Laboratory of Economics and Management
Sant’Anna School of Advanced Studies
Piazza Martiri della Libertà, 33 - 56127 PISA (Italy)
Tel. +39-050-883-343 Fax +39-050-883-344
Email: lem@sssup.it Web Page: http://www.lem.sssup.it/

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An emerging paradigm or just another trajectory? Understanding the nature of technological changes using engineering heuristics in the telecommunications switching industry

Arianna Martinelli°

° LEM and IE, Scuola Superiore Sant'Anna, Pisa, Italy

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An emerging paradigm or just another trajectory? Understanding the nature of technological changes using engineering heuristics in the telecommunications switching industry

Arianna Martinelli*

Abstract

The theoretical literature on technological changes distinguishes between paradigmatic changes and changes in trajectories. Recently several scholars have performed empirical studies on the way technological trajectories evolve in specific industries, often by predominantly looking at the artifacts. Much less - if any - empirical work has been done on paradigmatic changes, even though these have a much more profound impact on today's industry. It follows from the theory that such studies would need to focus more on the knowledge level than on the artifact level, raising questions on how to operationalize such phenomena. This study aims to fill this gap by applying network-based methodologies to knowledge networks, represented here by patents and patent citations. The rich technological history of telecommunications switches shows how engineers in the post-war period were confronted with huge challenges to meet drastically changing demands. This historical background is a starting point for an in-depth analysis of patents, in search of information about technological direction, technical bottlenecks, and engineering heuristics. We aim to identify when such changes took place over the seven different generations of technological advances this industry has seen. In this way we can easily recognize genuine paradigmatic changes compared to more regular changes in trajectory.

JEL classification codes: O30; O33; L96

Keywords: technological trajectories; patents; network analysis; telecommunication manufacturing industry.

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*LEM - Scuola Superiore Sant'Anna, Piazza Martiri della Libertá 33, 56127 Pisa (Italy). E-mail:a.martinelli@sssup.it

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1 Introduction

Concepts such as technological paradigms and trajectories are extensively used in the literature; however, from an empirical perspective, their use is still rather subjective. In fact, the challenge of their validation concerns both their empirical operationalisation and the availability of comparable data. Recent literature on innovation addresses these challenges by defining technological trajectories in terms of knowledge flows within a patent citation network (Mina, Ramlogan, Tampubolon & Metcalfe 2007, Verspagen 2007, Fontana, Nuvolari & Verspagen 2009, Barberá, Jiménez & Castelló 2010). In such settings, patents are the nodes of the network and citations indicate the knowledge flows between them (Jaffe & Trajtenberg 2005).

Such data are not only easily available, but also rather suitable for the investigation of technology dynamics as they also disclose qualitative information about the invention. The methodology applied is strengthened and validated in my paper by examining the evolution of the engineering heuristics specific to a technological paradigm. Therefore the novelty of this work is twofold: firstly, to identify and study the evolution of engineering heuristics applied in the telecommunication switching industry, and secondly, to explicitly link the artifact and knowledge level.

Patents are particularly suitable for these tasks as they must include the background and a description of the invention. In fact, in order to be granted a patent, applications must contain an explanation of an inventions novelty, utility, inventive steps, non-obviousness, industrial applicability, and *prior art.*[1] Thus all this information can be used to understand the type of technical problems tackled by engineers over time, the solution proposed, and therefore the research heuristics applied.

Differently from previous work using the same methodology, this paper emphasises how the quantitative and qualitative analyses complement each other. This link between quantitative and qualitative results is provided by validating the technological trajectory. Firstly, the main flow of knowledge within the patent citation network is identified, and then the patents belonging to this trajectory are scrutinized to find information about the engineering heuristics applied. Discontinuity in heuristics enables us to detect paradigmatic shifts. Therefore, this methodology can be considered as a meaningful combination of quantitative and qualitative research, enabling in-depth analysis (often lacking in quantitative approaches) and generalization (often missing in narratives).

Furthermore, according to the literature, paradigms and trajectories are features of both the artifact and the knowledge space. Whether those are isomorphic is an empirical question which this paper attempts to answer for the case of telecommunication switches. In this respect, it is commonly accepted that switches have evolved as a sequence of generations of artifacts. This sequence needs to be reframed into the technological paradigms and trajectories theory. In particular, for each generation some characteristics specific to technology are examined. These are: (i) the competencies needed, (ii) the engineering heuristics applied, and (iii) the perceived

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[1] See: `http://www.wipo.int/patentscope/en/patents_faq.html#protection` retrieved on 12 December 2011.

technical barriers. In this way it will be possible to link the artifact level of analysis to the knowledge level, and to associate artifact dynamics with the evolution in technology.

The telecommunication switching industry provides an interesting case for this type of analysis because in the period under examination, its technological evolution is characterized by "normal" and "revolutionary" periods. Therefore we are able to appreciate the methodology proposed in the trajectories as well as the paradigmatic shifts. Finally, it is an industry where different generations of switching technologies are easily distinguished.

The results shed some light on the microdynamics of technical change in the industry studied. They show that heuristics can coexist at artifact level, therefore, despite changes at technical and service level, a truly paradigmatic shift can only be detected at knowledge level. Finally, the empirically mapped trajectories correspond with what is commonly accepted. The engineering heuristics identified in the patents as part of the technological trajectories change over time. Consequently, technical change has evolved in different dimensions and a new technological paradigm emerged in the mid 1990s.

This paper is structured as follow: the next section starts by reviewing the empirical literature on technology dynamics, section 3 will discuss in detail the methodology, section 4 will realign the known history of telecommunication switches in the framework of technological paradigms and trajectories, and finally section 5 will present the empirical analysis, followed by conclusions.

2 Theoretical background

As observed by Dosi and Nelson (2009, page 5), technology entails "...particular pieces of *knowledge*, *procedures* and *artifacts*...". Therefore concepts such as technological paradigms and trajectories belong to both the knowledge and artifact space. Despite the fact that these two levels have similar characteristics, the scant empirical literature on technology dynamics tends to focus on the latter.

Following the seminal paper by Metcalfe and Saviotti (1984), some studies infer technical trade-offs from technological and service characteristics (i.e. performance indicators). This was done for some complex artifacts as: tanks (Castaldi, Fontana & Nuvolari 2009), helicopters, and aircraft (Frenken, Saviotti & Trommetter 1999). In the same conceptual line and again at artifact level, the $N-K$ model has been used to map the relationship between technical and service characteristics. This biological model lets you relate N technical characteristics to a number of functions through K relations. And so these two parameters inform you about the complexity of an artifact, the search path in the technological space, and the emergence of certain designs.[2] However, given the definition of technological paradigms and trajectories put forward by Dosi (1982), the artifact level of analysis provides only a partial view of technology dynamics.

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[2] For more details about the general $N-K$ model, see Kauffman (1993). For applications of this model in technology evolution see Frenken (2000) and Frenken & Nuvolari (2004) for steam engines.

In fact, if technical advance is a ‘problem solving activity’ carried out by engineers, the technological paradigm is defined “...as ‘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). Following the parallel with the idea of scientific paradigm developed by T. Khun (1962), the technological paradigm binds the extent of exploration by engineers in the technological space. These boundaries can be cognitive, related to the engineering background, or technical, related to the flexibility of production techniques, the artifact design, and technical bottlenecks. Certainly they pertain to the ‘challenge-and-response’ pattern followed by engineers (Rosenberg 1974).

Within the set of available solutions defined within the paradigm, the technological trajectory maps the microdynamics of technical change in a ‘normal’ technological evolution.

In this perspective, it is clear why the study of technology dynamics at the artifact level only partially captures the breadth of the theory of technological paradigms and trajectories. A recent stream of literature proposes a different approach by using patent and citation data for mapping technological trajectories at the knowledge level. These data sources are particularly useful because the description of the invention reveals information about the technical problems tackled and the engineering heuristics applied.

