patents and therefore using the thickness measure, it is worth spending some words on the relationship between this analysis and the one presented in section 6.4.1. In fact, looking at the set of persistent patents and figure 6.6 we can notice a great deal of overlap. However, as already mentioned before, figure 6.6 looks at direct links, whereas in the next section, we enlarge the perspective considering both direct and indirect links. Does this shift completely change the rationale behind the two analyses? The answer is clearly yes. In fact figure 6.6 has a "reductionist" approach looking at the shortest possible link between (persistent) patents and not considering all the remanding possible connections. From a network perspective, it is like moving away from a geodesic perspective and considering not only the "shortest" distance or path. This different perspective makes sense in this chapter because we are interested in studying how the technological space (i.e. the patent citation network) is explored. In this framework, the shortest way to link knowledge is not fully informative and an holistic approach to important patent connectivity allows us to assess the diversification of the descendants and therefore the extent of their inventive steps.

6.4.2.2 Reducing the number of links: the thickness measure

The aim of this section is to use the thickness measure to explore the properties of the paths (i.e. citation chains) that connect important patents. We use this indicator to discover whether the structure of these paths more resembles the upper, or, instead, the lower part of figure 6.2.

We find that the 79 important patents are connected through 1287 "unimportant" (i.e. not persistent) patents, out of the original 6214. Although this is only 20% of the 6214 patents, the number of citations made and/or received by these patents are around 10,250 which is half of all citations in the network (20,848). The fact that 20% of patents are responsible for half of all citations is clearly enough reason to believe that the patents in the focus set, and that their mutual connection, constitute a large and important component of the raw network. As the methodology is basically a network reduction, it assumes that the essence of the given network is hidden in the focus set, so one can analyze the network simply by focusing on the sub-network that consists of the patents in the focus set (and their connections), while the rest of the network is ignored. In a nutshell, it is possible to reduce the starting binary network to a network of the most persistent patents linked by a thickness-weighted link. In the case of telecommunication switches, this reduced network includes 79 patents and 1275 citations. This network is visualized in figure 6.8 using the weights as indicators of similarity for the Fruchterman Reingold energy algorithm. This means that patents connected by a structure resembling the lower part of figure 6.2 are plotted in the centre.

The visual analysis of such network is rather difficult; therefore table 6.7 and figure 6.9

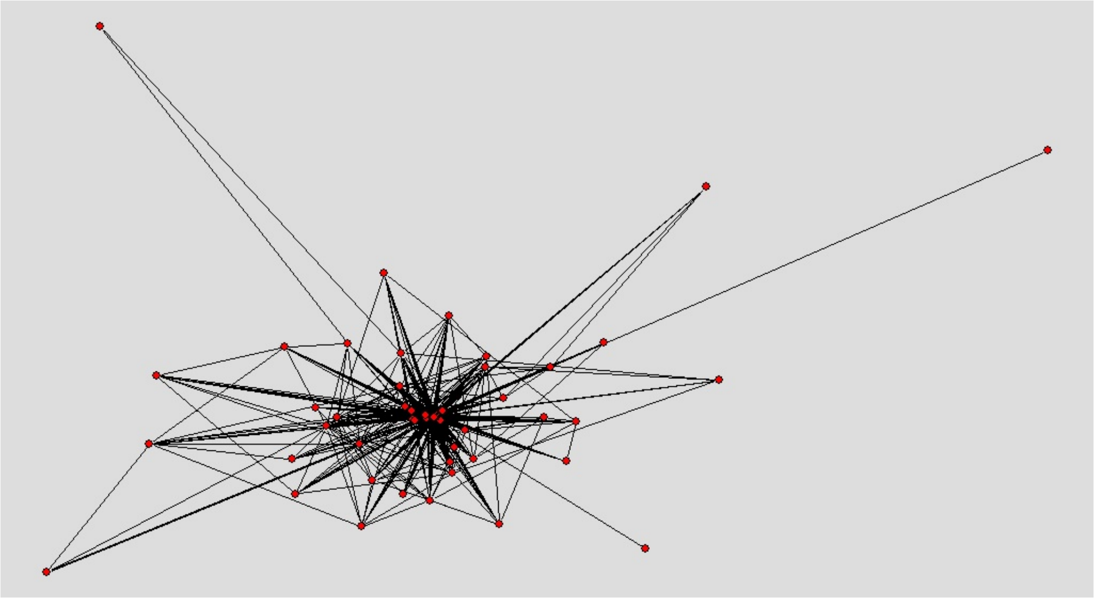

Figure 6.8: Network of important patents valued using the thickness

can help us to analyze the distribution of the thickness measure. Table 6.5 focuses on the number of possible paths between patent pairs, the citations (number of links) between these pairs, the average length of all the possible paths, and finally the thickness measure[18].

Table 6.7: Summary statistics

Variable	N	Mean	Median	SD	Min	Max
Paths in between	1275	355.359	12	1393.957	1	22247
Citation in between	1275	110.526	29	182.44	1	1282
Average paths length	1275	6.255	6.227	2.831	1	14.188
Thickness	1275	12.858	4.8	17.947	1	122.169

Several indicators included in the above table present a rather skewed distribution. For instance the number of possible paths between pairs varying from 1 to 22 247, or the number of in-between citations varies between 1 (direct citations) to more that 1000 intermediate

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[18] It is worth recalling that width is measured as the ratio between the first two.

citations[19]. The average path length between pairs is 6.25 and this is rather close to the average geodesic distance in the network (5.423). This means that despite the presence of long paths, the average of all the possible connections tends to be short. Finally, the thickness measure (i.e. width) of these links also shows great variation, ranging from 1 to 122.

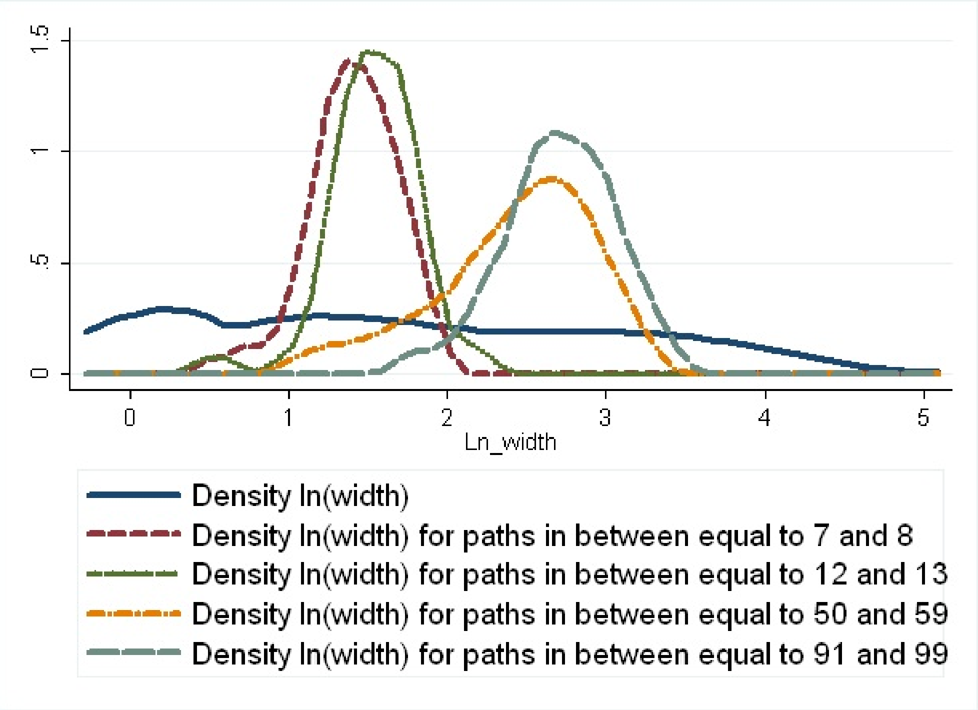

Figure 6.9: Frequencies of the logarithm of width

In order to unfold the properties of the thickness measure, we can look at its kernel density. Furthermore, as these “important” patents can be connected through a different number of possible paths (see the first row in table 6.7), they are differently “reachable” and it is interesting to look at the thickness measure distribution for increasingly “reachable” patents. Figure 6.9 shows the kernel density for the logarithm of the width (solid blue line) and the kernel densities calculated for specific number of paths in between. The plot shows that as the number of the possible paths between patents increases, the width also increases (as the peak of the kernel move towards the right). Later we will further explore the correlation of the measure of thickness with the number of possible paths and the time.

Following section 6.2.3 we can contend that the thickness index measures the extent of search and therefore the inventive step between patents. In particular, we expect higher values

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[19] In this case the maximum is between patent 2773934 and patent 5953330. Between them there are 22247 possible paths encompassing 545 patents.

for citations connecting patents belonging to different paradigms. In order to look at this, the 79 important patents (the most persistent ones) are divided in three groups[20] indicated in figure 6.10 depending on both their issue year and their position in the network in figure 6.4 and 6.6.

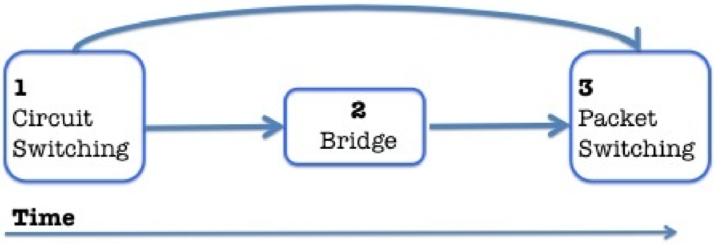

Figure 6.10: Representation of the three groups and their links.

As displayed in the figure, group 1 represents the old paradigm (circuit switching), group 3 the new one (packet switching), and group 2 "the bridge" between them. It follows that the 1275 links between these 79 patents can be classified in 6 different cases, three (indicated with 11, 22, and 33) within the same group (and in two cases within the same paradigm) and three (indicated with 12, 13, and 23) between groups and paradigms. Table 6.8 shows the frequency table for each group and points out that most of the links occurs between the two paradigms.

Table 6.8: Frequencies of the links within/between paradigms.

Groups	Frequencies	Percent	Cum.
11	38	2.98	2.98
12	132	10.35	13.33
13	554	43.45	56.78
22	40	3.14	59.92
23	405	31.76	91.69
33	106	8.31	100.00
Total	1,275		100.00

As already put forward before, we expect higher width for links connecting pieces of technology belonging to different groups, and in particular to two different paradigms. We therefore expect the links in group 13 to be the group with the highest thickness.

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[20] See appendix D for the list of the patents in each paradigm.

Table 6.9: Summary statistics of the *Width* within/between paradigms.

