Knowledge positions in high-tech markets: trajectories, standards, strategies and true innovators

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Standardization is an important yet underrated economic alignment mechanism, where the rate and direction of technological change is being negotiated between firms. In high-tech industries, standards are becoming increasingly important, as they are needed to ensure interoperability between complex products, services at various points in the value chain. An important aspect is the knowledge positions that firms occupy have in such technologies. Strong knowledge positions may increase chances for sustainable participation, market success, bargaining power and licensing revenues. In the recent literature, so-called essential patents have been used as an indicator for firms' knowledge positions in standardized technologies. These patents are found to be more valuable and have a longer citation tail than 'average' patents. There is growing evidence, however, that this indicator is biased because a considerable number of essential patents seem to the result of strategic conduct and not included because of their technical merit.

In this paper, we explore alternative ways to determine firms' knowledge position, based on network analysis and trajectories. We also propose extensions to already known methodologies. Our aim is to determine whether this alternative methodology better matches the technical/historical accounts of the technology field. To do so, we also look in detail at the strategic conduct of the firms in question. We present empirical results based on data from the field of mobile telecommunications. We conclude that, for our case, the various network-based methodologies offer better insights into actual knowledge positions. We expect our findings to hold in standard-based industries but likely also in other high-tech industries.

1. Introduction

In the last decades, there has been an increasing importance of what Cohen, Nelson and Walsh (2000) have called "complex product industries". In such markets, technology and knowledge have a systemic nature, relying on the integration of many different, interrelated and interdependent contributions. In the same industries, standards are becoming increasingly important, as they are needed to ensure interoperability between complex products and services at various points in the value chain. While such interoperability standards were initially found in the consumer electronics and telecommunications sector, now such standards start to become indispensable in other areas including service sectors (e.g. banking), IT systems, public transport, logistics and intelligent transport systems, biometrics and agricultural systems. Standardization is an important yet underrated economic alignment mechanism, where the rate and direction of technological change is being negotiated between stakeholders (Schmidt & Werle, 1998). Standards can dominate technical direction, activities and search heuristics, and thus influence technological change, whilst at the same time being the result of technological change. In many complex technology fields, standardization is the primary method of achieving alignment between actors.

An important aspect is the knowledge position that a firm occupies in such technologies. In fact, strong knowledge positions may increase chances for market entry, sustainable participation, and market success. For instance, Bekkers, Duysters and Verspagen (2002) show how one single company, occupying a strong knowledge position, was able to fully dictate market entry into the emerging GSM market. Knowledge positions may also contribute to bargaining power and, if secured in patents, also licensing revenues. Without wanting to overemphasize the latter, we observe that such revenues can be substantial. For instance, holders of patents relevant for DVD players charge a total of approx. US$ 9 or more per player (depending on the features); for mobile phones, firms pay approx. 8% (GSM) to 12% (GSM+3G) running royalties; for the Americal digital TV standard ATSC, IPR owners charge US$ 5.00 per receiver, and for including a Firewire port in a device, IPR owners charge US$ 0.24.[1] Parties that own relevant IPR themselves may enter into cross-licenses, reducing the fees to be paid (which again confirms the monetary value of knowledge positions and patents).

If knowledge positions are of such strategic importance, the question arises on how one can measure these. For high-tech, standards-dominated markets, a common way to do this is to analyse the distribution of the so-called essential patents. This method relies on information that is generated in an IPR-related process that is implemented in most standards bodies. Standards bodies face the challenge of ending up in situations where patent owners would not be willing to license other parties that want to adopt the standards. This is especially troublesome for so-called 'essential patents': those patents that are indispensible in order to make products that comply with the standards, because there are no alternative means to do so. To this end, most formal standards bodies have adopted a so-called FRAND (Fair, Reasonable and non-discriminatory) policy. Under this policy, members are obliged to notify of any essential patent they hold, and are requested to issue a public statement that they are willing to license these under the FRAND conditions (which almost every member eventually does[2]). Over time, the number of patents notified under FRAND policies has grown strongly. For recent mobile telephony standards, over 1,000 unique patents are claimed by more than

[1] DVD fees estimates are based on fees for the Philips/Sony joint licensing programme (Philips, 'Royalty rates for selected DVD and BD products', retrieved on 2 February 2010 from https://www.ip.philips.com/services/?module=IpsLicenseProgram&command=View&id=27&part=8) and the fees of the DVD6C Licensing Group (DVD6C, 'Offer letter to Existing Licensees, 1 September 2010', retrieved on 2 February 2010 from http://www.dvd6cla.com/), as well as fees of the DVA Discovision Associates, (DVA 'Licenses', retrieved on 2 February 2010 from http://www.dvd6cla.com/). Further licensing fees might be due to Thomson, the DVD Copy Control Association, and Microvision. ATSC and FireWire estimates are based on the licensing programmes published by the MPEG Licensing Administration (http://www.mpegla.com).
Mobile telecommunications fees are based on Interplay, 2010.

[2] If a patent owner refuses to do so, the standards body eventually has to find an alternative definition for the standard, not drawing upon that patented technology, or has to abandon the work on the standard altogether.

60 different owners (Bekkers & West, 2009). This may lead to considerable transaction costs and delays, as well as to high cumulative licensing costs ('royalty stacking'), though the latter point is a subject of discussion (see (Lemley & Shapiro, 2006) and (Geradin, Layne-Farrar, & Padilla, 2008) for proponents respectively opponents of this view.

A number of recent papers have studied essential IPR and essential IPR portfolios. These include the work of Bekkers, Duysters & Verspagen (2002), Goodman & Meyers (2005); Anne Layne-Farrar (2008), Bekkers & West (2008), and Rysman & Simcoe (2007, 2008). While each of these studies has a somewhat different focus, they all rely on essential patent databases as an expression of important knowledge and firms' knowledge position.

While lists of claimed essential patents are surely the most tangible expression of patents in relation to standardised technologies, such lists have some inherent limitations. Here, we discuss three causes of such limitations. First, patents greatly differ in actual value, and this field is no exception to this rule. Counting essential patents in order to estimate knowledge positions may therefore introduce a strong bias. A standard way to mitigate this problem is by weighting patent counts with citations. However, citations are far from a perfect indicator of economic value (see Gambardella, Harhoff, & Verspagen, 2008), and it also hard to decide how much weight should be attributed to citation performance. Second, given the strategic value that an essential patent offers to its owner, there is a concern that claims of essentiality are the result of strategic behaviour of the patent's owner instead (or in addition) of the actual technical relevance. A strategically operating patent owner might opt to get deeply involved in the drafting of the standard and use opportunities to suggest technologies that it owns patents on. If other participants have a similar agenda and incentives for such practices, it will result an increase of their own portfolio of essential patents. In a recent study by Bekkers, Bongard and Nuvolari (2010) it was shown that strategic involvement was a better determinant of claimed essentiality than the actual technical merit of the patent in question. Third, the design of the IPR procedures creates some degree of uncertainty about using the lists of essential patents as indicator for knowledge position. In particular, there are at least four aspects to consider: (1) Companies are allowed to submit 'blanket claims', stating that they will license essential patents on FRAND conditions. However, such blanked claims do not reveal individual patents. Companies that submit such claims may possess large portfolios of essential patents, but it is also possible that they do not own any essential patent at all. (2) There is some degree of strategic 'over-claiming', where firms declaring patents to be essential while in fact they are not. Such strategies are likely to differ between firms. (3) Standards bodies encourage early declarations, submitted before the patent is granted and/or before the standard is finalized. However, a granted patent may not be as broad as the original application and thus might not be essential anymore. Also, the final standard might be different from earlier draft versions, and disclosures that were appropriate for a certain draft version might not be essential for the final version of the standard. Since many standards bodies do not require parties to update or withdraw earlier disclosures, such declarations remain in the IPR database. (4) IPR owned by non-members may be missing. These parties are not obliged to disclose essential patents, although they may voluntary do so.

Attempting to explore better ways for estimating knowledge position, this paper turns to network-based methodologies. This paper uses the connectivity approach proposed by Hummond and Doreian (1989) for mapping technological trajectories. This method was originally devised for the analysis of publication networks, however it can be equally used for patent networks. Such networks link patents through the citations mapping the knowledge flows occurring between them. Without entering in the details of the indicators and the search algorithm used by this method[3], we can say that it consists in the identification of the "main flow of knowledge" within the patent citation network. This main flow of knowledge is a set of connected patents and citations (i.e. a path) linking the largest number of patents of the network. Because a citation is (also) a knowledge flow, this path cumulates the largest amount of knowledge flowing through citations in the network. This path represents therefore a local and cumulative chain of innovation consistent with the definition of technological trajectory put forward by Dosi (1982).

This methodology has been successfully applied to several patent networks (Verspagen, 2007; Mina et. al. , 2007, Martinelli, 2008 and Fontana et. al. , 2009), however the novelty of this paper is the analysis at firm level of such trajectory. This analysis goes beyond the count of the assignees owning patents on the trajectory. In fact, such approach would be too selective (i.e. considering a very limited number of patents compare to the firm's patent portfolio) and too granular (i.e. too dependent on small variations). In this paper we enlarge this perspective by considering not only the patents on the trajectory but also the patents contributing to the trajectories. In fact, respecting the direction of the knowledge flow, we can identify three types of patents. Figure 1 illustrates them and their characteristics.