According to the theory, a paradigm is composed by heuristics that are the “search strategy”, guiding engineers in their problem-solving activities.[3] These heuristics are rather important because they are peculiar to a technological paradigm, therefore their evolution over time indicates a paradigmatic shift. Furthermore, these heuristics are indicative of a paradigm but not of an artifact. For instance, the famous “Moore’s Law” that prescribed miniaturization for increasing semiconductor capacity is a very good example of an engineering heuristic. This law is known to be very stable over time and characteristic of several generations of semiconductors (e.g. from VLSI to the recent Intel Pentium Processors). This “scaling” heuristic is also found in other artifacts such as aircraft (Frenken & Leydesdorff 2000) and farm tractors (Sahal 1985). In his article about the diffusion of retractable airplane landing gear, Vincenti (1994) explains how this innovative feature (and all the research and tests related to it) has to be understood in the context of the heuristics and technical trade-offs faced by engineers. In fact, the new design of the gear was meant to improve the speed of the aircraft by reducing the drag.

These heuristics can be identified empirically by analyzing the artifact’s characteristics, using technical literature or interviews. However, similar information can be retrieved in patents. In this respect, the approach used in this paper incorporates both quantitative and qualitative methods. First, network analysis on patents and citations identifies a sequence of relevant

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[3] Vincenti (1994) explains the blind variation connected to the innovative process with an interesting metaphor. In his words:

> I think the seeker for knowledge as rather a blind person trying to reach a desired destination by going down an unfamiliar passageway, using tactile input from a cane and the constraint available from the passage’s sidewall. (Vincenti 1994, page 21)

The cane and the sidewall are the engineering heuristics which guide the search, and make the process not random but just blind.

patents and citations constituting the technological trajectory. Secondly, a qualitative analysis of those papers enables us to discern engineering heuristics and perceived technical barriers. The discontinuity or stability of such heuristics is characteristic of technological paradigms and trajectories, respectively.

The elements of the connectivity method used are explained in more detail in section 3, while here we provide a conceptual description in order to link it to the previous discussion. The rationale behind the network approach to patent and citation data is derived from the fact that a citation represents a direct link between the cited and citing patent. Such an approach is not new, however, as the authors of an exploratory paper (Ellis, Hepburn & Oppenhein 1978) were aware of the difficulty to compile useful data for patent citation analysis. Nowadays, thanks to the availability of several databases, this issue is no longer relevant and patent citation networks are increasingly used. Besides the mapping of technological trajectories, patent citation networks were used for studying technology diffusion and relatedness (Chang, Lai & Chang 2009) and for quantitatively detecting patent thickets (Clarkson 2004).

In this paper the use of connectivity indicators and a search algorithm allow us to identify a set of patents connected by direct citations that constitute the main flow of knowledge within the network. These citations link subsequent problem-solving information and the underlying heuristics embedded in a patent show an ordered path of local, cumulative, and irreversible technical changes. In this sense, the main flow of knowledge accomplishes the definition of technological trajectory put forward by Dosi (1982).

This method has been applied to several technologies. In particular, Verspagen (2007) applies it to fuel cells, directly linking the main flow of knowledge to the concept of technological trajectory. Through the analysis of ‘patents on the trajectories’ he identifies the decline and emergence of different streams such as the air metal batteries. Previously, Mina et al. (2007, 2009) applied the same method to both patents and publications, highlighting patterns of knowledge and technology co-evolution in the search for solutions to emerging problems in medical innovations. Fontana et al. (2009) applied this method to the LAN, highlighting the emergence of technological bottlenecks that can jeopardize and slow down the innovation process in large infrastructure systems (i.e. data communication standards). More recently, Barberá et al. (Barberá et al. 2010) explicitly focus on the artifact level, by validating the methodology for a product such as the artificial spinal disc.

In this paper we test the theoretical model for a different industry, the telecommunication switching industry. Furthermore, the novelty of the exercise is to study the evolution of the heuristics revealed in patents and to link artifact shifts (i.e. switching generations) to paradigmatic shifts. This will be done in section 4, where it will be shown that the same heuristics can coexist throughout different generations, and therefore a truly technological paradigm can only be detected at the knowledge level.

Finally, we can see that the possibility to map paradigmatic changes at knowledge level is only feasible with artifacts for which it is difficult to compile performance measurements. This is the case for telecommunication switches, where their ‘tailor-made’ nature and the specific needs of different users determine the co-existence of a large variety of switch designs (Frenken & Nuvolari 2004).

3 Methodology and data

In this article patents and citations are not used for compiling patent counts, but for building a network. If patent A cites patent B, we can imagine a directed flow of knowledge connecting B to A. Therefore, patents and citations can be used for mapping global[4] knowledge flows. Figure 1 displays a simple patent citation network composed of nine patents and eight citations. Following the jargon for directed networks, patents and citations are dubbed vertexes and arcs respectively (Wasserman & Faust 1994).

[Figure 1 about here]

This network is: (i) directed, with the arcs indicating the direction of the knowledge flow; (ii) binary, i.e. all the citations have the same value one, and (iii) acyclical, i.e. no cycles are present.[5] Furthermore, depending on the presence of flows starting or ending in each vertex, we can distinguish three types of patents:

1. *Startpoints*: are vertexes whose indegree equals zero, meaning that no arc is ending in that vertex. In figure 1 these are patents A and B.
2. *Endpoints*: are vertexes whose outdegree equals zero, meaning that no arc is starting in that vertex. In figure 1 these are patents E, G, and I.
3. *Intermediates*: are vertexes whose indegree and outdegree are different from zero. In figure 1 these are patents C, D, F, and H.

The identification of the technological trajectory corresponds to pinpointing the 'main flow of knowledge' within the patent citation network using connectivity measures. This approach was firstly applied by Hummon and Doreian (1989) to a publication network. However, recent articles (Mina et al. 2007, Verspagen 2007) exploit the similarity between publication and patent networks (i.e. directionality and acyclicity) for applying to patent and citation networks.

The procedure applied in this paper consists of three ordered steps:

1. **Transformation of the binary network in a weighted network.** In a binary patent citation network, all the citations are equally important as they all have value one. However, depending on the number of vertexes they connect, different knowledge flows through them. Hummon and Doreian (1989) propose two indicators for capturing the level of connectivity of each citation. These are: the Search Path Link Count ($SPLC$) and the Search Path Node Pair ($SPNP$). The former consists of how many times one arc lies in

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[4] *Global* indicates the possibility to examine knowledge flows beyond direct citations. See below for further considerations on the contraposition of *local* and *global* level, and the complementarities with patent and citation counts.

[5] This property intuitively emerges from the fact that patents can only cite previous patents.

all the possible search paths between all the *startpoints* and *endpoints*.[6] For example in Figure 1, six search paths are present (A → E, A → G, A → I, B → E, B → G, and B → I), therefore for citation <CD>, $SPLC$ is equal to three as it lies on the first three listed search paths. The latter assigns to each arc the product of all the upstream and downstream vertexes. In the case of citation <CD>, $SPNP$ is equal to eighteen, the product of three upstream and six downstream vertexes.[7]

2. **Identification of the network of main paths.** From each *startpoint*, a search algorithm selects the arc with the highest SPx.[8] If more arcs have the same highest values, all of them are selected. This procedure is repeated from each selected vertex until an *endpoint* is eventually reached. Repeating this procedure for all the *startpoints* will identify several main paths (however some can converge to the same *endpoint*) whose union constitutes the network of main paths. This procedure results in a reduction of the complexity of citation network by deleting 'unimportant' links, where the importance is measured in terms of the SPx.
3. **Identification of the top main path.** Verspagen (2007) proposes an extension to the Hummon and Doreian method by identifying (within the network of the main path) the path with the highest overall connectivity. This corresponds to pinpointing the top main path, which is the path whose sum of SPx is the highest.