Groups	Observations	Mean	Std. Dev.	Min	Max
11	38	1.507	0.909	1	3.857
12	132	5.095	5.994	1	33.45
13	554	23.604	22.2	1	122.17
22	40	2.005	1.746	1	8.918
23	405	5.797	6.985	1	53.85
33	106	1.524	0,968	1	4.741

Table 6.9 presents the summary statistic for width, by different groups. It emerges that, on average, the citations width between groups is higher than the one within groups. In particular the largest width is observed in pairs connecting different paradigms (13). The Wilcoxon-Mann-Whitney test for equality of the median rejects the null hypothesis that the three groups are extracted by populations with the same median. The results in the above table confirms that persistent patents belonging to different paradigms are connected through thicker connections, meaning that knowledge is transferred by a larger number of paths. Again, this suggests that given the uncertainty of a paradigmatic change where heuristics and competences are not useful anymore, a lot of searching around takes place. Alternatively, we can conclude that technological advances within a paradigm are more cumulative.

6.4.2.3 Robustness check

This result is further strengthened in two ways: (i) through a qualitative analysis of the technical contents (and therefore of the knowledge base) of the thickest links, and (ii) correcting for the time correlation between the thickness measure and the time (and therefore also for the number of possible paths between *startpoints* and *endpoints*).

The statistics and the shape of the distribution (Figure 6.9) support the idea that most of the inventive steps involves a narrow exploration, whereas, very few involve a lot of "search around". Indeed, we know that paradigmatic shifts are rare compared to "normal" development of a technology. This becomes more clear looking at the right tail of the distribution. In the 99^{th} percentile of our thickness measure (79.06) there are only 12 links and in the 95^{th} percentile (52.46) the links are 65. Given the high number of patents included in these links[21] it is not possible to systematically look at their technical contents; for this reason, we will focus on the *startpoints* and *endpoints* of the paths in the 95^{th} percentile. These 65 links connect 13 unique *startpoints* and 12 unique *endpoints* reported in table 6.10 and 6.11. It is

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[21] It is worth recalling that these links include also 1287 "unimportant patents".

extremely important to observe that in this case *startpoints* and *endpoints* are ontologically different from the same entities in the HDA and in the calculation of the persistence index. In the latter cases, *startpoints* and *endpoints* are picked because of their lack of backwards and forward citations (see section 5.3 and footnotes 2 and 3), whereas here this definition depend on the structure of the all possible paths between the persistent 79 patents. In fact, the *startpoints* and *endpoints* under examination in this section belong to the sample of persistent patents identified using the genetic decomposition.

Patents in the two tables are issued in non overlapping periods (1956-1978 for *startpoints* and 1991-2000 for *endpoints*), so we can conclude that these few extremely thick connections are only to be found between rather early patents and rather late patents. Furthermore, the screening of the technical issues suggests that patents tend to be similar within group (*startpoints* and *endpoints*) and dissimilar between groups. This might look trivial if we consider that 20 years of technical progress has passed and therefore technical issues change. Therefore, the next step will be to show that those differences imply a paradigmatic change. In the previous chapter, we looked at the technical contents of patents searching for changes in: (i) engineering heuristics, (ii) technical bottlenecks, and (ii) required technical competences. In this chapter we analyze IPC technological classes. It was preferred to focus on this classification, rather than the USPTO one because the latter was used for extracting the sample and therefore it is certainly biased[22]. Looking at the *startpoints* (table 6.10) we can see that apart from three exceptions all the patents have the same IPC technological classification, that is $H04Q11/04$. This class covers *Selecting arrangements for multiplex systems for time-division multiplexing*, which means that these patents deals with the functioning and arrangements of (digital) TDM switches. Within these early patents, two already deals with data switching networks ($H04L12$).

Looking at the table summarizing the *endpoints* (table 6.11) we can notice that in this case all patents have more than one IPC class. Actually, the table reports only the common ones, however each patent is assigned to at least three (at most seven) IPC classes[23]. It is difficult to infer anything from this. However we can conjecture about the increasing scope of the technology proposed. In fact, the adoption of packet switching (in the form of ATM) allows the co-existence of narrow and broadband transmission, in particular both voice and data. Examining the common technological classes among the *endpoints*, we can find that the most recurrent are: $H04Q11$ and $H04L12/56$. The first class is also the most recurrent in the *startpoints* (dealing mainly with voice switching), the second class indicates these patents systematically involve packet switching[24].

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[22] However a first round of cited patents was added, so according to this classification some variety can also emerge.

[23] It would be possible to claim that increase in the number of IPC classes depends on the diffusion of computers and therefore a more accurate classification by patent assignee. See Appendix E, about this point.

[24] The $H04L12/56$ IPC class title is: Data switching networks (interconnection of, or transfer of information or other signals between, memories, input/output devices or central processing units, using packet switching.

Table 6.10: Information about *Startpoints*

Paradigm	Startpoint	Issue year	Technological class	IPC	Title/summary
1	2754367	1956	370/360	H04Q 3/00	Automatic exchange
1	2773934	1956	370/351	H04Q 11/04	Electronic Telephone System
1	2917583	1959	370/362	H04Q 11/04	Basic TDM System
1	3049593	1962	370/360	H04Q 11/06	Basic TDM System
1	3172956	1965	370/376	H04Q 11/04	Time slot interchange
1	3456242	1969	709/251	H04L 12/423	Data handling and method
1	3458659	1969	370/370	H04Q 11/04	Non-blocking digital system
1	3736381	1973	370/370	H04Q 11/04	TDM Switching system
1	3740480	1973	370/371	H04Q 11/04	TDM System using time slots interchange
1	3761894	1973	710/53	H04Q 11/04	Memory access for TDM switch
1	3766322	1973	370/422	H04L 12/64	Data switching
1	3796835	1974	370/355	H04Q 11/04	TDM system for voice or low speed data
2	4074072	1978	370/388	H04Q 11/04	Modularization and increase switch capacity.

Table 6.11: Information about *Endpoints*

Paradigm	Endpoint	Issue year	Technological class	IPC	Title/summary
3	5161152	1991	370/463	H04Q 11/04; H04L 12/52	High-low speed transmission interface
3	5214642	1993	370/471	H04Q 11/04; H04L 12/56	ATM
3	5233606	1993	370/418	H04L 12/56; H04Q 11/04	ATM
3	5276678	1994	370/267	H04Q 11/04; H04L 11/04	TDM advanced service (conference)
3	5351236	1994	370/358	H04Q 11/04; H04L 12/50	TDM for broadband communication
3	5355362	1994	370/222	H04Q 11/04; H04Q 11/04	Integrating a new protocol allowing narrow and broadband services
3	5390175	1995	370/398	H04Q 11/04; H04L 12/56	ATM
3	5570355	1996	370/352	H04Q 11/04; H04L 12/56	ATM and Packet switching
3	5623491	1997	370/397	H04Q 11/04; H04L 12/56	ATM
3	5784369	1998	370/358	H04Q 11/08; H04Q 11/04	Methods and system for switching time-division-multiplexed digital signals of different rates
3	5953330	1999	370/352	H04Q 11/04; H04L 12/56	TSI for data communication
3	6115390	2000	370/443	H04Q 7/22; H04L 12/56	Bandwidth reservation

Following 5 it is possible to control for the assignee of the "important patents". In that context it emerged a change in the type of assignees over time: newcomers from the computer network industry ("Netheads") become more central in the innovation process over time. A similar analysis performed on the assignees of the *startpoints* and *endpoints* listed in the previous table does not give such definitive results. In fact, the distinction between the assignees is more blurred as only two (out of twelve) patents are assigned to "Netheads". However, this result might be spurious because the persistence index can not be calculated for *endpoints*[25], therefore the method might be under representing todays knowledge. In this respect, for this method it seems more appropriate to keep the validation procedure strictly related to the technological contents (and the IPC classes).

The second robustness check controls for the potential correlation between the thickness measure and the time difference. By construction, the width will correlate to time, so higher thickness between patents belonging to different paradigms might be spurious, and simply depend on the "flow of time". This happens because the higher is the time difference between *startpoint* and *endpoint*, the higher is the number of in-between patents and citations, and therefore higher is the thickness. A hint of such correlation is given by the kernel densities displayed in figure 6.9, where for a given number of possible paths the range of width values is limited and increasing (the peak is moving toward the left). This possible bias is controlled in two ways: (i) running regressions between the logarithm of the thickness and the logarithm of the year difference between *startpoint* and endpoint, including also "transition" dummies indicating the type of link in figure 6.10, and (ii) looking at the summary statistics of the residuals for each of the 6 groups.

Table 6.12: Regressions

Variable	Model 1	Model 2	Model 3
$Lnyeardiff$	1.264***	0.88***	0.873***
$group13$		.902***	1.092***
$group12$			0.087
$group22$			0.369
$group23$			0.227
$group33$			0.138
$cons$	-1.747***	-1.086***	-1.256***
N	1275	1275	1275
R^2	.43645034	.51079075	.51145318
$RMSE$	.98978791	.9221963	.92157173

Legend: * p<0.05; ** p<0.01; *** p<0.001

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[25] See section 6.2.1 for the details.

Table 6.12 shows that the time difference is always highly significant and that the only significant dummy is the one about the transition between the two paradigms (group 13). Therefore, this table confirms the presence of a time trend but also a net effect of "transition to a new paradigm" (model 2 and model 3).

In order to control for the time effect, we perform the same analysis as in the previous section, summarizing the residuals by groups of regression 1; in this way all the effect of time difference should be wiped out.

Table 6.13: Descriptive statistics of residuals.

	Obervation	Mean	Std. Dev.	Min	Max
11	38	-0.1972	1.073	-1.835	1.746
12	132	-0.4634	0.8538	-2.674	1.744
13	554	0.3308	1.0379	-2.635	2.332
22	40	0.2608	0.7652	-1.285	1.747
23	405	-0.3088	0.8566	-2.102	1.966
33	106	0.0002	0.7690	-1.589	1.747

As we can expect, the values of displayed are much smaller and less clear cut when one compares within and between groups values. However, group 13 still shows a higher mean. Therefore, the transition between different paradigms (group 13) is the one with the largest width (unexplained by time). This result is statistically significant as the mean of this group is significantly different from that of the rest of the population.

Given these qualitative and quantitative robustness check we are confident about the results for the telecommunication switching industry.

6.5 Conclusion

The accessibility of patents and citations data boosted their use in innovation studies. In particular, scholars have used them for computing several indicators of innovative performance (e.g. simple patent count, citation weighted count, etc.). Recently, a new way to employ them has emerged, which is to consider them from a network perspective. In this setting, a citation represents a knowledge flow connecting the citing and cited patents. However, as patents can only cite earlier patents, the resulting network is directed and acyclical. These characteristics make such networks difficult to analyze using the standard tools of social network analysis that (mostly) assume symmetric relations. Therefore, the aim of this chapter was to propose an empirical method for the analysis of patent citation networks, and to apply it to the telecommunication switching industry.