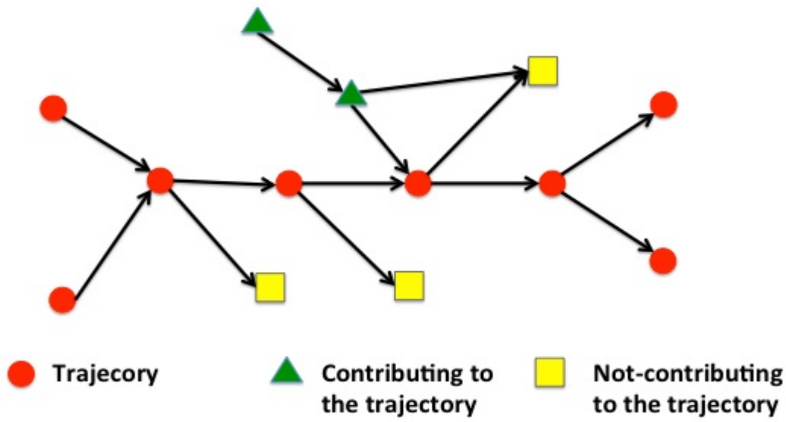

Figure 1. Network example

Patents indicated with a red circle are the ones that belong to the technological trajectory. Green triangles are patents not belonging to the trajectory, however, they contribute to it as some of their knowledge flow to it. In broad sense, the potential to contribute to such trajectory corresponds to the technological opportunity faced by each company. Finally, the yellow squares are not contributing to the trajectory.[4] Given this, it

[3] For the details of the approach see Hummon and Doreian (1989). For an application to patent citation network see Verspagen, 2007.
[4] With some caution, the distinction between yellow and green patents has some similarities with the weak and strong component concepts. In a network sense, green patents are strongly connected to the trajectories, as there is a path

is interesting to decompose the firms' patent portfolio by looking at their proportion of red (circles) and green (triangles) patents. The comparison by firm of such proportion and its evolution over time allows evaluating the firm's knowledge position in the technology under examination.

To conclude, this paper has three aims:

- Test whether the network trajectory analysis does a better job in predicting knowledge positions than approaches based on essential patent analysis
- Propose an adaptation of the common network trajectory analysis approach in order to better capture knowledge input and generate less selective results
- Extend network trajectory analysis with a firm-based approach

For our empirical data, we turned to the two most important generations of mobile telecommunications systems. Not only do they represent a very sizable market and of strategic value to its players, it is also one for which there is good availability of data, both for historical accounts and for patenting position. In this paper, we focus at the transition from 2G to 3G technologies.

In order to fulfil its aims, this paper starts with an extensive technical narrative of the case study we will use to test the various approaches (Section 2). We believe that this narrative needs to go into a considerable degree of detail, not only to do justice to the quite complex development path of such technologies, but also to be able to judge upon the actual knowledge positions of actual firms. Knowledge positions are assessed upon the (a) actual contribution of firms to key technical advances and (b) the licensing payments between firms, which we believe reflects the bargaining position on the basis of knowledge position. Section 3 of this paper reports the results of an essential patent analysis, and confronts these findings to the technical narrative. Section 4 of this paper presents our alternative approach, using network trajectory analysis, and proposes several new additions to this field. Again, we confront these findings to the technical narrative. Finally, Section 5 compares the outcomes of the two approaches, draws conclusions and offers a discussion.

2. A technical narrative of 2G and 3G mobile telecommunications

This section aims to introduce the main technological developments in the field of mobile telecommunications, the involvement of specific actors, and the associated standardisation efforts. In this field, it is common to distinguish between four main technological generations, dubbed 1G to 4G. Each generation has its own, distinct standards. Table 1 provides an overview of the various aspects of the four distinct generations. This section will specifically focus on the second and third generation, which are the generations on which we will focus our empirical analysis.[5]When discussing the technology and standardisation for these generations, we will pay specific attention the engineering challenges that came with the various new developments.

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linking them to the trajectory. Whereas, the yellow are only weakly connected as there is a semi-path connecting them to the trajectory.

[5] For two different reasons, the other generations are not very suitable for our empirical analysis. At the time of the first generation, firms did not patent many inventions. The fourth generation yet has to crystalize; there is no good insight in the relevant or essential patents yet, and many patens will be relatively new and therefore have few incoming citations, if any.

While we aimed to keep this a brief narrative, we feel it is necessary to go into some degree of detail in order to be able to use this narrative as a reference point of the knowledge position of firms. Unfortunately, as with other treats on standards, the extensive use of acronyms is unavoidable. For the convenience of the reader, we do not spell each of them out in the text but instead offer an annex with acronyms.[6]

Table 1. Summary of main technological generations / standards

	1G	2G	3G	4G
Most successful standard(s), main decision	AMPS/TACS (1970s) NMT (1970s)	GSM (1986) IS-95 cdmaOne (1993)	WCDMA/UMTS (1998)	'3.9G': LTE (frozen December 2008) 4G: LTE-A
Commercial services[7]	1983 (US), NMT (1981)	1992 (GSM) 1995 (IS-95 cdmaOne)	2002	2009 (small scale)
Sub-standards /improvements	Various	2.5G: GPRS (2000): packet data services EDGE (2003)	3.5G: HSPDA (2006): Improved data rates	
Design requirements	- Low to medium capacity mobile telephony	- High-capacity voice capacity at lower system price - Cost-efficient coverage in both urban and rural areas	- Support wide diversity of services including internet access; substantial improvement in data speed - Low costs for terminals and networks (minimizing required number of cell cites / antenna towers). - Low power consumption at terminals - Operation up to 300 km/h - Cost-efficient coverage in both urban and rural areas - Handoff to 2G systems	- Substantial improvement in data speed - Lowering infrastructure costs per capacity unit - All-IP core network integration - Flexible spectrum use
Candidate technologies (*: winner for most successful standard)	*FDMA (analogue)	*TDMA CDMA	Advanced TDMA[(a)] TDMA/CDMA hybrid[(b)] *WCDMA[(c)] MC-CDMA OFDM/ODMS	WCDMA *OFDM
Main technological challenges	Various, including mobility management, handover, and handsets	- Synchronisation and timing within a cell - Multipath fading (solved by the channel equalizer ('Viterbi equaliser') and frequency hopping) - Efficient speech compression - Handover processes - Energy consumption	- Power control within a cell - PN code sets - Timing/synchronization between adjacent cells - Signaling / pilot channel - Integration with 2G (inc. handoff)	Increasing spectral efficiency

(a) Also known as A-TDMA or the 'FMA-1 without speading' proposal or the Gamma (χ) proposal
(b) Also known as TD/CDMA or the' FMA-1 with spreading' proposal or the Delta (δ) proposal
(c) Also know as DS-CDMA or the 'FMA-2' proposal, or the Alpha (α) proposal

2a. TDMA_based second generation mobile networks (2G)

Whereas first generation, analogue networks pioneered mobile telephony services, their system capacity was low and prices per subscriber were high, both for the infrastructure as well as for mobile terminals. More than a dozen, mostly national standards emerged, many of which lacked economies of scale. At that same time, consumer interest in mobile telephony grew and the technology started to attract more and more the attention of the highest management at the telephony operators and the

[6] While this text offers some sources, we refer to the following documents for a more complete listing of sources: Bekkers (2001), Garrard (1998) and Hillebrand (2003).
[7] It is often hard to determine when the actual introduction of commercial services takes place, as technology demonstrators and trials gradually become commercial services. This row aims to indicate the date when which the first real commercial services with a substantial geographical coverage were offered.

network equipment manufacturers (if fact, some of the earliest systems had been build without any knowledge from the top management).

Technologies. While the potential for a mass market was increasingly being recognised, it was evident that a huge leap in system capacity and in cost-performance ratio would be necessary. Opportunities to do this were recognised in adopting digital technologies. A digital mobile network would supposedly have higher spectrum efficiency than analogue systems, by introducing speech compression techniques and by allowing the re-use of frequencies between base stations that are relatively close to each other, among other things. Going digital would also allow the introduction of Time Division Multiple Access (TDMA). With this access scheme, users are not given a unique and exclusive frequency for a call, but are only given a slice of time (time slot) on a frequency. In this amount of time, they need to exchange all their (digital) voice data. In this way a number of users can share the same transmitter and receiver in a base station. This approach would allow for considerable cost-savings in the infrastructure. Finally, a digital system would result in great cost-savings in the mobile stations due to the anticipated, spectacular increase in performance/cost ratio of digital components.

Certainly, digital radio technologies also posed great challenges to the firms that were involved in its development. The main engineering challenges can be traced in the technical literature during the early development period.[8] These challenges included the synchronisation and timing within a cell (addressed by a method called 'timing advance'), dealing with reflection of fast radio signals ('multipath fading'), and efficient compression of digital speech. Furthermore, engineers had to anticipate the degree of data processing available in an affordable way to low-power mobile device.

Standardization and adoption. For the second generation of technologies, the (mostly government owned) European telephone operators were strongly in favour of a joint effort to define a standard. By combining their markets, they were hoping to fuel competition between suppliers and get a wide availability of cost-effective infrastructure and terminals. In addition, a common standard would allow them to supply lucrative roaming services to travelling business users. In 1982, the formal organisation of national telephone operators CEPT[9] established the Groupe Spécial Mobile and charged them with developing a standard. Most manufacturers were initially rather reluctant to support such a European standard, as it would break the practice of exclusive supply contracts with the national operators (which often included unconditional funding of all associated research and development efforts). However, over time they realised that none of them had the knowledge or financial means to design a full-fledged digital system and to recoup their investments in a national market only. Increasingly, companies turned into the strong proponents of the new standard. Although CEPT was normally only open to national operators, it allowed companies to contribute directly to the standardisation of what later be would known as GSM. In 1988, these activities were transferred to the newly established European Telecommunications Standards Institute (ETSI), an organisation with membership open to all stakeholders.

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[8] Particular valuable data can be found in the proceedings of IEEE conferences that brought together researchers in this area (see, for instance, (Fuhrmann & Spindler, 1986; Mäkitalo & Fremin, 1986). We also consulted various handbooks such as (Garrard, 1998), Calhoun (1988), (Hillebrand, 2003), (Mouly & Pautet, 1992). Particularly revealing are the proceedings of the '*Nordic seminar on digital land mobile radiocommunication'* (Nordic_Seminar, 1995).

[9] CEPT: European Conference of Postal and Telecommunications Administrations.