By its construction, the top main path connects the largest number of patents, it therefore represents the critical backbone of knowledge flow in the network. Furthermore, given its intrinsic cumulative and incremental nature, it is consistent with an empirical representation of a technological trajectory (Verspagen 2007). It is interesting to note that in practice, the top main path is rarely unique, as some paths can have the same sum of SPx. However, this mainly happens with paths that share *intermediates* but not *startpoints* and *endpoints*. In practice, the exact number of top main paths analyzed will depend on the values and the distribution of the SPx sums.[9]

As anticipated in section 2, these trajectories are identified over time, therefore the above procedure is repeated for different time intervals. Trajectories are empirically (i.e. quantitatively) identified, whereas their stability discriminates between paradigms. Discontinuities of trajectories, changes in heuristics and in the technical issues reported in the patents, will qualitatively indicate a paradigmatic shift. The qualitative analysis of the patents was complemented with an in-depth case study of technology evolution in the industry (Martinelli 2010) and validated by interviews with engineers active in the relevant time period.

After reviewing the methodology applied, differences clearly emerge between the network approach and the approach of measuring the value of patents counting citations. The former

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[6] Note that Hummon and Doreian (1989) also discuss a case in which the search paths are calculated not only from the *startpoints* but also from each *intermediate* vertex.

[7] These indicators tend to show similar results, however, given the multiplicative effect, $SPNP$ tends to evaluate more citations in the middle of the paths. For more information see Batagelj (2002) and Batagelj et al. (2005)

[8] SPx indicates a genetic connectivity measure (either $SPLC$ or $SPNP$) used for weighting the network

[9] For more details about this practical aspect see note 29.

evaluates patents, looking at their network position depending on their global citation structure, whereas the latter evaluates patents, examining their number of direct ties[10] depending on their local citation structure. As shown by Fontana et al. (2009), these methods are not exclusive and some not highly cited patents can occupy pivotal positions such as junctions or bifurcations in the network of knowledge flow.

Finally, a caveat of this method is the use of only 'internal citations', where only citations between patents in the sample are considered. As *startpoints* (*endpoints*) can cite (be cited by) patents not included in the sample, these attributes are endogenously determined by the method. Therefore, an important step in such a method is the selection of a patent sample representative of the technology under examination.

In this work, the patent sample was retrieved from the USPTO website using technological subclasses that all belong to technological class 370 ('Multiplex Communication').[11] The criteria for selecting relevant technological subclasses were a combination of catchwords, analyses of specialized firms' patent portfolios, and careful reading of subclass descriptions. In order to account for the complexity of the technologies under examination, the first round of cited patents was added to the initial sample (selected through technological subclasses). The final sample includes 6214 patents covering the period 1924-2003. The relevant information about these patents was obtained by matching it to the NBER dataset and manually inserting the patents granted before 1963. Citations were obtained from the same dataset and the citations before 1975 were added manually. Finally, the patent citation network considered has 6214 vertexes and 20,848 arcs.

4 Re-framing the history of switches: a paradigm-trajectory approach

Telecommunication switches (from now on simply switches) are the network infrastructure that allows for establishing the phone connection between the caller and receiver without having a direct connection between them. According to the technical literature and the book 100 Years of Telephone Switching (1878-1978) by A. E. Joel and R. J. Chapuis (1982, 1990)[12] there are seven switch generations. These and the corresponding models are listed in table 1.

[Table 1 about here]

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[10] According to the way the directionality is defined, in this network outdegrees correspond to forward citations.

[11] 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).

[12] Note that this book is a well known source for technological history. It provided the technical content for several pieces of economic research about switches performed by Fransman (1995) and Sutton (1998).

The aim of this section is not only to summarize the technological milestones for the telecommunication switching industry, but also to link the artifact level (i.e. various switch generations) to the knowledge level. Finally, these generations will be assigned to different paradigms defined at knowledge level. This procedure consists of the discussion about the technical differences between generations, and the tracing of such differences back to the underlying technology. In particular, following section 2 these paradigms are distinguished through three dimensions: (i) the technical skills and competencies needed in each generation, (ii) the perceived barriers and bottlenecks on which engineers were focusing, finally (iii) the consequently applied engineering heuristics. These dimensions solely refer to the type of capabilities and skills. However, according to the definition of technological paradigms, it appears as the most relevant with which to cognitively distinguish paradigms.

Switches are complex systems and their technological evolution can occur depending on several technical characteristics. According to the specialized literature,[13] the most referred to (and therefore relevant) 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[14] is actually organized in the whole network and within the switching network;
3. The **multiplexing technology**,[15] which determines the way 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 transmission elements or components;
4. The **nature of the end-to-end traffic** that the switch supports (e.g. voice calls and various 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 refer to the components used in the switch, their characteristics and technology;
7. **End-user signaling**, which refers to the way a telephone set actually exchanges numbering information with the switch.

Table 2 summarizes the earlier listed differences in technical characteristics through the generations. In particular, this table shows that no generation distinguishes itself from the

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[13] In particular Electronic Switching: Central Office Systems in the World (Joel 1976) and Electronic Switching: Digital Central Office Systems of the World (Joel 1982).

[14] This function allows the exchange of information on the establishment and control of a connection and the management of the network (for instance failure and congestion in some parts of the network).

[15] In telecommunication networks (but this is also valid 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 demultiplexer. The integration of these devices in the network allows for economizing on expensive transmission resources.

previous one regarding all the characteristics considered and therefore each generation retains some technological characteristics from the previous one.

[Table 2 about here]

The manual generation (switchboards) could switch only analogue information, in this particular case merely voice. As columns 4 and 5 show, this would continue until the emergence of digital switches. All the calls were switched through the operator who was performing the control function and manually testing whether the receiver was available and not busy with other calls. Finally, switchboards were built of wires, cords, and jacks, and the connection was physically established through patchcords.

The latter generations (electromechanical direct and common control) differ in the way their control was organized. In the direct-control switches, subscribers' numbers were 'hardwired' in the switch, meaning that each subscriber number had a fixed inlet in the switch. On the other hand, with the common control some control function would become programmable thereby increasingly flexible. In particular, this programmability would introduce the separation between traffic and signal, which would be distinctive of 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 a few electronic devices such as tubes.[16]

The electronic generation displays a long-lasting change in the nature of the crosspoint with the exclusive use of electronic components and circuits. Every subsequent generation would replace all the mechanical parts with electronic ones. Furthermore, this generation saw the introduction of the 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 diffusion of SPC was driven by the availability of new electronic components with an increasing scale of integrating circuits. These components improved switches' performance by reducing network latency, maintenance and labour costs, and the size of the switch (i.e. the floor space). In addition, the use of software allowed for more flexibility in the routing, easier upgrading, and opportunities for expansion. Finally, it is interesting to note that this generation, together with the previous ones uses the same SDM technology, meaning that the different circuits/calls occupy a separate space along the same wire.

The next two generations, the digital ones, differ significantly from the previous ones. Firstly, the multiplexing technology changed from space division multiplexing (SDM) to time division multiplexing (TDM), which eventually would become dominant. 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 constraint to the transmission speed of telephone networks.

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[16] Vacuum tubes had a limited diffusion in switching because of severe heating dispersion. However, they were extensively used in transmission systems for amplification, among other things.

The last generation considered in table 2 differs from the previous ones in the switching mode. In particular, we observe a transition from circuit switching to packet switching. The characteristic feature of the former is that the end-to-end connection is established for the entire duration of the call. This is not very efficient as bandwidth is statically allocated and occupied even if no information is transmitted (e.g. when both speakers are silent). On the other hand, packet switching dynamically allocates the bandwidth. In fact, information is split into packets of different length that are individually routed to the address they carry in the header. In this way, data traffic of different types (e.g. bursty data or continuous media) can be efficiently handled. Packet switching can also be used for transmitting voice (often referred to as VoIP service), however this cannot guarantee a quality of service (QoS) similar to a circuit-switched network.