Ultimately, the method proposed is inspired by population genetics: as geneticists are interested in studying patterns of migration and therefore the common origins of people, in innovation studies we are interested in tracing the origin and the evolution of today knowledge. In this respect, the genetic parallel is rather clear: as patent A cites patent B we can say that patent A inherits some knowledge from patent B. The persistence index introduced in this chapter measures how much knowledge from older patents is retained (and therefore persists) into the recent patents (technically *endpoints*). The persistence index is computed applying the Mendelian law of genetic inheritance for calculating how much knowledge disclosed in a patent is spread and retained in its descendant patents. It follows that this index constitutes the basis for identifying important patents and links. In this framework the novelty of a patent derives from the recombination of inherited knowledge. The citation structure between persistent patents represents both the scope of the underpinning knowledge and of the exploration of the technological space. Therefore it carries information on the scope of the recombined knowledge and on the radicalness of the inventive step.

These indicators are applied to the telecommunication switching industry and the results are validated through a qualitative analysis carried out by reading the patents and, when necessary, comparing the results with the ones obtained using the Hummon and Doreian approach (see chapter 5). Summarizing we can conclude that:

1. There are two fields of empirical analysis dealing with patent citation networks: complex systems analysis and innovation studies. The first one uses sophisticated mechanical statistics for studying network structure and dynamics. However, most of their hypothesis are “neutral” and focus the similarities between natural and human complex systems. Therefore, they do not add much to our understanding of technology dynamics. The second one includes a few recent studies using the HDA taken from bibliometrics, therefore meant to study publication networks;

2. Publications and patents share several similarities in term of network properties, however, they are used for studying different topics (dynamics of science vs dynamic of technology). Given the availability and accessibility of both patent (and citation) data and software for network analysis, a development of new indicators meant specifically for technology evolution has become more accessible. A patent citation network can be conceived as the space of “technologically possible solutions”. Therefore, the possibility to analyze its structure and dynamics sheds some light on technology evolution and its dynamics.

3. The method proposed is successful in reducing the number of both nodes and links considered. This reduction might look arbitrary as it is based on cut-off points. However, both indicators (persistence and thickness index) display a highly left-skewed distribution that mimics a scale-free distribution. This makes easier to justify cut off choices and confirm the idea that few patents are “important”, both in terms of economic value, but also in terms of knowledge contribution.

4. Confirming our hypothesis, patents belonging to different paradigms displays a statistically significantly higher level of thickness measure, indicating that several technological alternative solutions (i.e. paths) are explored by the establishment of the new paradigm.

5. Our method is indeed successful in clustering patents according to different paradigms. Patents linked by very thick connections (and therefore recombining a wide spectrum of knowledge) display technological differences. This emerges from the reading of those patents and from the analysis of their IPC technological classification. Furthermore, we can notice how recent patents cover a technology which at service level (i.e. in term of voice and data transmission) simply expands the previous one. Early patents focus on voice transmission with a limited interest in data transmission; recent patents use a different technology for coping efficiently with both services.

6. The operationalisation of the persistence indexes is (necessarily) based on assumptions. The use of the Mendelian laws for measuring inherited knowledge implies the assumption that the innovative step in each patent is in the recombination of existing knowledge (i.e. inherited by the previous patents). From this perspective the patent network represents a system of both knowledge creation and retention. Furthermore, through the use of the thickness measure we are able to assess the diversification of the knowledge recombined and of the search strategy applied.

7. Differently from other network studies, in this chapter we do not make any assumption about optimality or efficiency structure. The exercise is about trying to unfold patterns of technological change studying the structure and the evolution of the persistent network.

8. The last remark regards the relation between the genetic approach (GA) and the Hummon and Doreian approach (HDA). Although they both aim to identify important flows of knowledge, they have a complete different rationale. This emerges also from the comparison of the results, which partially overlap. However it clearly emerges that the plain use of direct links can overestimate the degree of cumulativeness of a patent citation network.

Part IV

Conclusions

Chapter 7

Conclusions and future lines of research

7.1 Focus and approach

The rejection of the linear model of innovation does not call for a new representative model of technological change but rather for the recognition of its heterogeneity. Unlike the orthodox approach, the evolutionary approach acknowledges this feature, and therefore, stresses the importance of coupling quantitative and qualitative studies for understanding how new technologies emerge. In fact, the recognition of the dynamic nature of a phenomenon is not *per se* informative about how it takes place, as different dynamics can be involved. For instance, the emergence of technological bottlenecks can jeopardize and slowdown the innovation process.

In this respect, the technological paradigms and trajectories framework is helpful in characterizing these dynamics (Dosi, 1982). If technological change results from the "problem solving activities" carried out by engineers, the proposed solutions emerge from their technical (and cognitive) *shared* background. In particular, according to the definition, the technological paradigm sets the boundaries of all the technically possible solutions, whereas technological trajectories comprise the ones selected and implemented. Ultimately, the analysis of such trajectories shows the underlying selection mechanism. Accordingly, in the first place, this theoretical framework highlights the local, incremental, cumulative and irreversible nature of technological change, and suggests the existence of a technology *inner dynamics* interacting with market dynamics (Dosi, 1988*b*). In the second place, and in adherence to the philosophical parallel, this approach characterizes technology evolution as a sequence of "normal periods" disrupted by "revolutionary periods" characterized by a paradigmatic change.

From a dynamic perspective, technological paradigms or trajectories are related to the extent of the inventive step, where a paradigmatic change represents a radical change affecting the underlying cognitive domain, and technological trajectories represent an incremental and gradual refinement within the existing paradigm. It is worth pointing out that linking paradigmatic shifts to radical changes and technological trajectories to incremental ones places emphasis on the differences involved in the two processes, and does not undermine the relevance of the latter. On the contrary, the literature has often stressed the importance of incremental adjustments for the success of a radical innovation (Silverberg and Verspagen, 2005; Verspagen, 2007).

Following what was said above, technological progress can be "normal" or "disruptive" involving different level of uncertainty and therefore of technological opportunities. In case of "revolutionary periods", when a paradigmatic change takes place, the technological space is reshaped and the way engineers explore it (i.e. engineering heuristics) changes (Vincenti, 1990). The absence of established heuristics implies some "search around" for new possibilities, and therefore more uncertainty derived from the exploration of a larger portion of technological space. Using concepts taken from a different field, organizational learning, we can say that a "revolutionary period" consists of exploration of different heuristics, whereas, a "normal period" is characterized by the exploitation of existing ones (March, 1991). In a nutshell, a paradigmatic change introduces a discontinuity that breaks up the (otherwise) continuous and cumulative chain of existing technological trajectories.

From the previous pages it emerges that looking at the way the technological space is explored it is possible to assess the extent of cumulativeness and detect disruptive paradigmatic changes. Although the theoretical concepts above exposed are clear, the way to operationalize them, and therefore to study technology dynamics empirically, is still a challenge. One of the contributions of this thesis is the analysis of technology dynamics by means of patents in the telecommunication switching industry. In particular, a new conceptualization of knowledge flow and a new empirical method for studying knowledge cumulativeness (and persistence) are proposed. In this thesis, quantitative research is coupled with in-depth qualitative research through the use of secondary sources such as technical literature, technical articles, and patents[1]. In this respect, this methodology accomplishes the suggestion by Sahal (1981*b*; 1981*a*) of departing from both a neoclassical (market-driven) and "Pythagorean" (i.e. based on patent counts) view of technological change, and focus on the investigation of technology *inner dynamics*. Furthermore, the attention on the qualitative analysis of the search strategies applied by engineers (i.e. engineering heuristics) corresponds to taking a "microview" on technological change.

Patents and citations represent a valuable data source about the technological space. In fact, if we adopt a stylized (but still realistic) view on patents and we consider them a collection of "technical problems and newly proposed solutions", they represent the building blocks of a technology. As citations represent a knowledge flow between cited and citing patents, they can be used for building a knowledge network. Furthermore, a patent citation network represents the empirical counterpart of a lattice representation of technological space,

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[1] Please note that the results of analysis in chapter 5 were also extensively discussed in an interview with one of directors of the R&D program for the development of the digital platform at Philips.

with the limit of incorporating only "technologically possible" solutions. It follows that a quantitative analysis of both the structure and dynamics of such networks is informative not only about the radicalness of each inventive step but also about the way the technological space is searched.

The use of patent citation networks is a rather new approach in innovation studies. Those networks tend to be large and dense. Therefore some empirical tools are needed to identify relevant areas. The need for new empirical tools is even more stringent given some structural characteristics of patent citation networks, such as directionality and acyclicity, which makes it difficult (or even meaningless) to use standard social network analysis.

At the state of the art, most of the analysis of patent networks is carried out using bibliometics tools. In fact, publication networks share some of the above-mentioned features and they have been studied already since the 1980s. An example of these bibliometric indicators is the main path analysis proposed by Hummon and Doreian (1989), which allows the identification of the main flow of knowledge within a publication network. The first step of the method is the transformation of the binary patent citation network into a weighted network using connectivity measures. Indicators such as $SPLC$ (*Search Path Link Count*) and $SPNP$ (*Search Path Node Pair*) assign to each citation a value proportional to the number of paths they lie on. It follows that citations with the largest connectivity are the ones linking the largest number of nodes. Secondly, a greedy algorithm selects from each *startpoint* the series of citations with the highest connectivity until reaching an *endpoint.* The resulting network is the so-called network of main paths. Verspagen (2007) applies this method to patent citation networks, adding a final step which is the identification of the top main path. This corresponds to identifying the path whose sum of weights is the highest and therefore finding the path within the network connecting the largest number of patents. Using the metaphor of a river and its tributaries, the top main path corresponds to the path carrying the largest amount of water. The analysis of the top main path highlights the emergence and decline of streams of research, technical solutions, and engineering heuristics. This explicitly links these series of patents (and citations) with the concept of technological trajectories defined by Dosi (1982). The advantage of this approach is the possibility to extract (and use) more information from citations. From a network perspective, a citation count gives a partial view of direct ties. By contrast, a connectivity analysis evaluates patents with respect to all the others and to the knowledge flows within the network. Fontana, Nuvolari and Verspagen (2009) point out the complementarities of these approaches, showing the presence of little-cited patents in the top main path.

The connectivity approach relies on the idea of cumulativess as "integrating knowledge", and the use of a greedy algorithm for the identification of the network of main paths. This puts some limitations on the study of how technological space is explored. In a nutshell, it can identify the area of the network where knowledge flows are more intense, but it ignores the underlying mechanism and it does not make any structural assumption about how a paradigmatic change should appear in a patent citation network.