A large conflict loomed over the choice of technological specifications, though. Eight proposals were presented and demonstrated to the representatives of the national operators within the CEPT meeting in Madeira (Portugal) in February 1987. Four proposals originated as collaborations between German and French companies, some with Italian involvement as well. Some of these proposals were technically very advanced and their proponents felt assured of success. Furthermore, these projects benefited from substantial public research funds in those counties. The remaining proposals originated from Scandinavia. While technically more modest, they managed to win the support of the many national operators that served substantial rural areas with low traffic densities and that felt that these systems better met their needs. Eventually, a Scandinavian proposal was selected, but this decision was hard to accept for Germany in particular. Tension raised, and at the top of diplomatic efforts to solve the issue, *"the heads of state in West Germany, France and Britain got personally involved to break the deadlock"* as recalled by the chairman of the CEPT working group at that time.[10] Eventually, a consensus could be reached on one of the Scandinavian proposals, slightly adapted to include some German/French preferences. This was the standard that would eventually be known as GSM. It was initially called after the group that drafted the standard and later christened to Global System for Mobile Communications, reflecting it later ambitions. Not long after the agreement on the basic technology was reached, uncertainty and chaos arose when Motorola, claiming to own several dozens of patents that were essential for the standard, refused to grant non-discriminatory licenses. Because ETSI at that time did not have any specific rules on property right issues (neither did any other standards body, in fact), this posed a serious problem. The strategy chosen by Motorola, which was to enter into cross-licenses with a few large firms but leaving many medium-sized and Japanese firms in the cold, had a decisive impact on market access/structure (see Bekkers et al, 2002 for an extensive discussion). As a direct effect of this conflict, standards bodies all around the world started to establish IPR policies that aimed to guarantee the availability of licenses at reasonable terms (Iversen, 1999). Indeed, after such policies were in place, other companies gradually managed to obtain licenses from Motorola.

After the sky was cleared, GSM was heading towards great success. In a rather unique way, market demand, technology, and political development (including the liberalisation of the European telecommunications market) all acted in concert and created a breeding place for what arguable became Europe's greatest technological success ever (Pelkmans, Garrard, Bekkers). New versions supported new frequency bands and thereby allowed GSM to be used in North America and elsewhere in the world. GSM eventually became the dominant world standard, serving more than 3 billion users. While GSM was certainly the most successful 2G standards in number of adopters, there were other 2G standards as well. D-AMPS and PDC, conceived for the US market and the Japanese markets respectively, were TDMA-based systems that were to a large degree based on the similar technologies as those in GSM.[11]

GSM clearly had its champions and the market was rather concentrated. By 1996, five years after the first commercial network went live, Sweden's Ericsson had a 48%

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[10] Mobile rivals prepare for Paris take-off. (19 January 1998). CommunicationsWeek International.

[11] Most US operators that initially selected D-AMPS for their second generation networks migrated to GSM later on. The Japanese PDC standard did see virtually no adoption outside Japan.

market share of GSM infrastructure, and Nokia, Siemens, and Alcatel shared another 45%.[12] The terminal market was similarly concentrated, with a particularly high share of Nokia from Finland.

2b. CDMA-based second generation mobile networks (2G)

Technology. While all the above 2G technologies were based on TDMA, US company Qualcomm departed from the mainstream path and started working on an alternative technology called spread spectrum (or: CDMA). In this technology, the transmissions of different users are identified by very fast, unique codes. The birth of CDMA can be traced back to the period of the Second World War, to an unprecedented story. Trying to develop a radio link that was immune for jamming, multi-talented Hollywood movie star Hedy Lamarr and piano player George Antheil invented a method of radio communications that continuously jumped from one transmission frequency to the other, in a quasi-random matter.[13] Both transmitter and receiver needed to know this secret, semi-random pattern. In their patent, there are 88 frequencies - similar to the number of keys of a piano - and the pattern was coded in mechanical roll similar to the one in a pianola. Being resistant to jamming, they considered this system to be particularly useful for guiding torpedoes. Lamarr and Antheil patented their invention and offered it to the US army at no charge, hoping to help the allied forces (in fact, their patent No 2,292,387 shows a remarkably detailed application). The military showed no interest, whatsoever. Only in the 1960s, after the patent's expiration, that its value was recognized. This invention not only could withstand active jamming, but also offered excellent security against interception of sensitive communications (eves-dropping), and even dismissed the enemies' ability to locate military units through their radio transmission. The technology became standard in confidential military communications, but its knowledge and main patents remained suppressed until the late 1970s (Calhoun, 1988: 341).

By the 1980s, some creative engineers realised that CDMA could potentially be a powerful and economical basis for large-scale mobile telephony networks.[14] Its broadband nature would - at least in theory - make it immune to many problems that limited the capacity of traditional systems, such as multipath fading. In contrast to military applications, the system would be used in a context where many different communications take place at the same time. Whereas almost all radio systems at that time were designed to minimise interference, CDMA went fully against that logic and has many different users transmitting on the same frequency and at the same time. A handbook on digital telephony technologies of the late 1980s comments: '*viewed from [the] orthodox perspective, the vision of spread-spectrum transmission seems so contrary, even perverse, that it might almost be taken for a jest upon the inflamed sensitivities of the interference-bedevilled radio community*' (Calhoun, 1988: 340). In order to use spread spectrum as the basis for a mobile telephony networks, some great hurdles needed to be overcome. One of them is known as the near-far problem. As explained above, multiple

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[12] Calculations are based on MTA-EMCI data (*Mobile Communications International*, April 1997) and printed in Bekkers & Liotard, 1999.

[12] Anna Couey (1997). About Spread Spectrum. Retrieved from http://people.seas.harvard.edu/~jones/cscie129/nu_lectures/lecture7/hedy/lemarr.htm

[13] Anna Couey (1997). About Spread Spectrum. Retrieved from http://people.seas.harvard.edu/~jones/cscie129/nu_lectures/lecture7/hedy/lemarr.htm

[14] The earliest CDMA systems were based on a principle called Frequency Hopping (FH-CDMA). For mobile telephony, a somewhat different principle is used, known as Direct Sequence (CD-CDMA).

users would be transmitting on the same frequency and at the same time. To distinguish the signals of these users by their code, it is necessary that the received power of each phone at the base station would be almost identical. In a real life situation, where the actual received power constantly changes because of distance, obstacles and reflections, this deemed impossible by many an engineer. In fact, many initially regarded CDMA with great scepticism and claimed that it would never work in practice. Such beliefs are obvious from the following quote: *'From the beginning, critics warned that the compelling theoretical potential of CDMA would never prove out in the field; dynamic power control in rapidly fading environments would be its Achilles heel; interference would vastly limit capacity; systems under heavy load would be unstable; and power balancing would make infrastructure engineering a nightmare.*[15] The sceptics proved to be wrong. Power control, the single biggest engineering challenge for a functioning CDMA system, could indeed be mastered. It was done by so-called open and closed loop power control methods that were conceived, developed and patented by Qualcomm. Soon after, Qualcomm developed a full mobile standard on its own, which was standardised as IS-95 in the US (later known as cdmaOne). As pointed out by Steele & Hanzo (1999), Qualcomm's IS95 system successfully addressed all the major and minor problems that were generally perceived to prevent the use of CDMA in a large scale mobile telecommunications system.

Standardization and adoption. In 1995 – four years after GSM - the first commercial CDMA-based network was launched (Harte et al, 1999). Equipment was initially supplied by Qualcomm only, who started manufacturing IS-95 products by lack of other parties willing to do so. Qualcomm soon found allies in South Korea when that country stipulated CDMA as its mandatory technology in 1996 (Lee et al, 2009). LG and Samsung, among others, supplied the large-scale infrastructure and the handsets, after entering into a licensing agreement with Qualcomm. Also in the US, operators showed interest in this standard. By the end of the 1990s, 114 out of 431 US wireless service providers had chosen IS-95 as their technology (Singh & Dahlin 2007), of which Verizon is nowadays one of the largest ones. As a result, more suppliers joined the bandwagon, including Motorola and Lucent and more than a dozen Japanese companies. Perhaps more reluctantly, also the GSM-champions Nokia, Siemens, and Alcatel started to offer IS-95 products in the late 1990s.[16] Even while IS-95 had considerable success in the US and in South Korea, it came to late to dethrone GSM as the dominant 2G technology. By 2008, the global share of IS-95 in the 2G market was approximately 10%, whereas GSM held 88.5% (Informa Telecoms & Media, WCIS, Sept. 2008)

2c. Third generation mobile networks (3G)

Although the various 2G technologies were later upgraded to support data transmission, their data speeds and other features made them quite unsuitable for the demanding data applications that were becoming popular in fixed networks, such as multimedia and internet access. It was perceived that a new, third generation of technologies would be necessary, capable of supporting a wide range of new services, including high-speed data transmission. At the same time, 3G systems were supposed to meet many other –

[15] Source: Bill Frezza, Wireless Computing Associate, "Succumbing to Techno-Seduction," Network Computing, April 1, 1995.

[16] Source: CDMA moves forward, both narrowband and wideband. Mobile Communications International, July/August 1997, p. 47-52.

often conflicting - design requirements, as shown in Table 1. Perhaps most importantly, it was understood that subscribers wanted much higher data volumes but would not be willing to pay much more than they currently did. As a consequence, the new technology had to considerably reduce the cost price per unit of data.[17]

Technologies. The success and extensive geographical coverage of GSM created high expectations from the public, raising the bar for 3G networks. The earliest investigations were aided by R&D funding from the European Union. In particular, the 2nd Research and Development in Advanced Communications Technologies for Europe (RACE) program from 1992-1995 included specific grants for mobile phone technologies. Research efforts increased with follow-up research programmes funded by the European Commission, known as RACE-2, ACTS/FRAMES, and COST. With a budget of 100 million ECU for FRAMES alone, these projects were considerable in size. Contracts were awarded to several firms, including Ericsson, Nokia, Siemens, France Telecom, and CSEM/Pro, with participation from several European universities too. However, in the industry, opinions differed when it came to the most suitable technology to satisfy all the needs. Figure 2 provides an overview of the research frameworks, as well as the competing technical proposal and standardisation efforts as described below.