Table 2 shows that generations differ in several technical characteristics identified at the artifact level. However, for the purpose of this paper, these generations and differences need to be related to the knowledge level. As anticipated, the criteria set for discriminating paradigms at knowledge level are: (i) the technical skills and competencies needed in each generation, (ii) the perceived barriers and bottlenecks on which engineers were working, and (iii) the consequently applied engineering heuristics.

[Table 3 about here]

Switchboards were initially constructed in small workshops, often dedicated to other productions such as church organs or sewing machines. Therefore no exclusive competencies were actually required. The main technical barrier was the limit to network expansion because of the emerging diseconomies of scale.[17] Part of the solution to this problem entailed the development of some competencies in traffic and congestion management in a telephone network. Although more sophisticated tools and methods would be employed, these competencies would also be required for the development of all the subsequent generations.

The electromechanical switches (generations 2 and 3) are technically similar, necessitating mechanical engineering competencies. Engineers were still working on expanding the network (and reached what would be called universal service) under the constraint of limiting complexity and running costs. In fact, large electromechanical systems often required expensive maintenance interventions both for ordinary and extraordinary situations. However, the development of the electromechanical common-control switch responded to a new challenge. That was the increase in flexibility. In fact, switches are integrated in a large technical system and they have a long life cycle. Therefore, the possibility to adapt them thereby increasing the capacity or providing advanced services was a desirable feature on which engineers were working.

The fourth generation (electronic switch) is characterized by the use of electronic components, requiring the expertise of electronic engineers and making mechanical competencies obsolete. Furthermore, some limited programming skills were necessary in order to organize the control with the SPC. This electronic revolution required new competencies not only in the

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[17] In this period the so-called *switchboard problem* caused by the hardwiring of the inlets determined diseconomies of scale, raising the switching costs in highly populated areas (Mueller 1989).

R&D laboratories but also in the maintenance units.[18] Electronic components were needed to boost flexibility and offer new advanced services. Their high cost was fostering cost/efficiency in order to achieve reliability and economic feasibility.

The development of digital switches required the acquisition of new competencies in digital electronic circuits (vs. analogue circuits) and mathematical skills such as Boolean algebra. Furthermore, the decentralization of control enhanced the importance of software requiring advanced programming skills. As regards the perceived technical barriers, numerous technical books agree on the identification of analogue/digital interfaces as the major technical bottleneck for early development of digital switches. In particular, they refer to the BORSCHT circuit.[19] The development of the BORSCHT circuit started in 1972 but due to the continuous changes in technology, its development was rather slow. Regarding the last column in table 3 (the engineering heuristics), the introduction of digital switches fostered the integration between switching and transmission and the implementation of new services such as call forwarding and toll free calls. However, this integration was sometimes problematic because of the technical trade-offs in adopting TDM when transmission is both analogue and digital (Joel 1982)[20]. Finally, something constituting both engineering heuristics and a perceived barrier was the digitalization of the network. Before considering the possibility of the ISDN (Integrated Service Digital Network) and therefore the development of a single network suitable both for voice and data communication.[21]

The last generation is based on packet switching, a technology developed in the data communication industry and only recently adopted in the telecommunication switching industry. The external nature of this technology brought about the need to acquire completely new competencies in computer network. For instance, the complexity of the routing algorithms used required the massive use of mathematical modeling and simulations. Furthermore, because of the complexity of the software, the development and testing process was also completely different (e.g. using simulations rather than prototypes). The perceived barrier for engineers was the possibility to guarantee a minimum standard of quality for the voice service. In fact, as already explained, if on the one hand, packet switching is optimal for data communication, on the other, packet losses can deteriorate the quality for voice transmission quite dramatically. Finally, the engineering heuristics were related to the widespread deployment of NGN networks[22] boosted by the success of the internet (Fitchard 2003).

The results are summarized in table 3 that provides the support for distinguishing four paradigms.

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[18] Technical books report striking examples of network failures caused by using old methods for maintenance (e.g. 'old school' maintenance staff who lubricate electronic components with grease) (Chapuis 1982, Clark, McLoughlin, Rose & King 1988).

[19] The name Borscht is an acronym of the performed functions: **B**attery feed, **O**vervoltage, **R**inging, **S**upervision, **C**odec for analogue-digital coding and decoding, **H**ybrid to split the two-wire analogue speech circuit into two separate two-wire circuits for sending and receiving the coded digital signals, and **T**esting.

[20] See Joel (1982) page 114 for cost trade-offs.

[21] In fact, they failed to convince end users to purchase the much more expensive digital telephone sets, so the concept of a really integrated digital chain including the end user terminal was never achieved.

[22] Next Generation Network (NGN) generally refers to packet switching networks.

[Table 4 about here]

Table 4 displays the sequence of these paradigms, the corresponding trajectories, and the switch generations (i.e. artifacts). As already emerged from table 2, there is not an isomorphic map of technological paradigms and generation shift. In fact, a paradigmatic shift always (almost by definition) destroys competencies (Anderson & Tushman 1990), whereas, a generation shift only sometimes. Finally, it is interesting to point out that in practice these paradigms quite often overlap. This happens for two reasons: first, innovation is rather slow and engineers start developing new generations (based on different technological paradigms) decades before they became economically viable.[23] Second, diffusion is slow and different vintages are in use in the network at the same time.

In the last part of this section we will discuss the trajectories listed in the third column of table 4 and explain why they do not constitute separate paradigms. Because of the data availability, the empirical exercise will focus on the transition between the third and fourth paradigms, therefore the discussion about trajectories will cover only these two paradigms.

Within the electronic circuit switching paradigms we can identify three separate trajectories. In order to discuss their characteristics and evolution we need to focus on two technical characteristics listed at the beginning of this section: the way in which the information is coded (analogue vs. digital), and the multiplexing technology (space division vs. time division).

[Table 5 about here]

These alternatives indicate a 2x2 space (see Table 5) where a dynamic trajectory goes from cell 2 to 4. In fact, these combinations were the only ones implemented, the electronic and digital switches respectively. Besides the emergence of a different generation, the transition from 2 to 4 entailed the solving of several problems and in particular the efficient analogue digital interface (the BORSCHT circuit mentioned previously). Furthermore, it is also possible to see here selection at work, as the other two designs (3) and (2) never made it beyond the stage of proof of concept or prototype.[24] The changes in multiplexing technology and in information coding are technologically relevant, however they do not constitute a genuine paradigmatic change because neither of the two is affecting the aspects highlighted in table 3.

The third trajectory within the electronic circuit switching paradigm relates to the way control is organized, either centralized or de-centralized. These technical aspects characterize different generations, however they do not constitute a paradigmatic change as they imply just a deepening of existing competencies. 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

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[23] For instance, in the case of TDM digital centralized switches (generation 5), development started in the mid 1930s, 40 years before commercialization.

[24] Research on (2) was widely undertaken at the beginning of this period. Then 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 sacré* due to the high number of electronic components (around 180,000 including valves, diodes, and transistors) compared to the number of lines covered (only 600).

offered and in the software to implement them (Chapuis & Joel 1990), however, no real new architectural designs or skills were required.

The adoption of packet switching represents a paradigmatic shift for the telecommunication switching industry because it was developed in another industry, the computer networking sector. Furthermore, circuit switching and packet switching are not only different technologies but they rely on completely different assumptions about the network infrastructure management (Kavassalis, Solomon & 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. Consequently, packet switched networks cannot guarantee a defined QoS level, an unquestioned requirement for traditional telecommunication manufacturers (whose monopolist users had to pay for any network failure). ATM switches constitute a technological trajectory developed by telecommunication manufacturers trying to adapt packet switching to their competencies and needs. In fact, ATM can be defined as a Connection-Oriented Packet-Switched Network, a hybrid form between the two switching modes. 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. Conversely, IP-based switches emerged within the computer data networking sector. As a result of the huge market for office switches, as well as the fierce competition, the price/performance ratio of such IP-based switches decreased dramatically over the years. Their success was determined by the rapidly increased demand for data communication and therefore the push towards broadband networking. Although strictly technical 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).