In this respect, this thesis goes a step further, proposing a new conceptualization of knowledge flows in a patent citation network. The method proposed is inspired by population genetics: as geneticists are interested in studying patterns of migration and therefore the common origins of people, in innovation studies we are interested in tracing the origin and the evolution of “today’s knowledge”. The genetic parallel is rather clear: if patent A cites patent B we can say that patent A inherits some knowledge from patent B. Therefore, by applying the Mendelian law of gene inheritance we are able to compute a persistence index that quantifies how much knowledge disclosed in a patent is spread and retained in its descendant patents. In this framework, the novelty of a patent derives from the recombination of inherited knowledge and the patent network represents a system of both knowledge creation and retention. Furthermore, a second indicator, the thickness measure, is introduced for characterizing the structure of the links among persistent patents. In a very stylized way, two situations can emerge: on the one hand persistent patents might be linked by long and thin links (low level of thickness), on the other by short and thick ones. The first case represents the exploitation of existing heuristics and little “search around”, denoting a highly cumulative process of technological advance. On the other hand, the presence of numerous paths connecting persistent patents denotes the exploration of a larger portion of the technological space, therefore the presence of search for new heuristics.

7.2 Summary of main findings

A key point of the use of patent data for the qualitative analysis above described is the understanding of the engineering heuristics that provide the motion of technological change. In this respect, chapter 2 presents the technical background, describing technology evolution in the telecommunication switching industry. It emerges that telecommunication switches are a complex system whose advances can occur along several technical characteristics. The review of engineering literature allows me to list seven of the “most referred” ones. These are: (i) the switching fabric, (ii) the traffic logic, (iii) the multiplexing technology, (iv) the nature of the end-to-end traffic, (v) the nature of the service traffic, (vi) technical components, and (vii) end user signaling. Furthermore, it emerges that engineers apply the logic of “challenge-and-response” to specific technical bottlenecks (Rosenberg, 1974). Several technologies had a very long gestation before being actually integrated in the switches, showing engineers’ perseverance in their ideas about switching design and how to pursue efficiency. Finally, the account of the technological history shows that from the engineers’ perspective there are seven key technological generations. These are: (i) manual, (ii) electromechanical direct-control, (iii) electromechanical common-control, (iv) Space-division SPC, (v) Time-division digital centralized SPC command, (vi) Time-division digital decentralized SPC command, and (vii) Packet Switching.

Despite the internalistic approach, chapter 2 is not very informative about emergence of new paradigms, as the analysis is confined to a simple narrative of technical bottlenecks, new solutions, and new technologies. Therefore, chapter 5 re-frames the history into the technological paradigms and trajectories approach. This corresponds to classifying the seven switch generations in different paradigms and trajectories over the set of technical characteristics. This aggregation process is carried out by comparing the generations by three specific aspects: (i) the technical skills and competences needed in each generation, (ii) the perceived barriers and the bottlenecks on which engineers were working, and (iii) the dominant engineering heuristics applied. Analyzing the switches generation on the basis of these three aspects, four distinct technological paradigms can be identified. These are summarized in table 7.1, together with their corresponding trajectories.

Table 7.1: Paradigms and trajectories in the telecommunication switches

Time	**Technological Paradigm**	**Trajectories**	**Generations**
1870-1930	Manual	Switchboard	1
1930-1965	Electromechanic	Crossbar - Panel - Lorimer	2-3
1965-1990	Electronic circuit switching	Analogue - Digital Space-division (SDM) - Time-division (TDM) digital *centralized* control - digital *decentralized* control	4-5-6
1990-. . .	Packet Switching	ATM and IP-based switches	7

Note: Time is indicative and refers to the commercialization of the relevant switch generations.
Legend: (1) manual, (2) electromechanical direct-control, (3) electromechanical common-control, (4) space-division SPC, (5) time-division digital centralized SPC command, (6) time-division digital decentralized SPC command, (7) packet switching

The qualitative analysis of the evolution of the top main paths validates the paradigmatic shift from electronic circuit switching to packet switching. In particular, network analysis highlights a sudden change in the direction of technological change occurring in the mid 1990s. The analysis of the technical contents covered in a patent shows a change in the technical problems tackled and in the solutions proposed. This is evident looking at the evolution of expectations about data communication and packet switching. Manufacturers did forecast the upward trend in data communication demand. However, they rejected pure packet switching technologies because of the uncertainty related to a paradigmatic change. This uncertainty was both technological, concerning the lack of efficiency and quality-of-service features, and institutional, concerning changes in the established system of billing and accounting. Therefore, manufacturers focused on the development of a technology that was closer to their own circuit-switched technologies while adapting some selected features of a "real" packet switching technology. The resistence to adopting an external technology (as developed in another industry, data communication) was related not only to the high switching cost but also to the conceptual difference about network infrastructure management implied in the two paradigms. Furthermore, the data not only shows the paradigmatic shifts, but also supports Constant's view (1973) about the differences between scientific and technological paradigmatic shifts. In the telecommunication switching industry a shift took place when an alternative (and better) paradigm existed and its superiority was tested and demonstrated.

In the connectivity approach a radical technological change is classified as paradigmatic through the qualitative analysis of the heuristics contained in the patents. By contrast, as explained in the previous pages, the genetic approach makes structural assumptions about how to detect paradigmatic changes. These assumptions are based on the extent of the exploration of the technological space. Looking at the results in chapter 6, we can conclude that "today's knowledge" descends from a very limited number of persistent patents. Furthermore, confirming the hypothesis, patents belonging to different paradigms display a statistically significantly higher thickness measure. This indicates that several technological alternative solutions (i.e. paths) are explored before the establishment of the new paradigm. The main finding is that indeed both the persistence and thickness measure successfully cluster patents according to different paradigms. In fact, patents linked by very thick connections (and therefore involving a wide exploration of the technological space) covers different technologies belonging to different technological paradigms. This result is further validated by the analysis of the frequencies and differences between the IPC technological classes for early and recent patents.

Ultimately, both chapter 5 and 6 aim at presenting an empirical method for reducing complexity (i.e. the number of nodes and links), although they are based on completely different rationales. In particular, only the latter provides insights about the exploration of the technological space around the persistent patents.

Finally, it is interesting to note that the methods discussed in this thesis define paradigmatic changes (and therefore radical changes) by looking at the characteristics of the underpinning knowledge, rather than performance improvements. This is particularly useful in cases where it is difficult to elaborate and compare technological performance measures, or, where designs with different service characteristics co-exist. This is clearly the case of the telecommunication switching industry where both high levels of technological uncertainty (e.g. the uncertainty about future development and prices of microprocessors) and users with different infrastructural legacy brought about the co-existence of highly diversified designs.

The second contribution of this thesis is to provide an account of the *structural evolution* of the telecommunication switching industry. Therefore, we move the attention from the technology to the industry level. One of the main results of evolutionary economics is to explain the link between technology (and more precisely the "technological regimes") and industrial dynamics. In particular, this link is twofold: on the one hand, the knowledge-base of a technology defines the boundaries of an industry (Balconi, 1993); on the other hand, patterns of entry, concentration and stability are considered endogenous and depend on technology characteristics such as its knowledge base and extent of cumulativeness (Breschi et al., 2000). Finally, according to the evolutionary framework, technology and industry should co-evolve, reciprocally influencing each other. The rigorous and robust econometric analysis of co-evolutionary process represents a challenge for evolutionary economists. In fact, given all the relevant aspects, all their possible links, and directions of causality, it becomes difficult to put forward testable hypothesis. In this thesis, we are going to quantitively examine a specific aspect of co-evolution, focussing on firm's innovative behavior and performance. For this reason, the results obtained using the patent citation analysis will be also discussed from the assignee (i.e. firm) perspective and interpreted using the detailed account of firms' history presented in section 4.3.

Chapter 4 describes an industry with a slow dynamics, rooted in a slow process of innovation and adoption. This oligopolistic market shows a rather stable demography, despite the emergence of several waves of radical technological change. The entry of newcomers was blocked by the presence of both technical and institutional barriers to entry. Technical barriers relate to the complex system nature of telecommunication switches and the high R&D costs. The institutional barriers emerge not only from the manufactures but also from other relevant actors such as the network operators (which deployed the switches in their networks) and "the government[2]". From the systematic account in chapter 4 it emerges that protectionist policies for national companies, subsidies, public procurement policies, and pricing policies, strongly affected not only the possibility of entry for new companies but also the level of competition in the individual domestic markets. This seems to change with the emergence of the packet switching paradigm when we observe the (lateral) entry of companies active in data communication and changes in incumbents' innovative performance. In particular, the analysis of the assignees for the patents belonging to the technological trajectories shows the presence of new entrants in the part related to packet switching. The concentration of new entrants on the new paradigms confirms the presence of differences in incumbents and new entrants' technological preferences (Antonelli, 1995). Incumbents willing to exploit their legacy and capabilities tend to favor centripetal technologies that enhance the relevance of existing economies of scale, scope and density. Furthermore they simply try to adapt existing technologies to new developments. Instead, new entrants call for centrifugal technologies where specialized technologies reduce the role of inter-functional economies of scope and segmental technologies that reduce the role of network externalities (Antonelli, 1999).

Finally, the account of the *structural evolution* also entails the analysis of the evolution of firm competences. In the case under examination this is particularly interesting because of the limited number of players descending from four companies founded in the early 1900s.

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[2] The government is between inverted commas because it indicates a generic *government-related entity*. Depending on the specific case, it can be the Ministry of Telecommunications, or the Ministry of Industry or the Regulatory Agency, etc.

Despite these common roots, firms are rather heterogeneous in term of degree of internationalization and degree of telephony specialization over time. Incumbents shows an heterogeneous innovative persormance. Some firms (i.e. Lucent and ITT) lead both in terms of the relevance of their knowledge base and in term of their “net contribution" to the knowledge network. Alcatel and the Japanese manufacturers show the tendency to get closer to the relevant knowledge (i.e. the technological trajectory) but this happens because the acquisition of external knowledge. Comparing the market and innovative performance, it appears that technological advantage does not secure survival in the telecom switching industry. Other factors, such as strong political intervention (like in France) or a committed network operator (like in Japan) are of pivotal importance for the long run success.

In particular there is some evidence about the relation between drops-out and specialization. In fact, all the companies leaving the market after the emergence of the time-division SPC switches were not specialized in telecommunication switching. It seems that the slow dynamics of technology and profitability (Antonelli, 1991) require some “foresight” and financial long-term planning that non-specialized firms might lack. The major implication is that technological advantage does not secure survival in the telecom switching industry. Other factors like strong political intervention (like in France) or a committed network operator (like in Japan) are of pivotal importance for the long run success.

7.3 Future lines of research

As a final step of this thesis we will discuss future lines of research. Following the structure of this thesis we can suggest two lines of research: the first one primarily focusing on industrial dynamics, and the second one on patent citation networks.