Within these frameworks, one group of firms worked on what essentially can be seen as extending the TDMA technology of GSM (dubbed A-TDMA, later known as FMA-1). While such extensions did allow for more capacity, it was increasingly understood that technology would be insufficient to really meet the design requirement for third generation systems. As the advantages of CDMA became clearer over time, the group added some CDMA elements to its design. Companies that were particularly active were Siemens and Nokia – although firms were not exclusively tied to one single group. Another group of firms was focussing on CDMA technology instead, as pioneered in the US for 2G systems. Their design was initially known as CoDIT and later as FMA-2. Particularly for 3G systems, CDMA would have additional benefits, being able to deal well with many different traffic patterns at the same time (e.g. telephony, video, internet traffic, telemetric). In terms of system capacity, these 'Wideband CDMA' (W CDMA)designs went quite some steps further than the existing 2G IS-95 CDMA system by Qualcomm. Nevertheless, they heavily drew upon the latter. In research reports, it can be seen that many studies evaluated system performances 'based on a IS-95 like system', and a number of tests were actually using IS-95 chipsets, because they are 'readily available providing a very flexible solution'.[18] In the WCDMA group, Ericsson was the primary contributor. This company also developed its own 'test bed' in order to test features of the technology. Eventually, both groups pushed forwards their design as the basis for the European 3G standard.

[17] As an illustration: per 2005, the network infrastructure costs for a subscriber that was generating 300 Mb/user/month accounted approximately 45 Euro for the older GSM/GPRS standard and approximately 7.5 Euro for the WCDMA HSPA standard. Nowadays, with newer versions of HSDPA, the costs reduced further. Source: Source: GSA, 2005.

[18] For details, see European Commission. (1999). COST Action 231: Digital mobile radio towards future generations systems. Final report. (EUR 18957), especially page 313–318 and page 376.

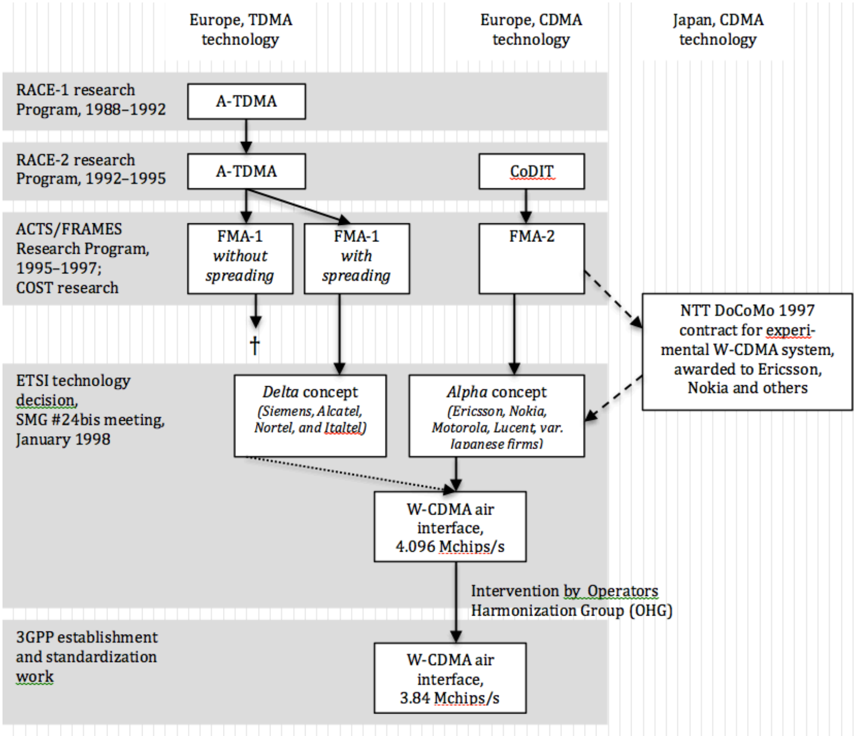

Figure 2. Overview of research and standardization activities for WCDMA

Standardization and adoption. While research progressed rapidly, European standardisation efforts were simmering. The 3G developments were largely ignored by GSM operators – the principle customers – who were focusing on increasing subscribers numbers of their existing 2G systems (Garrard, 1998, p. 478). In Japan, where the domestic industry had very limited success on the global market for 2G, plans were made for a rapid standardisation. The alignment with European manufacturers was a key element of that plan, hoping to set a world standard. Before Europe decided on its 3G standard, NTT DoCoMo of Japan, at that time the largest mobile telephone operator of the world, decided to procure an experimental WCDMA system. Orders were not only placed with domestic companies but also engaged foreign firms, including Ericsson, Nokia, Motorola, and Lucent. By involving foreign suppliers, NTT DoCoMo tried to increase its chances of having the WCDMA technology adopted in other world regions. With NTT DoCoMo being so dominant on the national market, the Japanese standards body was placed at a *fait accompli* and eventually set WCDMA as the formal standard. The actual design was in fact very close to the 3G system that Ericsson had been designing in the European research programmes. At about the time the Japanese contract was granted, Nokia – quite understandably - shifted most of its research efforts towards WCDMA (Karlsson & Lugn, 2009).

Under increased pressure from the events in Japan, Europe's standards body ETSI prepared itself to define the European standard. Fierce technical discussions took place, both within and outside ETSI. Some two dozen of proposals were categorised into five 'concept groups'. Two strong, opposing camps formed. One camp, now including Siemens, Alcatel, Nortel, and Italtel, proposed what was called the Delta (δ) concept group. This was basically identical to the Advanced-TDMA / 'FMA-1 with spreading', the standard on which several of these firms already had been working on in the abovementioned research programmes.[19] This proposal was notably different from the one adopted by the Japanese. The other camp supported the so-called Alpha (α) concept group, which is essentially the CoDIT/FMA-2 research work. Because this was also similar to what was already being built in Japan, it will come at no surprise that the chosen suppliers of the Japanese operator - Ericsson, Nokia, Motorola, Lucent and several Japanese firms – were the main backers. Would they be successful than they would have a significant head start, having already developed products for this technology?

With stakes that high, a record number of ETSI members and representatives from many organisations, including the European Commission, gathered in Madrid on 15 to 17 December 1997 at ETSI SMG#24 meeting, on which the decision for the European standard UMTS was to be made. Not only the strongly divided opinions, but also potential IPR issues made it impossible to reach a definitive decision at the meeting, which was then postponed for a month. These IPR issues take up more than half of the length of the minutes of the meeting and already reflect that the ETSI members were quite aware that some contenders were heavily drawing upon technology that was developed elsewhere, and that the owner of the related intellectual property would require compensation. When it was proposed that the participations would pool their patents, one of them commented: *"[...] in the case of a certain company outside the IPR pools asking for 6% license fees, a pool license agreement of other companies in order to keep the license fees at 1%, would result in a 7% license fee of total.".*[20] There cannot be much doubt this 'certain company' was Qualcomm, the company that pioneered CDMA for mobile telephone and owner of a large stock of related patents. Industry experts warned that *'If forced to pay stiff royalties, Ericsson and Nokia may be unable to afford the cost of developing and manufacturing third-generation WCDMA systems.'*.[21] The fact that many firms (including Nokia, Siemens, and Alcatel) were already Qualcomm licensees because they were supplying 2G IS-95 products means that these firms must have had a very good understanding of the exact scope of this patent portfolio.

In the month following the meeting, both camps undertook intensive lobby activities, trying winning the support of voting ETSI members (operators, administrations, other manufacturers). Eventually, the Alpha group seemed to have gained more momentum than its competitor. Hillebrand (2002), at that time the chairman of the committee responsible at ETSI, notes how a hotel room meeting of the high executives took place just before the next official meeting, and that these executives agreed on a compromise that was mostly based on Alpha but also had some elements of Delta (including so-called TDD-mode operations, which eventually never got implemented in commercial products). When the official meeting took place, on 28 and 29 January 1998 in Paris, the compromise proposal was put on the table and then easily won the required 71% of all votes. Understandably, the Japanese stakeholders warmly welcomed this decision and immediately announced they would ensure that their own standard would see some modifications so it would be fully identical with the European one. When also the Korean standards body TTC showed interest in cooperating, a new body called Third

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[19] The Delta proposal is known as TD/CDMA. It was principally based on TDMA, like GSM, but over time, some CDMA elements had been added to improve its performance.
[20] Source: ETSI. (1998). Consensus Decision on the UTRA concept to be refined by ETSI SMG2 (ETSI/SMG (98) 1 Annex 6 (DRAFT dated 17.2.98). Interestingly, this statement was removed in the final version of the minutes that were published several days later, possibly because of legal concerns.
[21] Mobile rivals prepare for Paris take-off. (19 January 1998). CommunicationsWeek International.

Generation Partnership Project (3GPP) was established. Its partners were standards bodies around the world (including ETSI from Europe, ARIB from Japan, and TTC from Korea). Finally, the work could commence on drafting the final specifications. It did not take long before a major conflict emerged. Qualcomm, being the owner of many CDMA patents but not having been involved in the European standardisation activities, felt that some implementation decisions were taken with the prime goal of creating incompatibility between the European standard and its own CDMA-based standardisation efforts. More specifically, the European proposal specified a so-called chip rate of 4.096 chips/s, whereas Qualcomm had settled on 3.6864 chips/s. An essential point here is that the latter was chosen in order to maintain upwards compatibility with an earlier standard (IS-95, with a chip rate that is exactly one third of that value), whereas the first is not designed to be compatible with any earlier radio standard and hence the designers were free to chose any value. Others argued that lowering the chip rate would result in a significant decrease of system capacity. Having a harmonised chip rate among different standards would facilitate multi-mode devices, lower market entry for chip makers, and drive down prices. At some point Qualcomm made the availability of its IPR conditional to its request to harmonise the chip rate. When the (mostly European) companies refused to do so, the parties came into a clash. Eventually, operators around the globe, who feared a lack of interoperability and unnecessary high price levels, exerted pressure on their suppliers and ultimately commanded them to lower the chip rate to the value Qualcomm had been suggesting. The fact that operators forced this harmonization of chip rate strongly suggests that there was not a significant downgrade of performance, as they would never have accepted that.