5 Empirical analysis

The empirical analysis is conducted in two stages: First of all we take a brief look at the evolution of the patent citation network structure before discussing the evolution of the top main paths. In particular, section 5.2 will focus on the technical content and so the heuristics disclosed in the patents on technological trajectories. It is worth noting that the available data cover the period from 1924 to 2001, therefore only allow us to analyze the transition to the last paradigm identified in table 4.

5.1 Network analysis

Table 6 reports the sample size for the periods considered in the empirical analysis. Consistently with the general empirical evidence (Hall, Jaffe & Trajtenberg 2001), the network increases in size both in terms of number of patents and citations. Furthermore, the number of components sharply decreases with the emergence of one large component[25] including 98% of all the patents.

[Table 6 about here]

[Figure 2 about here]

Figure 2 shows the time structure of the network. It reveals a levelling-off of the *isolates* and therefore the emergence of a highly connected network. The increasing number of *startpoints* coupled with a decreasing number of *endpoints* indicates that new streams of research converge at a limited set of *endpoints*. A mechanism of sharp selection seems to be in operation. Finally, the number of components hits a low in the late 1970s, mid 1980s, and at the end of the period considered. The process whereby new patents connect previously disconnected components is consistent with a process of knowledge integration and consolidation. Although we do not make any assumptions about how to relate the emergence of new generations and paradigms to the network structural evolution, the time of the lows is consistent with the consolidation of different generations of digital switches and the emergence of the packet switching paradigms.

A standard way to describe networks is looking at how centre and periphery relate. Common centrality indicators, such as indegree, outdegree, and betweenness are reported in table 7.[26]

[Table 7 about here]

In the patent citation network described in section 3, the direction of the arcs follows the direction of the knowledge. Therefore, outdegree and indegree represent the number of forward and backward citations respectively. It follows that vertex outdegree is a measure of the importance and economic value of the patent (Gambardella, Harhoff & Verspagen 2008). Outdegree and indegree centralization indexes display opposite trends. The decrease in the outdegree centralization index means that despite the increase in the number of citations, "highly cited patents" are relatively less important. This is consistent with the idea expressed by Chapuis and Joel (1990, page 10) that switches are ". . . collective undertaking. . . " where ". . . very few names [...] because they have directed successful projects [...] emerge from anonymity. . . ". Finally, we notice an increase in the betweenness centralization index, indicating an increasing variation in vertex betweenness.

5.2 Connectivity analysis

The aim of this section is to apply the connectivity method presented in section 3. This will lead to the identification of different technological paradigms and trajectories in the telecommunication switching industry. In particular, the search algorithm will analytically recognize

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[25] A component is a subnetwork in which there is a path between all pairs of nodes (i.e. all the nodes are reachable) and there is no path between a node in the component and any node not in the component.

[26] Note that closeness centrality is not calculated here. Due to the unconnected nature (there is no path between each vertex pair) of the network, it is not possible to calculate an overall closeness indicator. All the measures indicated are generally calculated for an undirected network, however with some qualifications they can also be used for a directed graph (Wasserman & Faust 1994).

trajectories, whereas paradigms will be distinguished by looking at the trajectories over time and the analysis of the technical contents of the patents.

Figure 3 displays the largest components of the network of main paths corresponding to the second step explained in section 3.[27] The network in the figure is ‘suspended’ as it is not possible to give a meaning to the horizontal and vertical dimension. However, because of the acyclicity of the network, the direction of the links incorporates the direction of the time. Patents with the same colour converge at the same *endpoints*. The size of the *endpoints* depends on the number of *startpoints* converging on it. Therefore, it proxies the power of attraction of an *endpoint*.

[Figure 3 about here]

A visual analysis of the network of main paths highlights the presence of two environments indicated by A and B. In environment A it is possible to distinguish one *endpoint* (6400711), which is attracting more than half of the *startpoints*. This means that chains of innovations start independently, however the selection process points to the same few patents. On the other hand, in the B part of the network, paths are rather isolate, indicating independent or stand-alone chains of innovation. Given such differences, it is interesting to explore in what way the two groups of patents differ. Frequencies and ranks of assignees and technological classes greatly overlap, revealing no differences among these aspects. However, when the top main path is considered, it emerges that all the technological trajectories are found in the area indicated A. That is, all the patents singled out in figure 4 belong to the A side and the junction in the network in figure 3. It follows that in environment A, technological advances are more integrated (as they converge), whereas environment B represents secondary and more explorative research, which ultimately does not emerge. Finally, the peculiar topology of the network in figure 3 calls for the analysis of central betweenness. The main junction is patent 5345446 whose importance (and technical content) is discussed below.

Figure 4 illustrates the evolution of the top main paths (i.e. the technological trajectories) calculated on nested subsamples. The figure should be interpreted in a cumulative way, starting on the right side with the trajectory calculated for the period 1924-1979. As longer time periods are considered, more nodes and branches are added to this early trajectory. For instance, the trajectory for the period 1924-1994 is the union of the trajectories indicated by A, B, C, and D.[28]

[Figure 4 about here]

For each period, more than one trajectory is selected, which means all the paths whose sum of $SPLC$ is above a certain threshold are displayed. As the distribution of the sum of $SPLC$ is skewed, the threshold is always evident, simplifying the choice of which trajectory to display.[29]

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[27] Notice that all the results in this section are derived by using $SPLC$ calculated for paths going from *startpoints* to *endpoints*. However, the use of the search path node pairs ($SPNP$) brings similar results.

[28] For the complete list of patents on these trajectories, their year of issue, and assignees, see Appendix A.

[29] The distributions of the sum of $SPLC$ are available on request.

These trajectories tend to share the main backbone and to differ in *startpoints* and *endpoints*, resulting in a "hub and spoke" structure at the beginning and end of each trajectory. For this reason, the analysis of the patents will mostly focus on the backbone of the trajectories. The qualitative analysis of the patents in figure 4 will validate the trajectories and will distinguish paradigms.

The patents in the first technological trajectory up to 1979 (indicated A) are related to the emergence of a fully electronic switch with the substitution of all the mechanical components with electronic ones. A major problem of early TDM platforms was the achievement of a comparable level of reliability to previous generations. This multiplexing technology implies information is sliced into a sequence of time intervals (the so called time-slots) corresponding to a speech sample. This system easily blocks when no channels are available or time-slots are idle.

Engineers tackled this "blocking problem" in different ways, such as by using the time-slot interchange[30] (patent 3172956)[31], the inclusion of buffering memories for providing delay (patent 3632883) or suggesting an increase in the redundancy knowing already that this is very costly in large systems (patent 3737586).

The solution mostly applied was the time-slot interchange. With the use of time-slot interchange, engineers began building switching networks composed of different switching stages (named T or S depending on the use of TDM and SDM respectively), expanding the overall capacity. For instance, patent 3851105 introduces the problem of choosing how many T and S stages to include and how to link them. The purpose of the invention is clearly stated:

> It is a 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. [...] the provided network has the advantage that is a nonblocking network. (patent 3851105 col.1)

The engineers' task was clearly aimed at the reliability of the system and the cost reduction. They were therefore working on how to make digital switches economically feasible and boost their adoption. In terms of table 5, this early set of patents refers to two trajectories and in particular to the transition between two different multiplexing technologies. Furthermore, these patents also refer to the third trajectory identified in section 4, which regards the control problem. In particular, they tackle the important issue of how to organize the distributed control. Finally, looking at the perceived barriers it emerges that even in this early phase, engineers were conducting preliminary research on how to switch data on a TDM switched telephone network (patent 3974340) and the improvement of existing services such as conference calls (patent 4112258).