In the empirical part of this thesis we analyze patents. However, as each patent is generally assigned to a company, there is the possibility of analyzing a patent citation network from a firm perspective. In a nutshell, if a patent citation network represents the technological space, there already exists a “natural” way to link the technological level to the firm level. This means the possibility to study in a straightforward way a firm’s position in the technological space. Just as an example, it might be meaningful to quantify a firm’s centrality in the technological space, its distance from the technological trajectories, or the total persistence of a firm’s patent portfolio. These exercises are purely empirical, but, through a theoretical research effort it would be possible to link them to the concept of technological regimes. In fact, patent citation networks might represent the opportunity to develop more systematic empirical research about technology characteristics, and therefore to enlarge the empirical characterization of technological regimes. Furthermore, it would be possible to put forward new technology indicators and to discuss (and test) their link to Schumpeterian patterns of innovation.

The same indicators might be used for the investigation of the determinants of firm performance. Since the seminal work by Zvi Griliches (1981), scholars started building a consistent bulk of empirical evidence supporting the idea that intangible assets, and in particular knowledge stock, has a significant positive impact on both firm market value and productivity. Over the years, with the availability of more data, measurements of knowledge stock have been refined. In particular, the inclusion of citations has allowed researches to include a control for the quality of firm knowledge stock. In particular it emerges that if on the one hand citations do not add explanatory power to an econometric model that includes R&D expenditure, on the other hand the size of their coefficient makes them a very strong regressor (Hall et al., 2005). Recently the attempt to improve the explanatory power of the variable knowledge stock has moved in different direction, to focus on technological characteristics. For instance, Nesta and Saviotti (2005) claim that knowledge does not constitute a valuable asset for its own sake but it needs to be *coherent* knowledge, where coherence is defined as the extent of relatedness and integration of firm's knowledge base. In this sense, they refine the concept of stock of knowledge indicating a specific characteristic (in this case relatedness) that impacts firm's performance. This corresponds to moving from a concept of absolute value of the knowledge stock to a relative one: the value of an additional piece of knowledge depends on the existing firm's knowledge stock. Therefore, it becomes even more clear how idiosyncratic is the acquisition of new technological competences. In this spirit, the indicators derived from patent citation network could be used as complementary to the usual ones, as they would better characterize a firm's technological competences in the industry technological space.

A more specific line of research regards the case study of the telecommunication switching industry. The empirical analysis of this thesis focuses on technology *inner dynamics* leaving unresearched its link to market dynamics. Following the work of some technology historians about the slow response of engineers to market changes (Constant, 1973), it would be interesting to investigate (and quantify) how slowly they adapt, and what conditions might affect this process. Therefore, a natural line of research would be the possibility of studying market and technology dynamics at work. This type of research would naturally contribute to the reconciliation between "technology push" and "demand pull" approaches (Freeman, 1994), but even more important it would help to explain the process of technology selection. In fact, if on the one hand it appears that the evolutionary approach has paid lot of attention to the "mutation side", which is the generation of novelty (at various levels, but in this work we refer to the heuristics level), on the other the "selection side" has been understudied. In this respect, we have to point out that patents data are available for "failures". For instance, in the case of telecommunication switches, we found the declining technology related to ATM switches, a platform that reached the market but was quickly abandoned. This means it is possible to identify in the patent citation network areas of technically possible but unsuccessful solutions.

Regarding the second domain of research, the analysis of patent citation networks, we have to point out that it is still a rather uncharted field, offering several research opportunities both at theoretical and empirical level. Furthermore, the availability of both patent data and free software make this line of research rather attractive: the "barrier to entry" for this type of analysis is the construction of a relevant dataset. In this respect, there are several strategies (e.g. technological classes, keywords, assignees), but, there is no single exclusive right way to do it. Therefore it is important to access technical knowledge in order to build meaningful samples. Furthermore, this raises related questions about whether to use the European or the American database, or to focus on patent families.

The first opportunity in this line of research regards the deepening and widening of the method proposed in this thesis. In fact, it would be interesting to apply the genetic approach to other technologies, in order to further explore the properties of the indicators used. In the second place, it would be possible to refine the analysis of both the persistence and thickness index. In chapter 6 we discussed the genetic metaphor and, despite the similarities of the research questions, we pointed out the impossibility of using the same empirical tools. However, it would be possible to improve the analysis by finding new ways to assess patent similarity depending on the genetic decomposition. Ultimately, the comparison of genetic decomposition between ancestors and descendants should unfold recognizable patterns of technological change. For instance, in the case of parallel development of technologies we would expect patents not to share any ancestors or descendants.

In general, any indicator based on patent citation networks and characterizing technology (or its dynamic) can be used for explaining higher-level phenomena. In a nutshell, the technological space (i.e. the patent citation network) represents a very micro level of analysis, so, it is possible to imagine research studying the link between this technological level and any other. In the previous paragraph, we discussed the possibility of using these concepts for explaining firms' success, but the same reasoning can be applied for regional or country growth.

Furthermore, it would be possible to contribute to the line of research on characteristics of academic patents. In fact, some scholars claim that the inventions disclosed in patents developed at the university are more basic than corporate patents (Czarnitzki, Hussinger and Schneider, 2009). These claims could be investigated from a network perspective, and using the persistence index it would be possible to assess (and compare) the impulse to future inventions of both corporate and academic patents.

The second line of research regards the validation of the statement that persistent patents are important. As we discussed in section 5.2, the use of patent data has some drawbacks, above all, the lack of information about the economic value of a patent. This information is not only important for itself, but also crucial in discriminating inventions from innovations. In the years, scholars have found ways to correct for this and we know that the number of citation, the number of claims, and the renewal fees can proxy such economic value (Griliches, 1991; Gambardella et al., 2008). The "importance" we discuss in this thesis is different: we refer to technological importance related to a patent's position in the network and its global citation structure (i.e. the contribution of a patent to future knowledge). However, as we could expect, economic and technological importance are indeed correlated (Barberá-Tomás, Gutierrez-Gracia, Jiménez-Sáez and Castelló-Molina, 2009). In this respect, we can imagine several research designs, such as the possibility of running a survey similar to PATVAL for the patents included in the sample, and to ask inventors retrospectively about the economic value of their patents. Or, it would be interesting to organize a survey of both engineers and managers in order to investigate the relation between economic and technological importance. Furthermore, the notion of technological importance might contribute to the field of IPR management, providing a way to detect fundamental patents, their contribution to problem-solving, and the identification of close patents and technolgies.

Moving to a different (empirical) field, a third line of research would be the study of the distribution of the connectivity and genetic indexes. The graphs displayed in appendix F show a positively skewed distribution of the persistence index at all truncations. This is consistent with the general finding that few patents are important/valuable. However, this calls for further exploration. In particular, first, it would be interesting to see whether this type of distribution is industry specific and therefore to look at their distribution for different technologies, secondly, to look at their evolution over time, and finally, to explore possible empirical regularities. This type of research has some similarities with the study of empirical regularities in complex networks. In fact, several complex networks (of which a patent citation network is an example) show the same property, which is the power distribution of number of links. In the case of patents, this means that a small number of patents have most of the forward citations, whereas the large majority has just few.

The lines of research suggested above are purely empirical and they are not about understanding the organizing principle of network dynamics. By contrast, researchers in the field of complex systems have studied the underlying dynamics able to generate a scale-free distribution of forward citations (Valverde et al., 2007). In particular, they propose a modification of the famous "preferential attachment" proposed by Barabási and Albert (1999; 2002), where a patent's probability of being cited depends not only on the number of current citations but also on the age of the patent. In a similar fashion, it would be interesting to root patent citation network structural characteristics to technological change. This would correspond to developing a new theory about how different processes of technological changes are reflected and represented in the patent citation network.

Part V

Appendix

Appendix A

Technological classes

Cat. Code	Category Name	Code	Sub-Category	Name Patent Classes
1	Chemical	11	Agriculture, Food, Textiles	8, 19, 71, 127, 442, 504,
		12	Coating	106,118, 401, 427
		13	Gas	48, 55, 95, 96
		14	Organic Compounds	534, 536, 540, 544, 546, 548, 549, 552, 554, 556, 558, 560, 562, 564, 568, 570
		15	Resins	520, 521, 522, 523, 524, 525,526, 527, 528, 530
		19	Miscellaneous-chemical	23, 34, 44, 102, 117, 149, 156, 159, 162, 196, 201, 202, 203, 204, 205, 208, 210, 216, 222, 252, 260, 261, 349, 366, 416, 422, 423, 430, 436, 494, 501, 502, 510, 512, 516, 518, 585,588

Cat. Code	Category Name	Code	Sub-Category	Name Patent Classes
2	Computers and Communications	21	Communications	178, 333, 340, 342, 343, 358, 367, 370, 375, 379, 385, 455
		212	Telephony	370, 375, 379, 398
		22	Computer Hardware and Software	341, 380, 382, 395, 700, 701, 702, 704, 705, 706, 707, 708, 709, 710, 712, 713, 714
		23	Computer Peripherals	345, 347
		24	Information Storage	360, 365, 369, 711
3	Drugs and Medical	31	Drugs	424, 514
		32	Surgery and Medical Instruments	128, 600, 601, 602, 604, 606, 607
		33	Biotechnology	435, 800
		39	Miscellaneous-Drug&Med	351, 433, 623
4	Electrical and Electronic	41	Electrical Devices	174, 200, 327, 329, 330, 331, 332, 334, 335, 336, 337, 338, 392, 439
		42	Electrical Lighting	313, 314, 315, 362, 372, 445
		43	Measuring and Testing	73, 324, 356, 374
		44	Nuclear and X-rays	250, 376, 378
		45	Power Systems	60, 136, 290, 310, 318, 320, 322, 323, 361, 363, 388, 429
		46	Semiconductor Devices	257, 326, 438, 505
		49	Miscellaneous-Elec.	191, 218, 219, 307, 346, 348, 377, 381, 386
5	Mechanical	51	Material Processing and Handling	65, 82, 83, 125, 141, 142, 144, 173, 209, 221, 225, 226, 234, 241, 242, 264, 271, 407, 408, 409, 414, 425, 451, 493
		52	Metal Work	29, 72, 75, 76, 140, 147, 148, 163, 164, 228, 266, 270, 413, 419, 420

Cat. Code	Category Name	Code	Sub-Category	Name Patent Classes
5	Mechanical	53	Motors, Engines and Parts	91, 92, 123, 185, 188, 192, 251, 303, 415, 417, 418, 464, 474, 475, 476, 477
		54	Optics	352, 353, 355, 359, 396, 399
		55	Transportation	104, 105, 114, 152, 180, 187, 213, 238, 244, 246, 258, 280, 293, 295, 296, 298, 301, 305, 410, 440
		59	Miscellaneous-Mechanical	7, 16, 42, 49, 51, 74, 81, 86, 89, 100, 124, 157, 184, 193, 194, 198, 212, 227, 235, 239, 254, 267, 291, 294, 384, 400, 402, 406, 411, 453, 454, 470, 482, 483, 492, 508
6	Others	61	Agriculture, Husbandry, Food	43, 47, 56, 99, 111, 119, 131, 426, 449, 452, 460
		62	Amusement Devices	273, 446, 463, 472, 473
		63	Apparel and Textile	2, 12, 24, 26, 28, 36, 38, 57, 66, 68, 69, 79, 87, 112, 139, 223, 450
		64	Earth Working	37, 166, 171, 172, 175, 299, 405, 507
		65	Furniture, House Fixtures	4, 5, 30, 70, 132, 182, 211, 256, 297, 312
		66	Heating	110, 122, 126, 165, 237, 373, 431, 432
		67	Pipes and Joints	138, 277, 285, 403,
		68	Receptacles	53, 206, 215, 217, 220, 224, 229, 232, 383
		69	Miscellaneous-Others	1, 14, 15, 27, 33, 40, 52, 54, 59, 62, 63, 84, 101, 108, 109, 116, 134, 135, 137, 150, 160, 168, 169, 177, 181, 186, 190, 199, 231, 236, 245, 248, 249, 269, 276, 278, 279, 281, 283, 289, 292, 300, 368, 404, 412, 428, 434, 441, 462, 503