After that final hurdle, the more detailed work of drafting the standard could be continued and the first 'frozen' version of the standard, dubbed 'Release 99', was published early 2000. The standard is generally known as WCDMA, but also referred to as UMTS (in Europe), 3GPP (worldwide), and FoMa (in Japan). From that point on, the standard has seen several new releases that improved stability and offered additional functionalities, and supported greater capacity and data speeds. The most significant addition was a higher data speed mode called High-Speed Downlink Packet Access (HSDPA) that increased the maximum data rate by a factor of 100 and further.[22]

The commercial up-take of the WCDMA standard get delayed for a variety of reasons, including steep spectrum licensing fees, the blow of the internet bubble, and slow initial adoption by end users. More recently, uptake started to grow with the popularity of smartphones such as the Apple iPhone 3G (launched in 2008). Some European operators noted almost a tenfold increase of data traffic as the result of smartphones.[23] WCDMA – often combined with GSM - is currently becoming the becoming the dominant mobile telecommunications standard in the world. Elsewhere, competing 3G standards were developed, including cdma2000 (in a body appropriately called 3GPP2), and TD-SCDMA, a technology proposed by the Chinese. Although cdma2000 is not as widely adopted as WCDMA, it is nevertheless a relevant technology in a number of important market, reflected by Apple's decision in early 2010 to introduce a special version of the iPhone 4 that works on Verizon's cdma2000 network in the US.

[22] The original release supported a maximal data rate of 384 kbps in a wide area setting. HSDPA and its successors have driven that up 42 Mbps (release 8) and future releases even plan higher speeds.
[23] See http://www.emerce.nl/nieuws.jsp?id=2965541&utm_campaign=rss&utm_source=rss&utm_medium=rss

In terms of equipment market share in WCDMA, Ericsson and Nokia are currently (late 2010) still the world largest suppliers of infrastructure and mobile phones, respectively. Asian firms have captured a substantial share of the market: in November 2009, Huawei from China became the world's second largest supplier of infrastructure, bigger than the merged Nokia Siemens Networks (NSN) and the merged AlcatelLucent company.[24] Early 2010, South Korean companies like LG and Samsung were occupying the second and third position in mobile terminals, after Nokia.[25] Siemens left the handset market, and Motorola is in the course of doing the same thing, after having sold its wireless infrastructure division to Nokia Siemens networks in July 2010.

IPR payments are one aspect that can indicate knowledge positions. In this industry, with more than 50 parties claiming to own essential IPR, many firms cross-license. For a WCDMA/GSM phone, it is estimated that the aggregate licensing fee for a party without the ability to cross-license is around 12%.[26] It is generally understood that Qualcomm charges approx. 5%. The other IPR holding firms share the remaining part. In 2005 a number of companies filed a complaint at the European Commission, arguing that Qualcomm's rates were excessive. The companies apparently failed to persuade the commission and the complaint was ultimately withdrawn.[27] In 2008, Nokia and Qualcomm entered into a cross licensing agreement. Industry experts commented that Nokia agreed to paying a 2% licensing fee to Qualcomm. [28] This can be seen as a reflection of the relative knowledge position of the two firms: Nokia does own valuable IPR (hence is not paying the 5% most other companies are paying), but its knowledge position is considerable weaker than Qualcomm, otherwise it would be a cross license with no monetary compensation, or Nokia would receive net payments.

Finally, when considering the market share in so-called baseband chipsets, the core component of a mobile phone in which the mobile telecommunications functionality is integrated, the shares of the largest players are as follows: Qualcomm (38% revenue share), MediaTEK (18%), Texas Instruments (15%), ST-Ericsson (10%) and Infinion (7%).[29]

If we consider the above narrative, we come to the following conclusions concerning the knowledge position of the most central firms concerning the basic technology of the dominant 2G and 3G standards (i.e. GSM and WCDMA).

- Ericsson and, to some lesser degree Nokia, had a strong knowledge position in 2G GSM, having developed the original technical proposal and having been the central actors in the further development of the standard.
- Qualcomm, being the pioneer of 2G CDMA in mobile telephony, holds a strong knowledge position in 3G WCDMA.

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[24] Source: ReThink Wireless, Huawei narrowly overtakes NSN in mobile infrastructure sales, 17 November 2009.
[25] Source: IDC Quarterly Mobile Phone Tracker. See http://www.electronista.com/articles/10/01/29/idc.says.korean.and.us.phone.makers.benefit/
[26] Source: Study on the interplay between standards and intellectual property rights (IPRs); Preliminary Results. Interim results of a study commissioned by the European Commission. Presented at the Open Workshop organised by DG Enterprise of the European Commission, November 23th 2010.
[27] Source: Bloomberg. Qualcomm Antitrust Probe Is Dropped by EU Regulators (Update2) November 24, and Daily News and Analysis. European Union studying anti-trust complaint against Qualcomm. Jun 17, 2010.
[28] Source: The New York Times, July 24, 2008. In Settlement, Nokia Will Pay Royalties to Qualcomm.
[29] The Free Library (March 15, 2010). MediaTek unseats TI as No.2 cellular baseband chip vendor.

- To some lesser degree, this is also true for Ericsson, the European firm that was most involved in early CDMA-based subsidized research in Europe.
- Nokia, having switched at a rather late stage from TD/CDMA to WCDMA, has a considerably weaker knowledge position in 3G WCDMA.
- Siemens and Alcatel, supporting the losing TD/CDMA proposal to the last moment, have the weakest knowledge in WCDMA.

We note that these firms might have improved their knowledge position by contributing to the field after the basic technologies were developed and/or commercialised, or my contributing technologies to future enhancements of the standard. Still, we believe that the knowledge that was held prior to the technology selection moment is the most relevant one.

3. Essential patent analysis

In this section, we estimate the knowledge position of firms using claimed essential patents. We start by discussing the relevant database. Because the outcome of such an exercise is strongly dependent on the cleaning and filtering of the data we pay particular attention to these processes.

The dominant second-generation technology GSM was standardised by ETSI. While the third-generation WCDMA standard was drafted within 3GPP (see Section 2), it was adopted and formally accepted by ETSI, as well as the other participating standards bodies such as ARIB in Japan and TTA in South Korea. A quick inspection of the data shows that the large majority of firms did submit IPR statements to ETSI. However, Japanese firms may have declared their patents at the Japanese standards body ARIB, possibly resulting in a bias if we only used the ETSI database. To prevent such possible underestimation, we complement the ETSI IPR database with patents that are held essential by Japanese firms.[30] There is less concern on firms in other world regions because they all disclosed their patents to ETSI.

For this analysis, our starting point is the online ETSI IPR database (data retrieved on February 14th, 2010), complemented by the list of patent families in the 3G licensing pool (all WCDMA product categories, as last revised on September 8th, 2010). In total, we found approximately 23,500 ETSI declarations and another 345 patent families in the 3G licensing pool (which is structured differently). The first filtering step consisted of selecting only the declarations referring to 2G GSM or 3G WCDMA technologies.[31] The subsequent cleaning step aimed to identify the patents in the claims. Unfortunately, the information as provided by the patent owners, is far from consistent. Some owners offer patent numbers, other serial numbers of applications, other again publication numbers of applications, and also within these categories there is a wide divergence of formatting. Quite often, the offered identities are incomplete or erroneous. For ETSI, we analysed all records that referred to patents at either the USPTO or the EPO. For the 3GL

[30] Unlike most other standards bodies, ARIB does not make its IPR database public via its website. However, most relevant Japanese companies have decided to pool their patents essential to WCDMA into a (relatively) small patent pool, known as 3G Licensing. For our analysis, we added all the patents present in that pool to the ETSI database.

[31] More specifically, for GSM we selected the the following project identifiers: 'GSM'; 'GPRS'; 'GSM - Release 7'; 'GSM/AMR-NB'; 'DCS 1800'. For WCDMA we selected the following project identifiers: 'UMTS'; '3GPP'; '3GPP/AMR-WB+'; '3GPP/AMR-WB'; 'UMTS/CDMA'; 'UMTS Release 8'; 'UMTS Release 7'; '3GPP Release 7'; 'WCDMA'; 'UMTS FDD'. The pool declarations by definition refer to WCDMA.

data, we took patents at the USPTO, EPO, and the Japan Patent Office. Serial numbers of applications were translated into publication numbers (preferably patent numbers, otherwise publications numbers of applications) by using the correspondence tables published by the USPTO[32]. Unfortunately, these tables help to identify most patents applications numbers, but not all.[33]In fact, some companies claimed serial numbers of recent patents of which the application is not yet published (or possible withdrawn). We obviously could not identify such patents.

In a next step, in order to validate the patent identity and to have access to patent metadata such as filing date, priority date, and patent family information) we linked all identified patents or applications to the EPO/OECD PATSTAT database. Approximately 88% of the ETSI records and 89% of the 3G Licensing pool records could be successfully matched. This resulted in 2987 distinct patent numbers. This is a quite satisfying score, especially if we take into account that not all USPTO serial numbers can be successfully translated (see above) and that recent applications may not be available in PATSTAT because they are not yet published by the patent office. The next cleaning step involved the harmonisation of the firm's names. Duplicate names (over 400 in our database) were handled on a case-by-case bases. If we were aware of a transfer of rights, or when such a transfer was registered in the legal registers (as reflected by the INPADOC database) we took the most recent owner. In case of multiple assignees of a patent we selected the 'economically most active' owner.[34]

Finally, we used the concept of patent families to remove duplicate patent claims. In fact, for a single invention, some firms would submit up to dozens of declarations (for each different legislation in which a patent was applied for, multiple patents, re-issued patents, continuations and continuations-in-part), while other firms argued that one declaration sufficed – typically the corresponding USPTO or EPO patent. By using the INPADOC patent family definition, we were able to identify multiple entries for one single invention. This resulted in a significant reduction of overlap: the 2987 patents that we could match with PATSTAT were reduced to 1729 families. We note that the degree of reduction differs greatly by patent and by firm. For one particular invention, we found no less than 73 USPTO or EPO patents, all member of the same INPADOC-defined patent family.

Table 2 presents the findings of our analysis of claimed essential patents. By any means, Nokia claims the largest number of different patent families (356 families), almost 1.5 times larger than the second-largest owner, Qualcomm (with 241 families). This is even without taken the 32 patents into account claimed by NokiaSiemens Networks, in which Nokia has a 50% share. Ericsson comes just after Qualcomm, claiming 189 families, followed by Interdigital with 164 patents. At some distance, the second league of WCDMA patent owners follows, each claiming considerable less than 100 patents. This second league includes Siemens, Motorola, and AlcatelLucent, among others.