The second trajectory, calculated between 1979 and 1984 adds to the previous trajectories'

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[30] This allows the displacement of a time-slot from one channel within a group to the time-slot of another channel, using a delay line adjusted to the code of the called line.

[31] It is interesting to note this patent was granted to Bell Laboratories and among the inventors is Hiroshi Inose, considered one of the fathers of the time-slot interchange.

few patents marked with squares and the letter B (see figure 4). The new trajectory only partially nests on the previous one. In fact, the connection takes place through a single patent (4160127) and patents 3737589 and 3632883 (in A) were substituted with patents 3736381 and 3649763. This change is explained by the technical content of these patents. In particular, patent 4160127 shows a direct improvement over patents 3736381 and 3649763. In the summary of the invention, these earlier patents are explicitly mentioned as inefficient:

> in real time communication switching systems 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 (patent 4160127 col. 1)

Again these patents highlight that the driver for technical change is the need for reliability and the possibility to guarantee a stable QoS. However, in the last part of this trajectory a new challenge is addressed, that is flexibility. In particular, patent 4254498 shows an invention that considers the use of software for flexibility and the controlling distributed processor. The aim of the patent is to provide a system:

> capable of economically and readily increasing or decreasing the switching network capacity [...and...] so that not only hardware but also software is utilized to control the speech path as modules (patent 4254498, col. 2)

Following on from what was stated in section 4, flexibility is a key feature for switches as it ensures the possibility to use the same technology and design for a large range of network sizes. Not surprisingly, this patent belongs to NTT, a network operator. In fact, flexibility is a feature highly valued by "users" (i.e. network operators). Given the high costs of switching equipment and deployment, flexibility ensures a long-life investment by adapting both to increasing and more sophisticated demand. As regards the trajectories pointed out in the previous section, these patents again addressed the control problem. For instance, patent 4484323 covers the control problem as it particularly reveals an invention for improving the reliability of separate control units that deal with routine functions independently of the main processing functions.

The inclusion of patents up to 1989 expands the trajectory with few patents marked with up-triangle and letter C in figure 4. This sequence is "technically" interesting because it shows the emergence of a new technical problem caused by the rising demand for data communication. As already mentioned, the rising demand for data transmission was a key feature of the telecommunication equipment industry between the mid 1970s and early 1980s. Therefore, Therefore how to switch data efficiently by using the existent TDM infrastructure became something engineers was working on. Patents on the trajectory C not only discuss how to adapt TDM for a different purpose (i.e. from voice to data), but they reveal the desire of the practitioners for packet switching. 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 (patent 4521880, col. 1)

Furthermore, the existing electronic circuit switching paradigm was believed to be superior, even when accounting for the 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. [...] It is well settled that digital time-division multiplexed transmission is preferred for **both** voice and data communications (patent 4644529, col. 1, emphasis added)

Therefore, despite the fact telecom engineers were aware of the efficient use made of packet switching in computer networking, they were not considering it as a solution for data transmission. In terms of technology dynamics, this set of patents suggests the engineers' awareness of some functional failure in the existing paradigms. However, the goodness of the new paradigm is still neglected (Constant II 1973).

The patents included in the calculation of the trajectory up to 1994 are diamond shaped and indicated with the letter D (see figure 4). The inventions continue the research performed in the previous period. In particular, patent 4644535 covers some advanced features of multiplexing techniques needed for the digitalization of the whole network and the implementation of the ISDN (the Integrated Service Digital Network). In this respect, the achievement of efficient analogue and digital interface would allow the integration of speech and data on the same lines, adding features that were not available in the classic telephone network. Furthermore, patents in this trajectory look at the problem of connecting different vintages of transmission systems to the switching system. For instance patent 4967405 recognizes that optical cables are the future and they will substitute copper wire, however, the replacement cannot be instantaneous and therefore different technologies have to co-exist.

Adding the data up to 1999 (patents indicated with down-triangles and letter E in figure 4) completely changes the structure of the network. The method detects an alteration in the direction of technical change, as patents indicated B, C, and D are no longer part of the trajectory. Patents in the E part of the trajectory are contemporaneous with patents discussed in the previous pages (for instance, patent 4451827 was granted in 1984, just like patent 4485467 in figure 4), however they only *become* relevant (belonging to the network of top paths) after 1994. In fact, a change was observed in what is perceived as technically relevant and in judgement about packet switching. The great technical differences between the patents in the B,C,D groups and the E group is that the latter does not focus on how to use existing TDM technologies for data communication but new solutions are examined. In particular, the superiority of packet switching (or more generically, cell switching[32]) is recognized. The visible obsolescence of the old trajectories identifies a paradigmatic shift. Patent 4956839 reports:

> 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

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[32] Cell switching generically refers to the practice of splitting the transmitted information in packets (or cells).

> 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 seemed 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. (patent 4956839, col. 1)

The paradigmatic change brings about a change in the technical issues addressed by engineers. These would focus on: the integration of the new technology into a (vintage) network infrastructure and the reliability of voice transmission over packet switching. Along this line, patents 4603416 and 4782478 propose to exploit the analogy between packets and time-slots to switch packets over TDM infrastructure. Later patents introduce the idea of a virtual circuit in order to mimic the dedicated bandwidth characteristics of the circuit switching network. As discussed in the previous section, this hybrid form of packet switching (such as Connection-Oriented Packet-Switched Network) allows for predetermination of the bandwidth available. The advantage of such a virtual network is twofold: to control the network usage (the connection is established in advance and will last for the entire duration of the transmission), and to reduce routing calculations (the routing algorithm is used only once for each virtual circuit and not for each packet). The introduction of this virtual circuit is a distinguishing feature of the Asynchronous Transfer Mode (ATM) switch, which represents a trajectory of the packet switching paradigm. 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 time-slot 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, also the idea of reliability changes, moving from the blocking problem to the loss of cells problem (506210), or the possibility to set a priority in the switching of cells in order to ensure different minimum QoS levels 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 and for narrowband communications, in particular voice.

The last technological trajectory is indicated in figure 4 by the letter F and it corresponds to the calculation of the top main path for the whole sample. In this case also, we can see a different direction of technical change, even if less dramatic than in the previous case. In fact, only the last part of the trajectory became obsolete as the new trajectory is only partially built on the previous one. Patents on the trajectory F depart from the use of ATM switches, despite patent 5390175 still being related to this generation. In particular that patent points out ATM is not efficient in handling simultaneous low and high speed traffic. However, the inefficiency is not solved by dedicating bandwidth but the prioritization of packets in order to differentiate the guaranteed level of QoS (patents after 534546). Therefore, the patents in this trajectory abandon the idea of the virtual circuit moving to the IP based switches. The discarding of the ATM trajectory is not surprising, as ATM was not a very successful switching platform mainly developed by telecom manufacturers (and not even all of them) as a compromise between circuit and packet switching. Finally, we can see how the two trajectories of the packet switching paradigms are visible by comparing the E and F parts of figure 4.

A final remark in support of the paradigmatic change observed in figure 4 regards the analysis of the assignees of the patents among the trajectories. Indeed, new entrants are observed in the last trajectories. Firms in the data communications industry (e.g. Malibu Networks, 3M Communications[33]) are able to tap into the relevant technology, represented by the trajectory of the telecommunication switching industry. The concentration of new entrants in the latest technology confirms something already emerging from the patent analysis, which is the presence of differences in incumbents and new entrants' technological preferences (Antonelli 1995). Incumbents who want to fully exploit their legacy and capabilities tend to favour 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 reduce the role of network externalities (Antonelli 1999).

6 Conclusions

Technological paradigms and trajectories are properties of both the knowledge and artifact space. The limited empirical literature on technology dynamics tends to focus on artifacts which is why this paper examines paradigms and trajectories in the telecommunication switching industry at the knowledge level. The rationale of focusing on such a level of analysis stems from the work of technology historians, who recognize that technologies have their own inner dynamics, which might hamper (or even prevent) prompt responses to market changes (Vincenti 1990, Constant II 1973). Therefore, we contend that the motion for such dynamics is provided by the engineering heuristics that guide the exploration of the knowledge space.