Appendix B

List of patents in the top main paths

Patent	Year	Assignee	1924-1979	1924-1984	1924-1989	1924-1994	1924-1999	1924-2003
2754367	1956	GEC	x	x	x	x	x	x
2773934	1956	Dynamics Corporation	x	x	x	x	x	x
2917583	1959	Lucent	x	x	x	x	x	x
3049593	1962	ITT	x	x	x	x	x	x
3172956	1965	Lucent	x	x	x	x	x	x
3458659	1969	Northtel	x	x	x	x	x	x
3461242	1969	Lucent						x
3632883	1972	US Phillips	x					
3737586	1973	Lucent	x					
3649763	1972	Lucent		x	x	x	x	x
3736381	1973	Lucent		x	x	x	x	x
3851105	1974	ITT	x	x	x	x	x	x
3974340	1976	Ericsson	x	x	x	x	x	x
4074072	1978	Lucent	x	x	x	x	x	x
4112258E	1978	Lucent	x					
4144407E	1979	Olivetti	x					
4160127E	1979	Lucent	x	x	x	x		
4164627E	1979	ITT	x					
4254498	1981	NTT		x				
4382294	1983	Lucent			x	x		
4402074	1983	Alcatel		x				
4485467E	1984	Infoswitch		x				
4480330E	1984	GTE		x				
4466095E	1984	Fujistu		x				
4400627E	1983	Lucent		x				

Patent	Year	Assignee	1924-1979	1924-1984	1924-1989	1924-1994	1924-1999	1924-2003
4484323E	1984	Lucent		x	x	x		
4521880	1985	Lucent			x			
4644529	1987	GTE			x			
4771419E	1988	Northtel			x			
4862451E	1989	IBM			x			
4644535	1987	Data General Corp.				x		
4967405	1990	TranSwitch				x		
5134614	1992	Alcatel				x		
5265090	1993	Alcatel				x		
5323390E	1994	Lucent				x		
5257261E	1993	TranSwitch						
4201891	1980	ITT					x	x
4451827	1984	Johns Hopkins University					x	x
4603416	1986	Individually owned					x	x
4782478	1988	Lucent					x	x
4956839	1990	Hitachi					x	x
5062106	1991	Kokusai					x	x
5233606	1993	Lucent					x	x
5345446	1994	Lucent					x	x
5422882	1995	Lucent					x	
5483527	1996	Lucent					x	
5623491	1997	DSC Communications					x	
5894477E	1999	Northtel					x	
5889773E	1999	Alcatel					x	
6002689E	1999	Alcatel					x	
5390175	1995	Lucent						x
5790806	1998	Scientific-Atlanta						x
5953344	1999	Lucent						x
6115390	2000	Lucent						x
6310886	2001	TiVo Inc						x
6377548E	2002	Malibu Networks						x
6452915	2002	Malibu Networks						x
6628629	2003	Malibu Networks						x
6272129	2001	3M Communication						x
6400711E	2002	Vertical Networks, Inc.						x

Appendix C

Ranking of most cited patents

1924-1979		1924-1984		1924-1989	
Patent	Citations	Patent	Citations	Patent	Citations
3458659	38	3458659	39	4063220	50
3263030	17	3597549	22	3458659	39
3715505	15	3956593	21	4322843	33
3597549	14	4063220	20	4251880	26
3736381	14	3263030	19	3956593	26
3678205	14	3678205	18	3597549	24
3529089	13	3715505	17	4154983	24
3597548	13	3736381	16	4161786	22
2917583	13	3529089	15	3851104	22
3544976	13	3597548	15	3678205	21

1924-1994		1924-1999		1924-2003	
Patent	Citations	Patent	Citations	Patent	Citations
4063220	54	4063220	56	4063220	57
3458659	39	3458659	39	3458659	39
4322843	38	4322843	38	4322843	38
3956593	28	4706121	34	4706121	35
4251880	26	3956593	30	4751578	31
4161786	26	4751578	30	4967405	30
3988545	25	4977455	29	3956593	30
4154983	24	3988545	28	4977455	30
3597549	24	4603416	28	4603416	29
3851104	23	4967405	27	3988545	28

Appendix D

List of "Important patents" using the genetic decomposition

Number	Issue year	Primary class	Secondary class	*Persistence index*
3458659	1969	370	370	1
3632883	1972	370	368	1
3736381	1973	370	370	1
2773934	1956	0	0	1
2917583	1959	0	0	1
3049593	1962	0	0	1
3172956	1965	370	376	1
3818142	1974	370	370	1
3975712	1976	714	800	1
4093823	1978	370	535	1
4229792	1980	370	447	1
4332027	1982	370	448	1
4412326	1983	370	448	1
4641304	1987	370	447	1
4773065	1988	370	362	1
4941141	1990	370	376	1
5012469	1991	370	322	1
5093827	1992	370	354	1
5214642	1993	370	471	1
5345446	1994	370	358	1
5390175	1995	370	398	1
5790806	1998	709	252	1

Continued on next page

Table D.1 – continued from previous page

Number	Issue year	Primary class	Secondary class	*Persistence index*
5953344	1999	370	443	1
6115390	2000	370	443	1
6272129	2001	370	356	1
4096355	1978	370	458	0.998
4074072	1978	370	388	0.994
5101404	1992	370	398	0.966
3761894	1973	710	53	0.924
4727536	1988	370	468	0.859
5467342	1995	370	253	0.815
4251880	1981	370	468	0.804
4759010	1988	370	379	0.804
5161152	1992	370	463	0.797
3737586	1973	370	370	0.788
4245341	1981	370	535	0.785
5303234	1994	370	442	0.774
5142532	1992	370	432	0.768
3770897	1973	370	510	0.758
3456242	1969	709	251	0.739
3694580	1972	370	371	0.728
4658152	1987	370	535	0.717
4556972	1985	370	354	0.705
3796835	1974	370	355	0.691
5327428	1994	370	353	0.682
5570355	1996	370	352	0.676
4736371	1988	370	236	0.675
4482999	1984	370	452	0.661
5894477	1999	370	353	0.652
3649763	1972	370	372	0.650
4312065	1982	370	230	0.650
4408323	1983	370	389	0.650
3854011	1974	370	510	0.645
5953330	1999	370	352	0.643
5005171	1991	370	522	0.640
3740480	1973	370	370	0.633
4763319	1988	370	397	0.623
5355362	1994	370	222	0.618
4488288	1984	370	393	0.607
5428608	1995	370	261	0.594

Continued on next page

Table D.1 – continued from previous page

Number	Issue year	Primary class	Secondary class	*Persistence index*
5623491	1997	370	397	0.593
4852089	1989	370	468	0.571
5384777	1995	370	337	0.568
4063220	1977	340	825	0.563
5351236	1994	370	358	0.563
5982767	1999	370	352	0.555
5233606	1993	370	418	0.550
4621357	1986	370	370	0.549
5276678	1994	370	267	0.539
3974340	1976	370	228	0.536
5144619	1992	370	353	0.526
5295140	1994	370	443	0.525
4679190	1987	370	355	0.523
4543574	1985	340	825	0.522
3766322	1973	370	422	0.519
4764921	1988	370	510	0.515
4947388	1990	370	411	0.512
2754367	1956	0	0	0.509
5784369	1998	370	358	0.500
5384777	1995	370	337	0.568
4063220	1977	340	825	0.563
5351236	1994	370	358	0.563
5982767	1999	370	352	0.555
5233606	1993	370	418	0.550
4621357	1986	370	370	0.549
5276678	1994	370	267	0.539
3974340	1976	370	228	0.536
5144619	1992	370	353	0.526
5295140	1994	370	443	0.525
4679190	1987	370	355	0.523
4543574	1985	340	825	0.522
3766322	1973	370	422	0.519
4764921	1988	370	510	0.515
4947388	1990	370	411	0.512
2754367	1956	0	0	0.509
5784369	1998	370	358	0.500

Appendix E

Average number of IPC classes.

In order to make some claims about the high number of IPC classes of the *endpoints* displayed in table 6.11, we need to compare them with the average number of IPC class in a larger but comparable set. The newly released NBER patent dataset allows to count how many IPC classes a patent is assigned to. Class H corresponds to “Electricity”, therefore it is (by far) the relevant subsample for the set used in this work.

Table E.1 displays the evolution over time of the number of classes and it shows how little is the variation. Given the fact that minimum number of IPC classes assigned to the *endpoints* under consideration is three (and the maximum seven), we can conclude that the number of classes in the extracted subsample is larger than the average observed in a comparable sample.