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[32] USPTO (2010); "Filing Years and Patent Application Serial Numbers Since 1882", available from http://www.uspto.gov/patents/process/search/filingyr.jsp.

[33] "In general, patent application serial numbers are assigned chronologically to patent applications filed at the U.S. Patent and Trademark Office. For this reason, application serial numbers and filing dates will generally correspond. Please note, however, that there are some applications for which the serial number and filing date may not fall within the time periods indicated in the above table.". Ibid.

[34] For instance, for patents both (independently) claimed by 'France Telecom' and by 'L'Etat Français', we selected the former. Similarly, if a one and the same patent was both claimed by a university and by a firm, we chose the latter.

This outcome, and particularly the suggestion that Nokia occupies the strongest knowledge position in this technology, does not match very well with the historical account presented in the preceding section. According to this account Nokia was originally on another technology path and 'switched' its R&D to WCDMA only after it was selected in Japan and just before it also was selected in Europe. We would therefore expect a weaker (or definitely not a leading) knowledge position for this firm. At the same time, the claimed essential patent families do not reflect the very central role Qualcomm played in WCDMA. All in all, we conclude that counts of claimed essential patents do not well predict actual knowledge positions – as also confirmed by royalty payments.

Table 2. Firms claiming 50 or more patent families essential to WCDMA

Firm	Essentially claimed patent families at ETSI and/or 3GL pool
Nokia	356
Qualcomm	241
Ericsson	189
InterDigital	164
Siemens	82
LG Electronics	71
Motorola	58
NTT DoCoMo	54
Samsung Electronics	53
Other 43 firms	461
Total	1729

Some better insights into knowledge position are found when looking at the temporal evolution of the claimed intellectual properties. Figure 3 shows the priority date of the patent families that are claimed to be essential. Interestingly, Qualcomm's early work in the CDMA technology area can be easily recognised here. Between 1990 and 1995 it filed more patents in this area than all other companies together. It can also be seen that, of the other companies, Ericsson was the most prolific patentee in the early period, also in line with our historical narrative. Despite being the largest owner of claimed essential patent families, most of Nokia's patents date from the period just preceding or after the ETSI technology decision is taken. Also this matches our historical narrative, where we found that Nokia switched its research from another technology towards CDMA at a quite late stage.

While this temporal analysis is not enough to provide estimates of knowledge positions, it certainly provides signals that the value of essential patents is far from homogeneous and counting essential patents is not enough to understand knowledge positions.

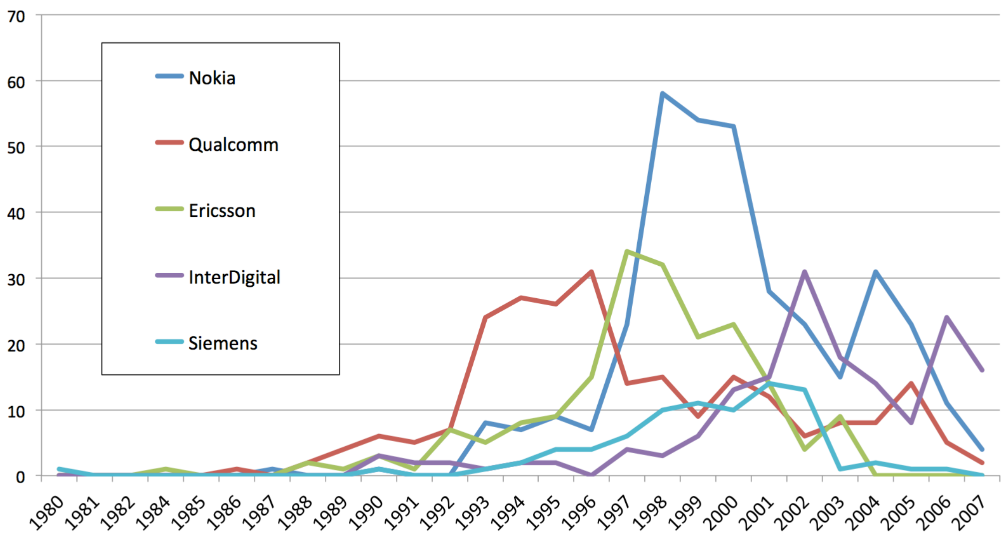

Figure 3. Time patterns of patent families claimed essential at ETSI and/or part of the 3G Licensing pool (five largest owners)

4. Patent and firm network analyses

This section outlines our attempt to find network-based methodologies that are better at determining knowledge positions than essential-patents based analysis. First, we analyse a firms' network built on the basis of patents and citations. In this network the nodes are the assignees and the strength of the links is proportional to the number of backward and forward citations between them. Section 4b reports the details about how the network was constructed and our findings.
Second, we deepen our understanding looking at the individual technical contributions (i.e. the patents). First, we map the relevant technological trajectory by using the Hummond and Doreian approach as explained in section 1. Secondly, we evaluate firms' knowledge position in respect to such trajectory. Section 4c presents the details of the indicators used and the results.
Both network analysis share the same underlying data set. Therefore, this section starts by discussing the dataset we compiled (Section 4a).

4a. Dataset for the various network analyses

The dataset for the diverse network analysis we performed was constructed using the Derwent Innovation Index (DII). One advantage of this database is that patent families are classified in a sensible way (see (Sipapin & Kolesnikov, 1989), among other papers, for a discussion on the different ways in which patent families can be constructed) and the so-called manual code and re-phrased abstracts help to adequately assess the scope of patents. On the basis of keywords and technological classes, aiming at a focussed set yet having a high recall, we identified 17,402 patent families that contained at least one US patent. These families contained more than one US patent, such as patent continuations or divisional patents (for a discussion see (Hegde, Mowery, & Graham, 2007)). After recalling these patents[35], we constructed a database of 19,196 unique US

[35] Our earlier efforts to construct technical trajectories were unsatisfactory, which in retrospect can be (at least partly) attributed to the fact that the structure of patent families in the US can result in the masking of key patents. Particularly for patents that are considered to be very valuable to their owner, it is worth the cost and effort associated with divisional and continuation patents.

patents related to our selected technological field. For constructing the citation relationships between the patents, we utilised the NBER patent database (Hall, Jaffe, & Trajtenberg, 2001). We used the update of this data set through 2006 that was compiled by Bronwyn H. Hall and made available in March 2009. Note that this data set does not include the most recent patents we retrieved, resulting in a final effective data set of 12,289 patents, with granting dates up to 2006. As the main technology decision for 2G/UMTS was taken in January 1998, and the first release of the standard was published in January 2000, we believe this time frame to be sufficient to analyse the technological field up to and including 3G. The assignee matching was done via the DII database[36]. In cases where patents were assigned both to individual persons and to companies, we attributed the patent to the company in question.

In order to appreciate changes over time, we analysed four distinct periods, each starting in 1976 and ending in 1985, 1990, 1995, and 2000 respectively. We assigned patent to these periods according to their application dates, as we believe this data comes closer to the actual invention. Table 1 shows all firms owning more than 27 patents[37], and their presence in the various networks (i.e. all patents that are not isolates). Note the relatively long tail; there are another 946 patent owners in the data set, of which 805 own 5 patents or less.

Table 3. Patent ownership in the networks at the different time periods

	Firm	Data set	Network 1976-1985	Network 1976-1990	Network 1976-1995	Network 1976-2000	Full network
1	Ericsson	877		12	140	663	790
2	Motorola	869	4	49	214	576	744
3	Lucent	805	18	38	113	570	699
4	Qualcomm	762		6	61	414	685
5	Nokia	712			47	454	633
6	NEC	672	28	61	143	475	576
7	Interdigital	444			33	156	413
8	Samsung	394			5	230	335
9	Northern	326		2	15	240	294
10	Matsushita	312			31	197	273
11	Phillips	231	5	27	55	154	189
12	Sony	228		1	18	147	191
13	Fujitsu	223	6	11	33	129	178
14	NTT	193	3	5	31	118	177
15	Siemens	191	2	3	19	129	158
16	Alcatel	161			35	123	141
17	Toshiba	156		2	30	83	131
18	Mitsubishi	136		1	16	74	120
19	LG	124			2	70	103
20	Hitachi	121		4	14	69	97
21	Other	3215	66	185	657	1860	2530
	Total	12289	150	452	1876	7522	10363

Note: this overview excludes isolates; i.e. patents that have no citing relations at all within the data set.

[36] In the DII database, owners are categorized into standardized names using a 'who-owns-who'-type of approach, where all subsidiary owners for 50% or more are attributed to a mother firm. Some firms using different legal entities were merged manually.
[37] This corresponds to consider the 50 largest patentees in the set.

4b. Empirical network analysis at the firm level

As patents are assigned to firms, there is a straightforward way to link the technology level to the company level. Therefore, a firms network can be built simply by partitioning the patent citation network. The arcs of the resulting directed network are informative on the inward and backward citation flows between firms. More precisely, the nodes of such network are the patent portfolios of each considered firms and the arcs have the value of the number of both the forward and backward citations between them. The network defined above represents just a subset of the possible knowledge-based ties between actors[38] and the usual caveats about the use of patents and citations hold. However, despite the partial view on knowledge exchanges, this type of network can still offer valuable insights about firm's reciprocal position in the knowledge space. Therefore, the analysis over time of such network sheds some light about the number of firms contributing to the technology, the relevance of such companies, and their role in the knowledge network.

In this part of the paper we focus on three most recent sub-networks, as we aim to focus on the third generation (CDMA) technologies. Table 4 provides a summary of the network size informing about the number of nodes (companies), the number of citations (arcs), the number of self-citations (loops), and the maximum value of the arcs (i.e. the maximum number of citations between any two specific firms). Detailed data about the citation behaviour of each of the firms in the whole set can be found in the Annex C, which also reports on the incidence of the self-citing. Table 5 presents the evolution of the key structural indicators for each period.