The aim of this paper was to investigate the microdynamics of technical change in the telecommunication switching industry by looking at the evolution of the engineering heuristics. In fact, the stability and discontinuities of such heuristics discriminate between 'normal' and 'revolutionary' patterns of technical change. The novelty of this paper is twofold: first, a validation of an increasingly applied quantitatively method for mapping technological change by singling out the engineering heuristics of the patents on the trajectories; second, to explicitly link the knowledge level to the artifact level. Patents are particularly suitable for these tasks as they provide detailed information about the invention and its background. In particular, according to the legislation, the validity of a patent depends on its novelty, utility, inventive step, non-obviousness, industrial applicability, and *prior art*. Therefore, a patent has to supply all this information that can be also used to understand the type of technical problems tackled by engineers over time, the solution proposed, and the heuristics applied.

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[33] See Appendix A for the complete list.

While moving to the conclusions, an explanation is required why the telecommunication switching industry was chosen for such an exercise. The industry is an interesting case for this type of analysis because in the period under examination its technology evolution is characterized by 'normal' and 'revolutionary' periods. Therefore, it is possible to assess the operating methodology in terms of trajectories as well as paradigmatic shift. Finally, it is an industry in which we can easily distinguish the different generations.

The established facts mostly told as a sequence of generations of artifacts were realigned into a theory of technological paradigms and trajectories. A paradigmatic shift brings about major changes at knowledge level. In particular, the transition to new technological paradigms makes existing technical competencies, engineering heuristics, and technical bottlenecks obsolete. The results of this 'realignment' process described in section 4 show that there is no isomorphic map of technological paradigms and generation shifts. In fact, the seven switching generations are clustered into four technological paradigms. We can conclude that a paradigmatic shift is always (almost by definition) competencies destroying (Anderson & Tushman 1990), whereas, a generations shift only sometimes. Therefore, engineering heuristics are characteristic of a paradigm defined at knowledge level and not at artifact level.

The technological trajectory identified by the network analysis on the patent citation network matches the paradigms and trajectories previously identified. Patents prove to be a valuable source of information about the drivers of each inventive step. It clearly emerges that the two paradigms empirically identified evolve in different ways, and in different technological dimensions and bottlenecks. The emergence and consolidation of the "electronic circuit switching" paradigm are led by the new opportunities offered by electronic (semiconductor) components and their employment for a reliable and economic viable switch. As time passes, patents highlight a shift in the technical problems that now address the challenge emerging from the continuously increasing demand for data communication. Patents capture not only such transitions but also the uncertainty about the new paradigm (i.e. packet switching). In particular, engineers recognize the emergence of a newly demanded service, their solution is a rejection of the new paradigms in favour of adaptation of the existing or hybrid solution. Again patents clearly document the uncertainty distinctive of a paradigmatic shift, which in this case is both technical and conceptual. The analysis of the dynamics of heuristics supports Constant's view (1973) about the dynamics of technological paradigms: the transition took place when an alternative paradigm existed and its superiority could be tested.

A further result of this paper is purely methodological and regards the power of the Hummond and Doreian approach to detecting a paradigmatic shift. Indeed, if on the one hand the 'main flow of knowledge' matches technological trajectories and the natural evolution of technology, on the other hand it is not so objective in its detection of paradigmatic change. However, the results in the empirical section show how the algorithms successfully detect the obsolesce of previous trajectories and the disruption of cumulative patterns. Even if it is not explicitly stated, the method successfully detects discontinuities. However, as these are not by definition paradigmatic changes, qualitative analysis of the patents is still needed to classify a radically disruptive technological change as a paradigmatic shift.

To conclude, the methodology applied can be regarded as a meaningful combination of quantitative and qualitative research, allowing for in-depth analysis (often lacking in quantitative approaches) and generalization (often missing in narratives). Therefore this method can be used to expand the systematic understanding of technical change for industries where patents are an effective way to appropriate innovations. The potential to apply it in several industries could provide the basis for a comparable body of results on technology dynamics. Furthermore, as shown in the case of telecommunications switches, such a method can extract the artifact level. Therefore, it can be used to study the evolution of technical change in industries where technological advances are not clearly measurable by artifact performance.

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A Appendix: List of patents on 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				
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

Patent	Year	Assignee	1924-1979	1924-1984	1924-1989	1924-1994	1924-1999	1924-2003
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

B Appendix: List of tables

Table 1: *Technologies and switching platforms*

	Time Frame[1]	Generation	Model
1	1870-1890	Manual switch	Switchboard
2	1889-1960	Electromechanical direct-control step-by-step system	Strowger, Lorimer, Rotary
3	1930-1965	Electromechanical indirect-control or common control	Panel and Crossbar
4	1965-1975	Electronic switch	No.1 EES, AKE, EWS, etc. etc.
5	1970-1985	Digital *centralized* SPC command	No. 4EES, AXE, EWS-D, etc. etc.
6	1980-1990	Digital *distributed* SPC command	
7	1990-...	Packet Switching	ATM

Source: Adapted from Chapuis & Joel 1990.

[1] The time frame is indicative and refers to their commercialization and diffusion.

Table 2: *Generations of switches and characteristics*

Generation	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Manual	Patchcord	Manual	No multiplexing		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, analog integrated circuits, transistors	
Digital 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 decentralized SPC command							
Packet Switching		"Intelligent" store-and-forward		Digital, packet switched, broad-band	Voice and high-speed, bursty data services	VLSI (Very Large Scale Integration) integrated circuits	Automatic dialing

Note: Numbers in the columns indicate the technical characteristics listed earlier: (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.

Table 3: *Emerging of new paradigms*

Generation	Competencies needed	Perceived barriers	Engineering heuristics
1	Handcraft	Up-bound of penetration ($\ll$100%) and *switchboard problem*	Connecting everybody
2	Limited knowledge of 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), cost of analog and digital interfaces	Integration of transmission, new services
6	Extensive programming skills	Quality of Service (QoS)	Digitalization of the full chain (ISDN)
7	Computer network skills, more math skills		Widespread deployment of broadband infrastructure

Note: Numbers in the rows refer to the switch generation: (1) manual, (2) electromechanical direct-control, (3) electromechanical common-control, (4) electronic switch, (5) digital centralized SPC command, (6)digital distributed SPC command, (7) Packet Switching.

Table 4: *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	analog - Digital Space-division (SDM) - Time-division (TDM) digital *centralized* control - digital *distributed* 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.

Table 5: *Possible combinations*

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

Source: Chapuis and Joel (1990).

Table 6: *Size of the network*

	Patents	Citations	Number of components	Size largest component	Percentage[1]
1924-1979	1459	2134	68	1095	(75%)
1924-1984	2089	4059	52	1784	(85%)
1924-1989	3046	7539	54	2749	(90%)
1924-1994	4060	10762	54	3662	(90%)
1924-1999	5623	16311	53	5180	(92%)
1924-2003	6214	20848	8	6120	(98%)

[1] Percentage of patents belonging to the largest component.