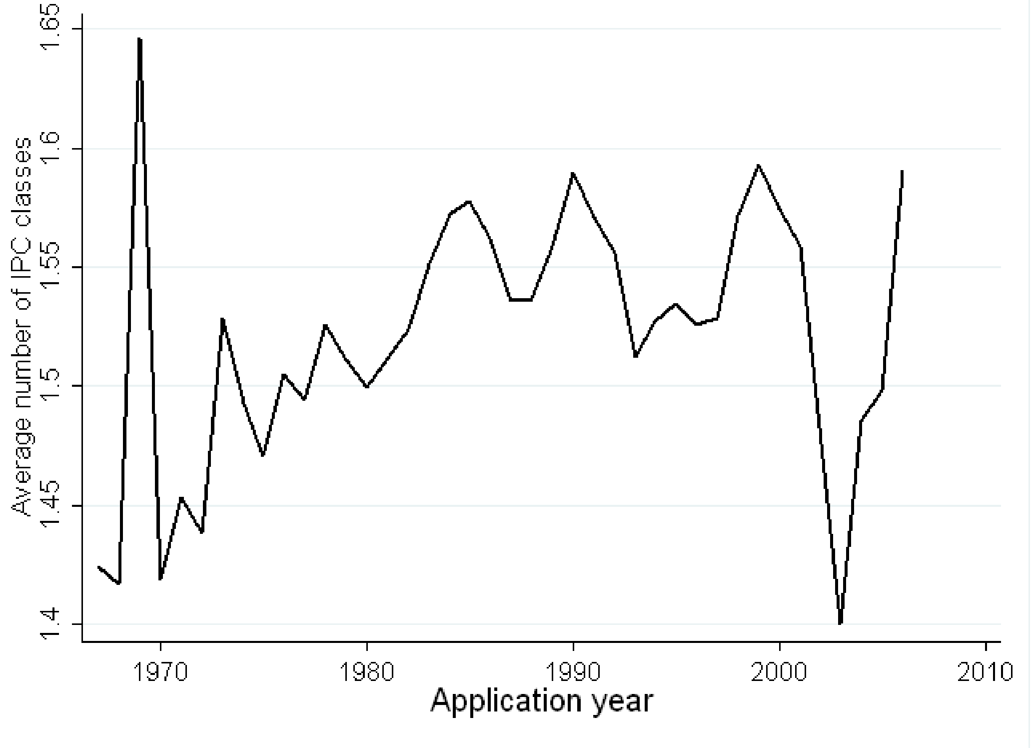

Figure E.1: Frequencies of the logarithm of width

Appendix F

Appendix: Distribution of the *persistence index*

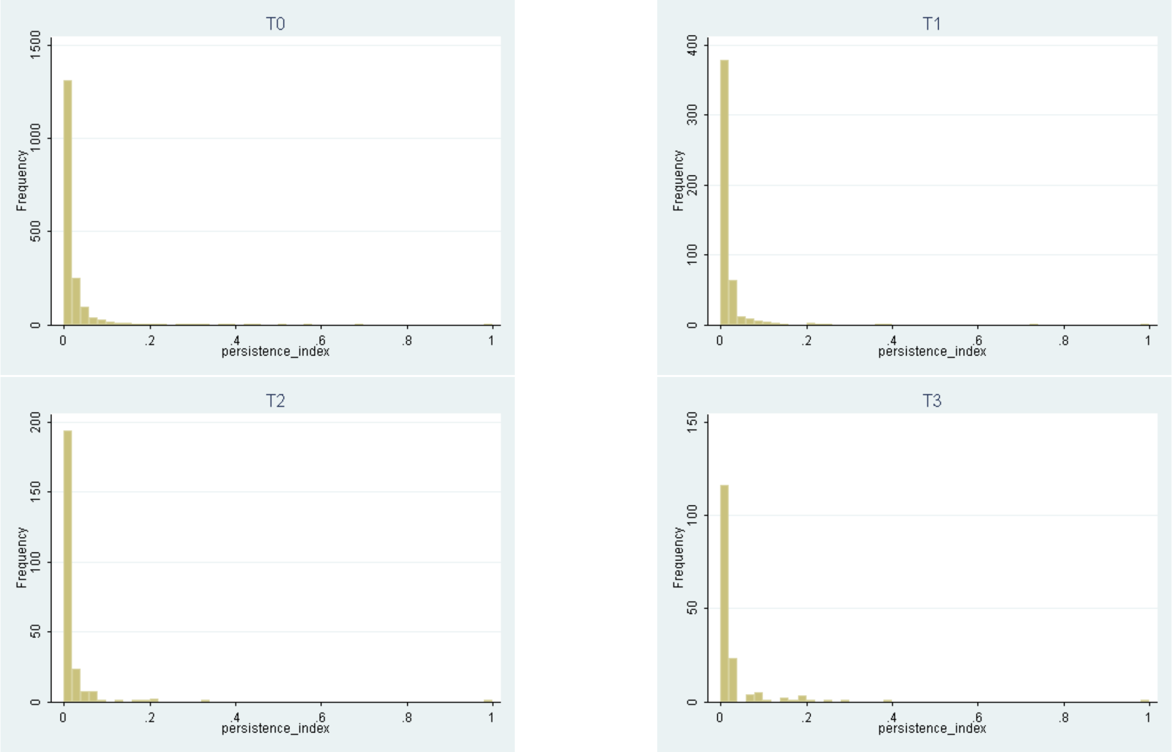

Figure F.1: Histogram of the frequency distribution of the persistence index for the first 8 truncations.

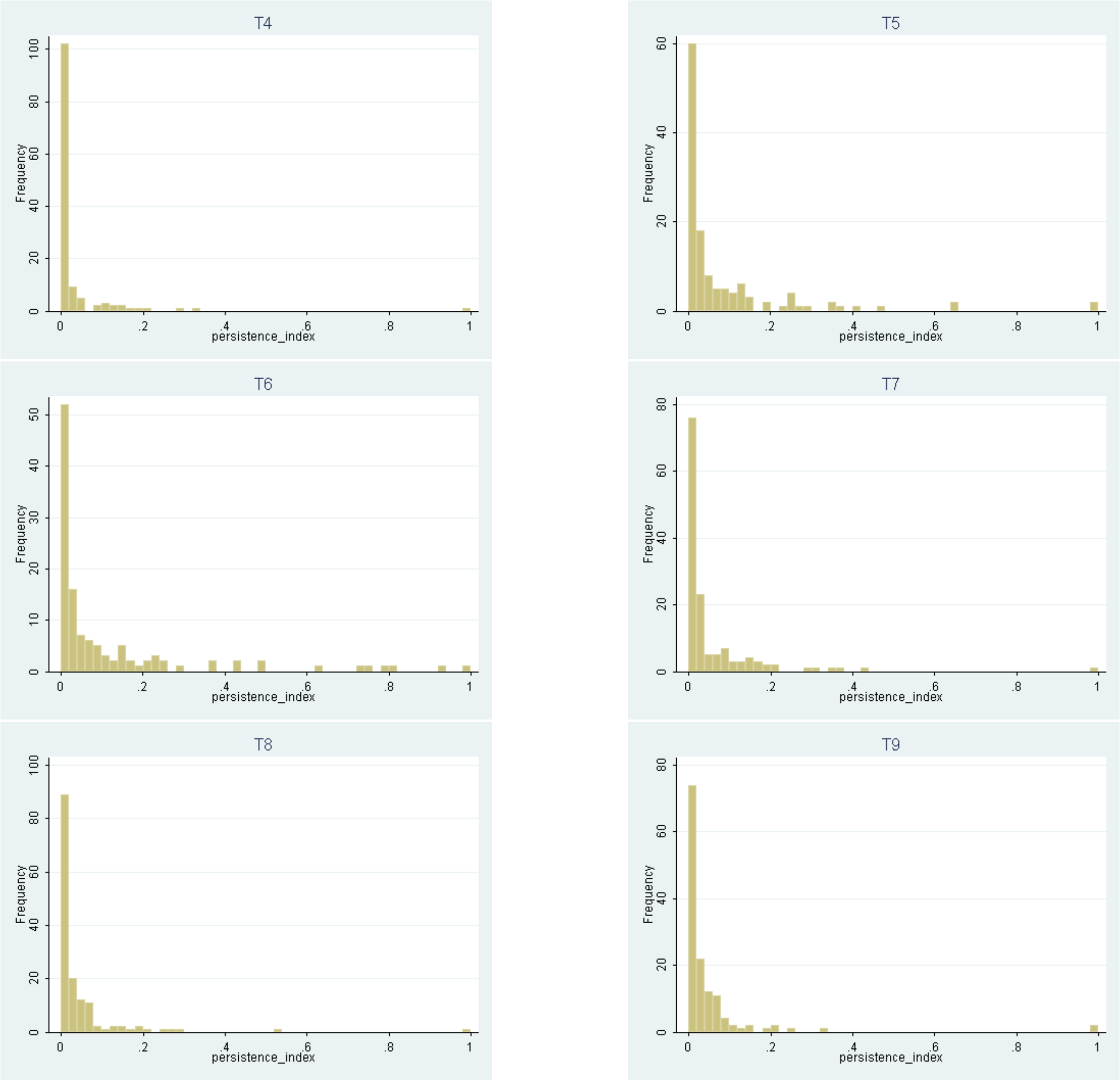

Figure F.2: Histogram of the frequency distribution of the persistence index for the second 8 truncations - Continued

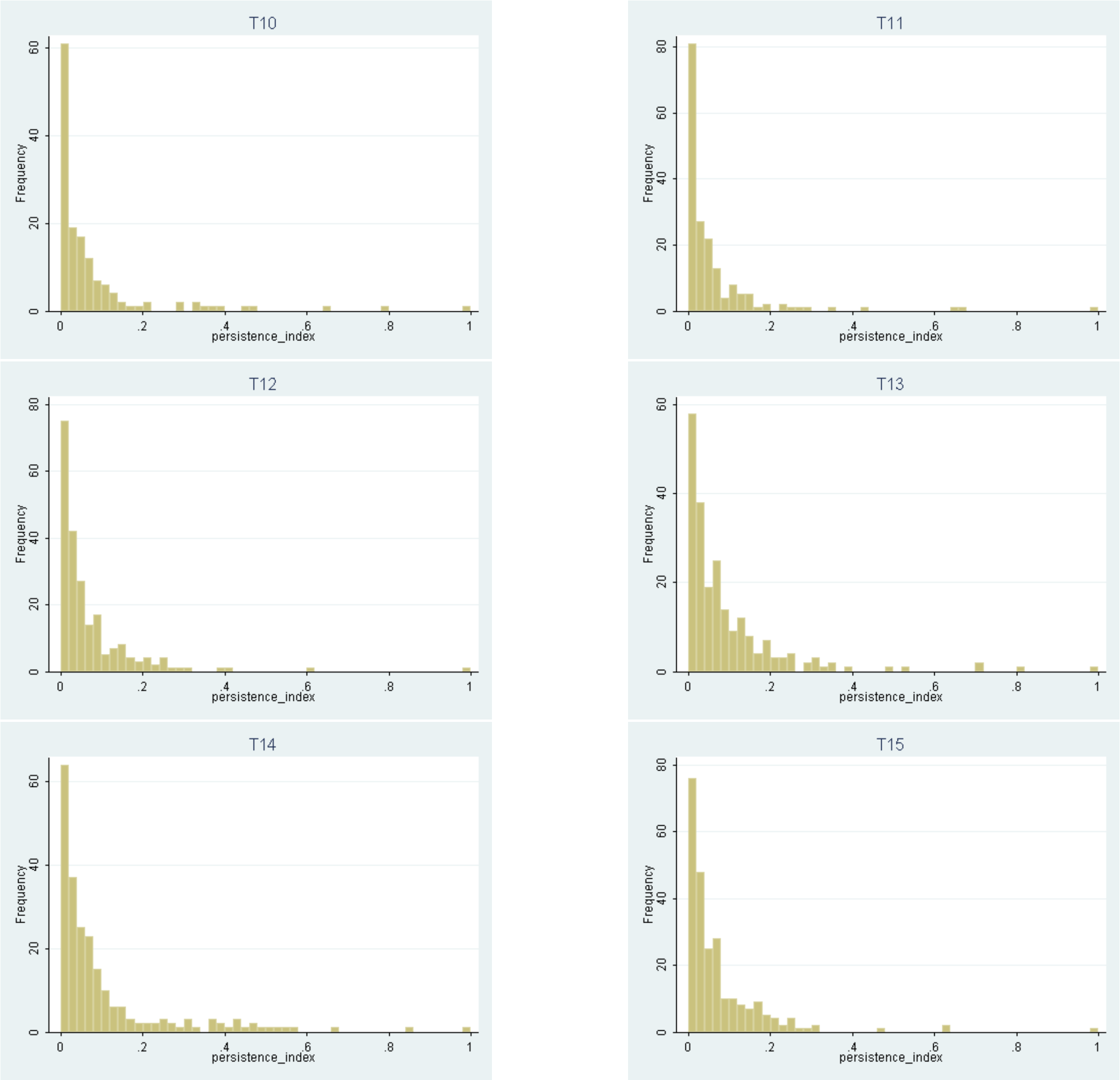

Figure F.3: Histogram of the frequency distribution of the persistence index for the last 5 truncations - Continued