Table 4. Summary of network size

	Number of firms	*Citations (Arcs)*	*Self-citations (Loops)*	*Max value of arcs*
1975-1995	38	435	29	149
1975-2000	47	1151	43	1075
Full network	47	1293	46	1622

Table 5. Changes in the knowledge network: descriptive comparative data[39]

	1975-1995	*1975-2000*	*Full network*
Density with self citations	2.4861	9.3617	13.1824
Density	2.110	7.577	10.582
Average distance (among reachable pairs)	1.699	1.468	1.426
Fragmentation	0.224	0.043	0.000
Mutual linkages on total linkages (%)	0.571	0.731	0.743
GINI Coefficient for firms' outdegree centrality	0.650	0.694	0.699
GINI Coefficient for firms' indegree centrality	0.667	0.620	0.614

It is important to note that patents cite and are cited; therefore links between companies are not necessarily symmetric. From a network perspective we have also to distinguish between incoming and outgoing links. These indicate citations made and

[38] According to the literature several other knowledge networks can be built using different data.
[39] For the definition of the indicators exposed in the table see Appendix B

received respectively[40]. Table 5 shows an increase in density and cohesiveness (i.e. average distance, fragmentation, and reciprocity). Given the cumulative nature of the network (in each period nodes and links are added to existing ones) these results is hardly surprising. However, we can still observe some interesting features. For instance, despite the significant increase in the percentage of mutual ties, the indicator stabilizes over time. This means some firms are persistently only using or producing knowledge.[41] The last two rows display the GINI coefficient for the forward and backward citation distributions. This captures the concentration of the knowledge linkages. The steadily increase of both indicators suggests an increase in the inequality of strength of the ties. In particular, in the case of outdegrees (i.e. forward citations) we observe the emergence of few highly cited companies. This is therefore compatible with the emergence of a concentrated technological leadership. A further step in exploring this network characteristic is to fit a core-periphery model. The core/periphery structure implies the presence of two types of firms, some belonging to a cohesive and dense core, and the others to a sparse periphery (Wassermann and Faust, 1995). The details of the procedure followed and the results are reported in Appendix C.

Figure 4 to Figure 6 visualise the firms' network for the periods considered. Such figures allow evaluating not only the whole network structure but also each individual firm and the underlying core-periphery structure. In particular, companies marked with red circles belong to the core, whereas the blue squares are in the periphery. Furthermore, the size of the node is proportional to the number of self-citations. As regards to the ties, only links larger than a cut-off point are reported. The thickness of the lines is proportional to the strength of the ties.

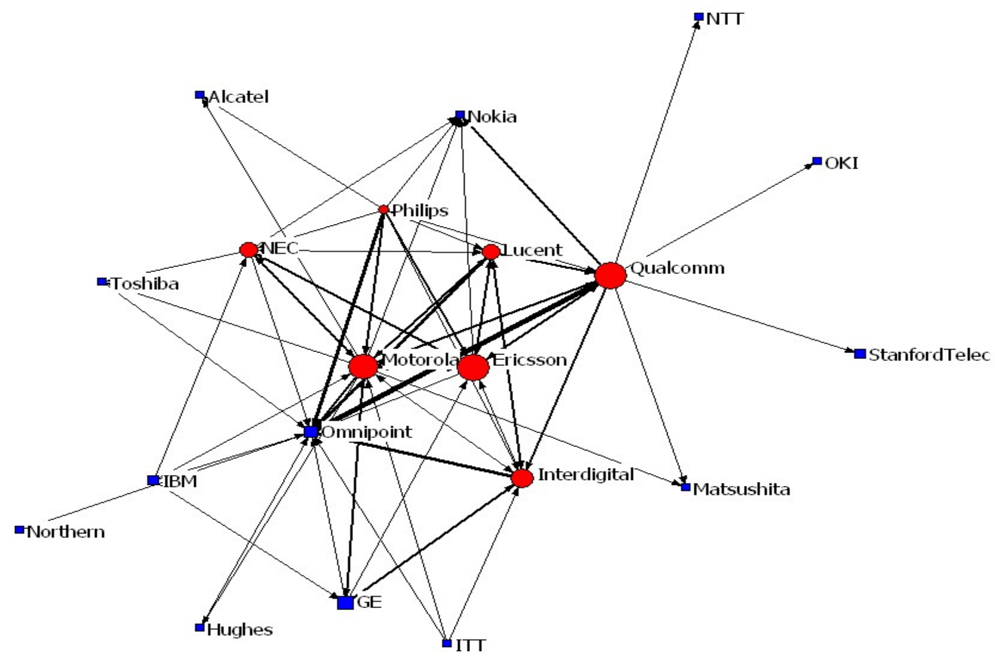

Figure 4. Firms' network 1963-1995(cut-off point 10)

[40] Note that the direction of the link indicates the direction of the knowledge flow in the citation.
[41] In this context "use of knowledge" refers to back-citing, whereas "production of knowledge" refers to forward-cited. If on the one hand, this jargon is rather simple, on the other hand, it clearly distinguishes between companies that only cites others and companies that only receive citations.

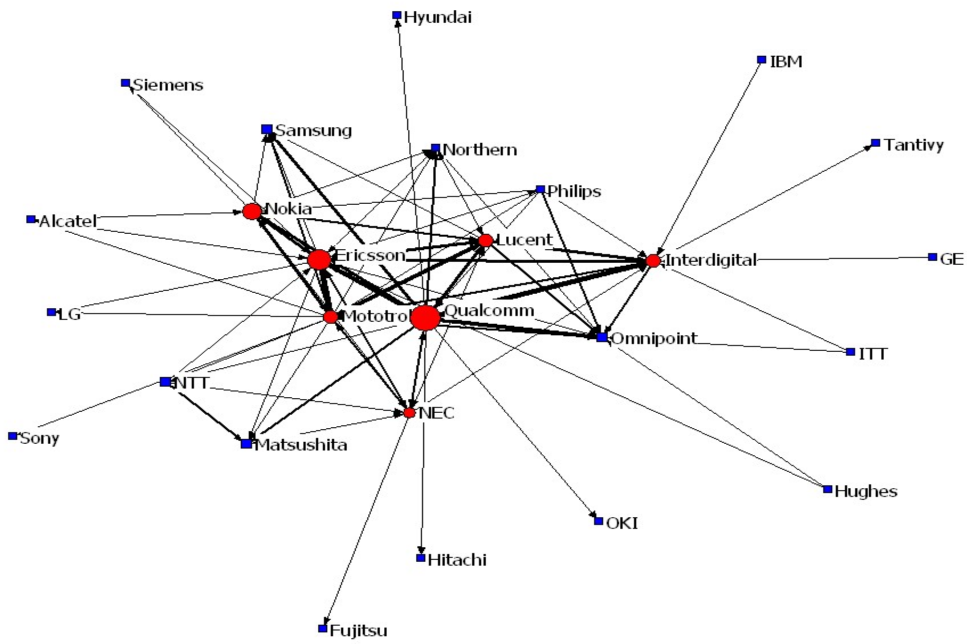

Figure 5. Firms' network 1963-2000 (cut-off point 40)

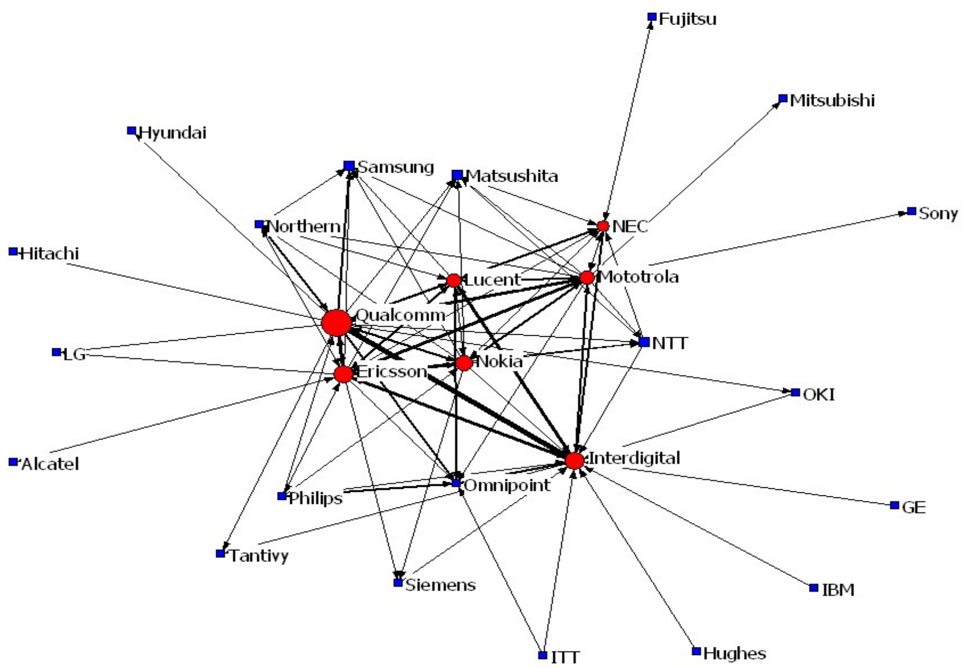

Figure 6. Firms' network Full (cut-off 50)

The densities reported in Appendix C shows that the network has a core-periphery structure. In fact, the goodness of fit, that measures the extent to which the network correlate to the perfect core-periphery structure is rather high. Furthermore, it is interesting to note that if on the one hand the core-to-core density increases over time, the periphery-to-periphery density does it but to a less extent. This suggests that the increasing number of citations regards the patents granted to firms in the core.

Furthermore, given the stability of the companies belonging to the core, it appears as this knowledge network is a dense network not characterized by a single leader but about a dozen of central players regularly drawing upon each other's knowledge.

In order to assess the knowledge positions in a more quantitative way, we now consider various metrics that are common in this type of network-based analyses. We present these in Table 6. First, we consider the centrality degree, one of the most conventional ways to evaluate the importance of nodes (Column 2). Centrality betweenness measures the number of time a node lies on the shortest path between all the nodes. In this case a node is central when it is shortly connected to several other nodes. This means that a company with high betweenness accesses the knowledge of several companies. Next, recognising that we are considering a directional network, we report both indegree and outdegree for each individual company (Column 3 and 4). Finally, we report the net citation count, which is calculated by taking the number of forward citations minus the number of backward citations. This way, we can disfurnish the "net producers" and "net consumers" of knowledge.