Table 7: *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%

C Appendix: List of figures

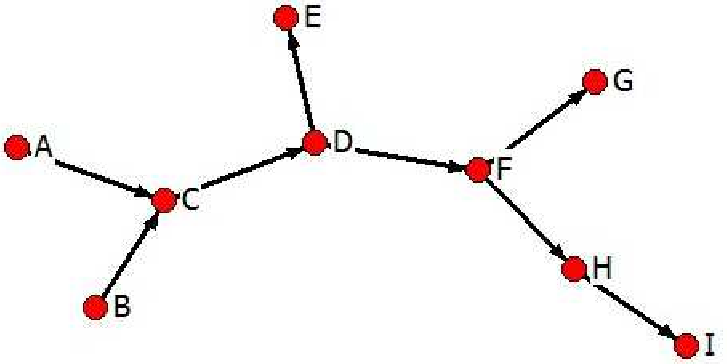

Figure 1: Example of a patent citation network

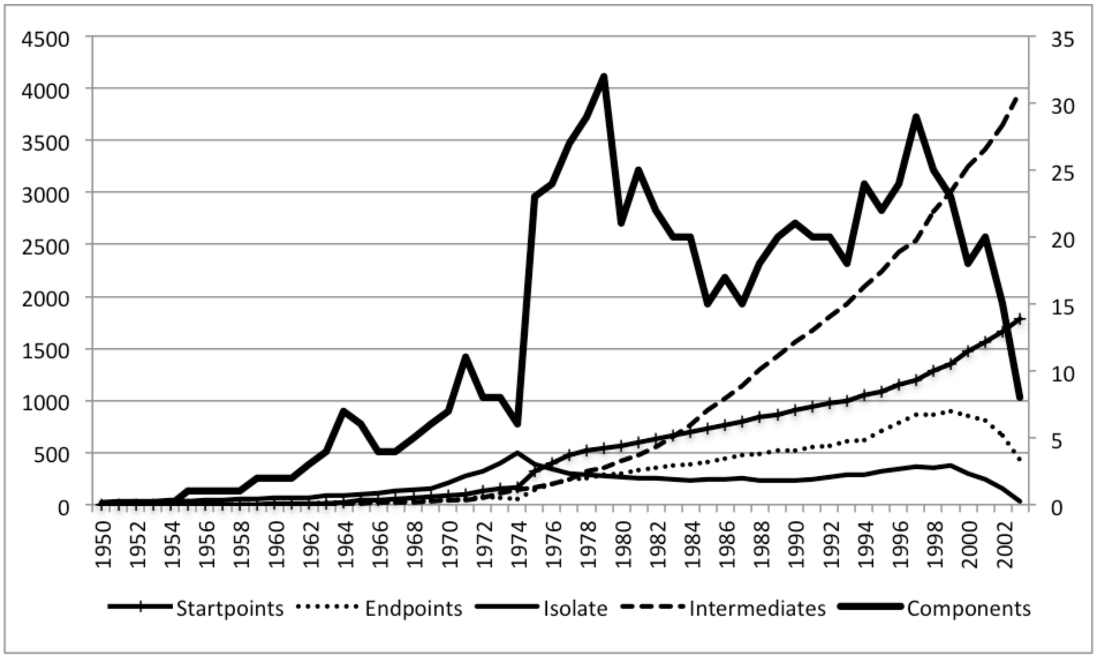

Figure 2: Timestructure of the patent citation network

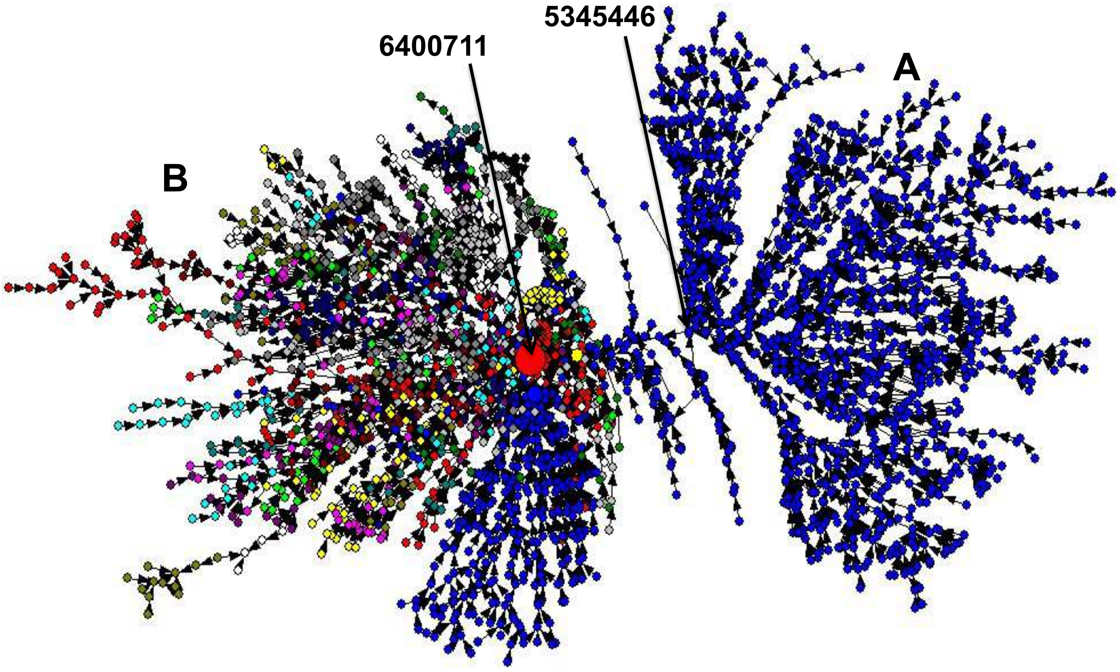

Figure 3: The largest component of the network of main paths

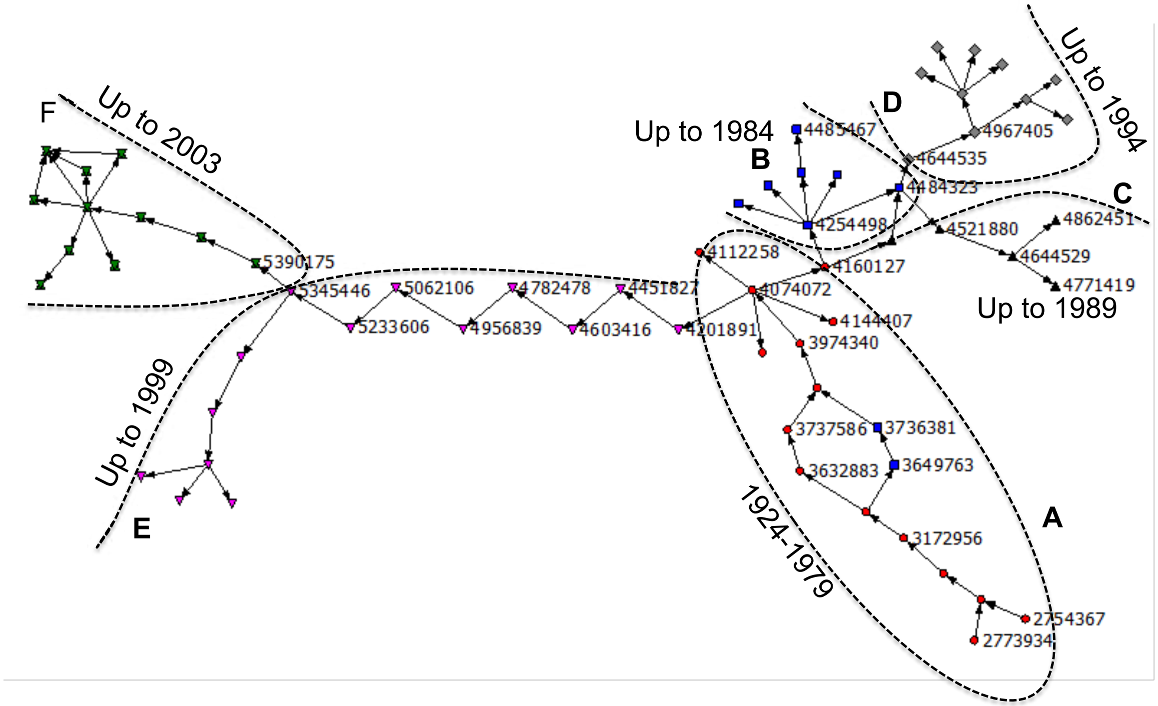

Figure 4: Union of the top main paths calculated on a nested subsample