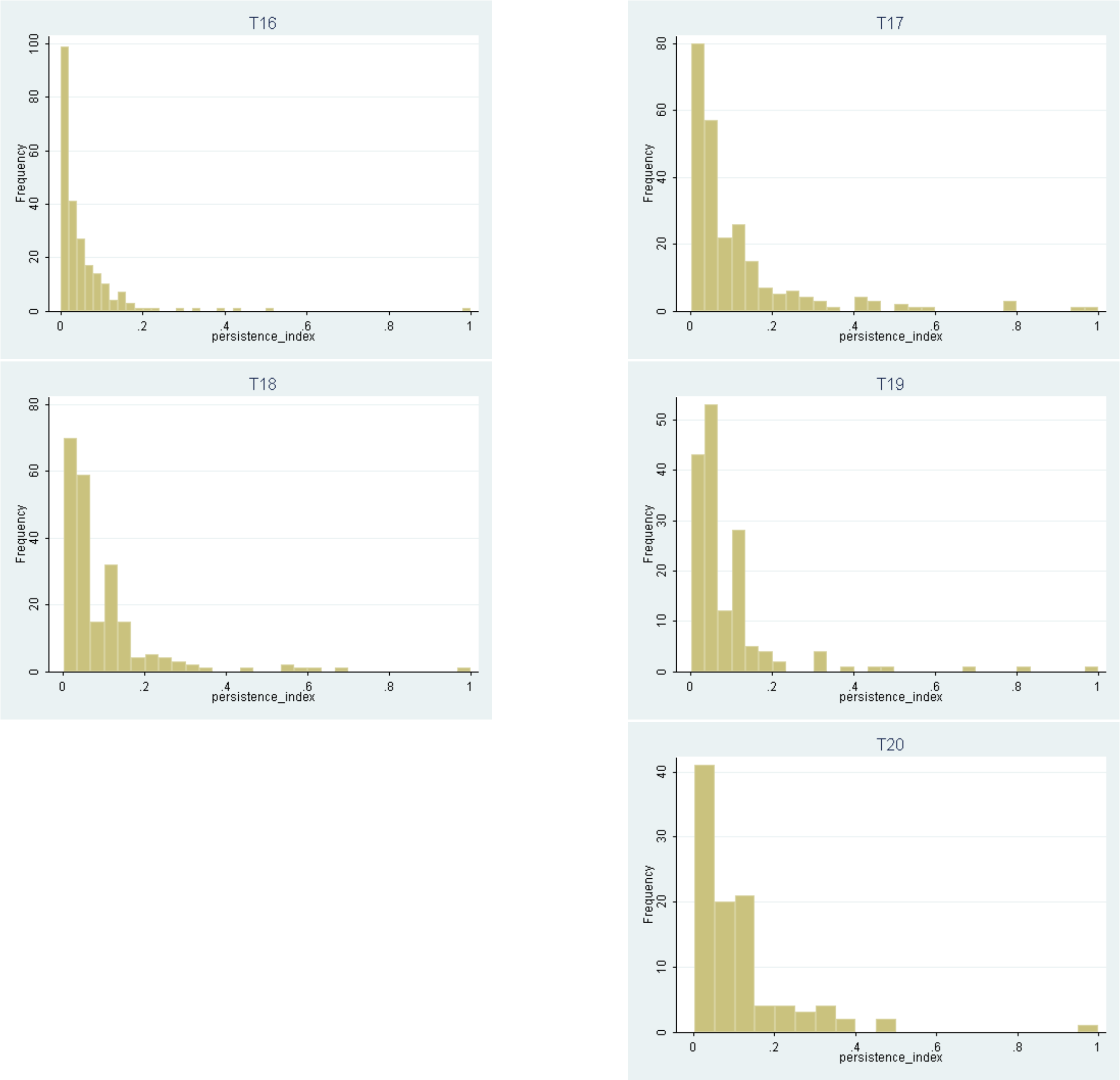

Figure F.4: Histogram of the frequency distribution of the persistence index for the last 5 truncations - Continued

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Summary

This work focuses on the long-term structural evolution of the telecommunication switching industry, analyzing both the technology and the firm level. The first contribution of this work is in the empirical representation of technological change. Following the growing field of research about the use of patent citation networks for mapping technological trajectories, this methodology is applied to the telecommunications switching industry. Furthermore, given the paucity of analytical tools for the analysis of patent citation networks from a technology dynamics perspective, a completely new method is developed. Loosely based on the notion of "inheritance of genes", some indicators of cumulativeness of knowledge are developed and used for detecting the emergence of new technologies within a patent citation network.

The second contribution is in the tradition of evolutionary economics, that is to provide an in depth case study of industry evolution. In particular, following the Sectoral System of Innovation approach, a chapter of this work is devoted to the analysis of the structural evolution of the telecommunication switching industry. This corresponds to considering the industry long-term development and focusing on several aspects, such as the emergence of new technologies, changes in firms competences and skills, firms' diversification and integration strategies, and the role of public authorities and institutions. The analysis of the structural evolution intends to enrich the bulk of appreciative theorizing about the co-evolution of technology and industry in an oligopolistic and regulated sector.

This thesis includes both qualitative and quantitative research methods. The former mainly consist of the use of secondary sources and empirical data for reconstructing technology, industry, and firm evolution. The latter is carried out analyzing a patent citation network built using patents related to telecommunication switching granted between 1963 and 2001.

Part I (chapter 2) introduces the reader to some theoretical issues covered in the thesis and provides the underpinning of what we could call the "general assumptions" of the thesis. These are: the theoretical support of an industry level study, the link between technology

and industrial dynamics, and a cognitive approach to technical change. Finally, this chapter ends with the explicit stating of the research questions. Part II (chapters 3 and 4) represents a piece of qualitative research that focuses on the technological development and the industry structural evolution. In particular, chapter 3 provides a detailed account of technology evolution in telecommunication switches, whose aim is to highlight the technological history of telecommunication switches and which technological bottlenecks materialized. This chapter argues that technological progress in the industry follows a "challenge-and-response" pattern where the main driver appears to be the solution of emerging technical bottlenecks. Furthermore, this chapter also underlines the issue of performance measurement (i.e. service characteristics) stressing the "not-off-the-shelf" nature of telecommunication switches and the interoperability to other network infrastructures. Chapter 4 is an account of the structural evolution of the telecommunication switching industry from its infancy until recent years. As this means to consider several aspects both at firm and industry level, the chapter is divided in two parts. In the first part the industry is considered as a whole and for each period five dimensions are systematically discussed. These are: (i) market structure, (ii) barriers to entry, (iii) demand, (iv) relevant actors end their relations, and (v) source of knowledge and technology. In the second part firms are considered individually with special attention to their (common) genealogy, their national context, their technological competences, and their patterns of diversification and specialization.

Part III (chapters 5 and 6) centers on the analysis of technology dynamics through the use of patent citation networks. In particular, the analysis tries to couple qualitative and quantitative research, moving beyond just considering patents as a "count unit" and considering also their descriptive contents. The analysis focuses on two aspects: (i) mapping the main flow of knowledge within a directed network using the established method proposed by Hummon and Doreian (1989) and (ii) the analysis of the newly introduced concept of knowledge persistence. We could consider these two chapters as an empirical counterpart of chapter 3, as they provide an empirical representation of the technological evolution and of the exploration of the available technological space. The first step of this type of analysis is the re-framing of the history of technology (chapter 3) in the technological paradigms and trajectories framework. This analysis examines the technological advance through the lenses of engineering heuristics and pinpoints what search strategies engineers used over time. In this setting, paradigms can be distinguished by looking at the stability of such heuristics, the need for new technological competences, and the emergence of new technical bottlenecks. The second aspect of technology dynamics is knowledge persistence and the long term knowledge flows in the network. A patent citation network represents a system of knowledge generation and transmission (through citations), and this makes possible to identify the most successful patents in spreading their knowledge to later patents. This corresponds to study each patent citation structure from a global network perspective. In chapter 6 this is operationalized by using genetic concepts such as the Mendelian law of genes inheritance.

Finally, in Part V, chapter 7 provides a summary of the main findings of this thesis, discusses their implications, and suggests future lines of research.

As regarding industry evolution we can conclude that despite several waves of radical technological change this industry displays a “slow dynamics”. This is rooted in a slow innovation process and adoption through long-term procurement contracts. Furthermore, looking at the major players reveals a large degree of heterogeneity in term of firms internationalization and telecommunication specialization.

As regarding the empirical investigation of technology dynamics we can conclude that the proposed method is successful in clustering patents according to different technological paradigms. Furthermore, it emerges that the adaptation of a new radical technology (i.e. packet switching) to the telephony network took place through the intense exploration of a limited part of the available technological space.

About the author

Arianna Martinelli was born in 1977 in Milan, Italy. She studied Economics and Social studies at Bocconi University in Milan, Italy. In 2001 she spent 9 months in Santiago de Chile for a student exchange at the Pontificia Universidad Cathólica de Chile and for an internship at the UN-Economic Commission for Latin America and Caribbean. In 2003 she continued her studies by pursuing a MSc. in Industry and Innovation Analysis at SPRU (Science and Technology Policy Research) in the University of Sussex, United Kingdom. On February 2005 she started her PhD at ECIS (Eindhoven Centre for Innovation Studies), at Eindhoven University of Technology, the Netherlands. Her thesis ("The Dynamics of Technological Discontinuities: a Patent Citation Network Analysis of Telecommunication Switching Industry") addressed the issue of using patent citation network in order to study the extent of cumulativeness of technological advances. Her research interests are rather broad focusing on the relation between technological change and industrial dynamics, and the empirical representation of technological change. Since February 2009, Arianna has been employed as post doc at the GSBC - EIC The Economics of Innovative Change, Friedrich-Schiller-University Jena, Germany.

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