When considering the historical narrative presented in Section 2, we concluded that centrality betweenness has little relation with actual knowledge position. Outdegree citations to a somewhat better job. While many of the core firms are net producers of knowledge, Interdigital is a remarkable outlier, being the only very large consumer of knowledge.

Table 6. Centrality betweeenness, outdegree, indegree, and net citations count by firm, full network

Company	Betweennes centrality	Outdegree (citations received)	Indegree (citations made)	Net citations count
Qualcomm	36	3989	1682	2307
Motorola	82	2790	1402	1388
Ericsson	83	2770	2126	644
Lucent	78	2119	1712	407
Nokia	58	1510	1558	-48
NEC	58	1288	1151	137
Interdigital	52	897	3012	-2115
NTT	27	788	454	334
Philips	43	720	335	385
Northern	30	640	658	-18
Toshiba	66	383	190	193
IBM	13	374	100	274
Hughes	15	322	160	162
GE	1	209	76	133
ITT	3	192	36	156
BT	2	105	29	76

Notes: Self-citations are not considered.

Our overall conclusion on the basis of the firm network analysis above is that not all the companies contribute to the same extent to the evolution of the technology. In particular, it emerges a small group of active companies "inspire" the research of other companies. For instance, both Qualcomm and Interdigital belong to the core of the network but their role is very different: the citations net count shows a positive contribution of Qualcom and a negative one of Interdigital. It follows that the latter seems to be able to plug (i.e. to cite) the relevant knowledge, without significantly contributing to it. Looking at betweenness scores also supports this different behavior. Interdigital displays higher betweenness centrality than Qualcomm highlighting the possibility to access a wider spectrum of knowledge. We can therefore conclude that network indicators allow to distinguish between different innovative behaviours undertaken by companies and to distinguish between truly innovators and companies waiting for the opportunities.

4c. Empirical analysis of technological trajectories

The results of our analysis are shown in Figure 7, which depicts the so-called top main paths that represent the main flows of knowledge in the network over time. The patents are labelled after their owner and a unique sequence number. The table in annex B provides the full owner name and the full patent number. The top main path of the earliest network (1976-1985) includes seven patents, starting with a patent by NEC (labelled NEC1, patent US 4,028,496). This patent can be found at the bottom of the smallest component in Figure 7. It is followed by several other patents, owned by Lucent, IBM, ANT Nach-richtentechnik, and several by NEC itself. From Annex B, which summarises the main focus of each of the patents in Figure 7, it can be seen that all patents in this earliest network are related to FDMA or TDMA systems (i.e. 1G or 2G systems). Indeed, we do see the various engineering challenges that were presented in Section 2 above, such as time offset / advance timing and burst synchronisation / formatting. Channel equalisation techniques do not show up in the top main path. Also speech compression techniques are absent, but can be attributed to the fact that our data set focused on radio interface technologies, which is a distinctly different field. Extending the period up to 1990 ‘bends’ the trajectory to include some other patents, but the technology fields do not change much.[42]

[42] Note that two of the three patents encompassed in this new trajectory are end points, and it is known that in the Hummon and Doreian methodology, the resulting start and end points of top main paths may be relatively arbitrary.

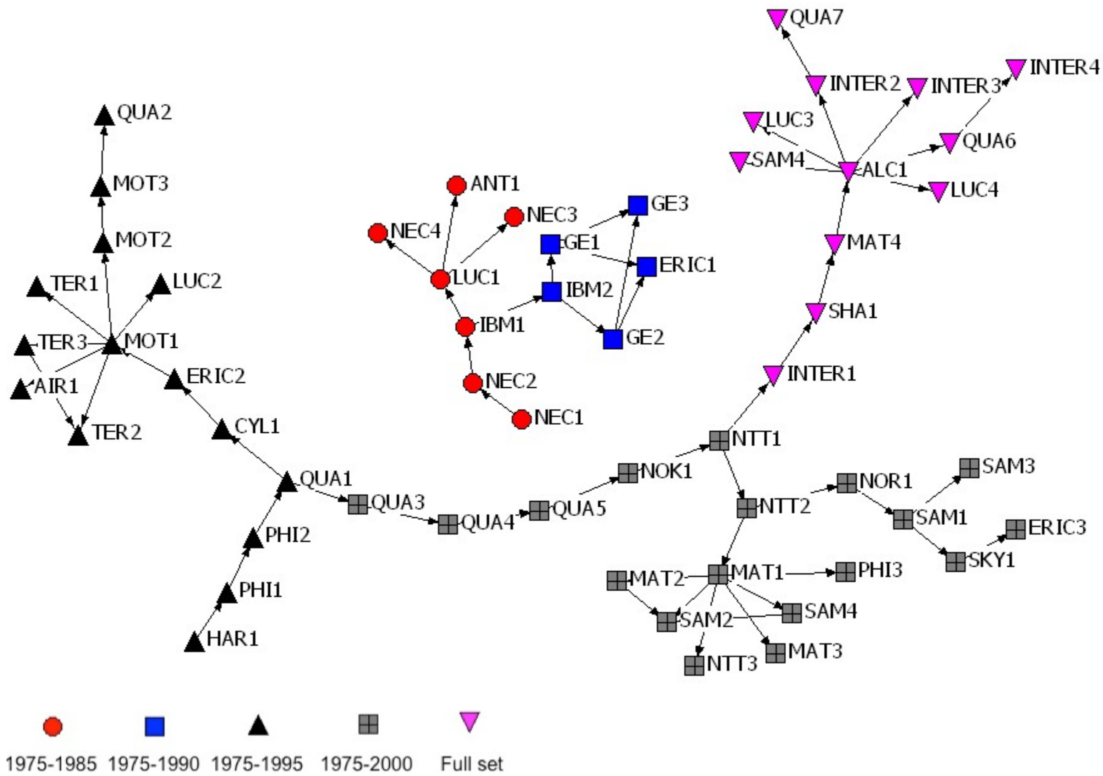

Figure 7. Technological trajectories and the patent's assignees, for five time periods

Interestingly, if the time period is extended to cover all patents with priority dates between 1976 and 1995, the trajectory 'breaks'. This is a feature that, to our knowledge, has not yet been observed in papers using this methodology in a technological field. There has been concern that the HDA methodology would have a (too) strong bias towards incremental, continuous technological paths (see Nomaler & Martinelli, 2010 for a discussion). Our finding, however, refutes such concerns and shows that if a newer, robust trajectory is emerging, which is solidly linked to other sets of early patents, the methodology is able to abandon the original path instead of trying to stick to it.

This third trajectory starts at the lower left corner in Figure 1 and ends at the left side, coinciding in time with the early development of the third generation CDMA systems. It starts with a patent from Harris, an American company that produces military equipment. Even though the CDMA technology originates from the military field, this particular patent is not really CDMA related and should be seen as an arbitrary starting point. That is not true for the two following patents, both invented by W. Schmidt of Philips Kommunikation Industrie (PKI) in Nürnberg, Germany, part of the Philips Company. These two patents are the earliest ones in our network actually using the words 'Code Division Multiple Access'. Interestingly, the first patent concerns asymmetric multiplex technologies for the up- and downlink, an idea that was not ultimately used for 3G but would eventually be chosen for 4G. If we look at the engineering challenges (see Section 2), we observe that CDMA came with its own, unique set of engineering challenges, often completely different from those relating to 2G/TDMA technologies. The major challenge, power control, is firmly embedded in the trajectory, including US patent No. 5,056,109, invented by K. Gilhousen[43] and assigned to Qualcomm. With no less than 632 forward citations in the DDI database, this is one of the top cited patents in the USPTO. The trajectory continues with a number of patents more diverse in nature but all relevant for CDMA. The fourth and fifth trajectory keep the same starting leg as the third one, but bend towards other patent sets, something that is often observed in HDA analysis. Power control technologies (including open and closed loop ones) are becoming more and more prominent.

Considering the ultimate trajectory, we observe that Qualcomm is the leading patentee. Not only is it the company that owns the largest number of patents in the trajectory (6 in total); its patents are also spread over time and in the trajectory. Other prominent companies are Interdigital (4 patents in the ultimate trajectory, of which 3 are endpoints[44]), Lucent (2) and Philips (2).

As mentioned in Section 1, one might have some concerns using such trajectories to determine important technological contributions or firm positions. First of all, some patents/companies might have contributed important knowledge that became part of the trajectory but are not part of the trajectory themselves, just because other patents happened to have a longer 'trial' in history. Second, a typical trajectory includes a dozen to two dozen patents, even if the knowledge field is as large as 10,000 patents or more. The question is whether such 'overselective' trajectories lack the necessary degree of granularity. Chance may play a too big role. One way to address such concerns would be to extend the analysis to patents that are close to the trajectory. Such a set, however, would also include patents that 'take' knowledge from the trajectory but do not contribute themselves. That is why we explored an alternative approach, where we analyse the category of patents that are directly or indirectly cited by patents in the trajectory. In other words: these patent contribute to the trajectory. While the trajectory encompasses just 20 patents, the groups of patents that contribute to the trajectory already includes 660 patents (of a total network of 8057 patents). Obviously, granularity is much better. Table 7 presents the firm-level findings when considering this new category. We propose a new indicator, which combines the share of patents on the trajectory and the share of patents feeding into the trajectory.

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[43] This inventor is one of the co-founder of Qualcomm and is listed as inventor in over 47 US patents, often together with another Qualcomm co-founder, I.M. Jacobs (who long served as chief executive officer of this firm). They both feature on two top citing patents, collecting a total of 1,160 and 782 citations in DII respectively. Both men worked together on aeronautical research in the 19070s for NASA.

[44] Note that endpoints are endogenous selected by the sampling method and the greedy algorithm used. Therefore, their interpretation can be cumbersome.

Table 7. Patents on the trajectory and contributing to the trajectory

Firm	*Patents on trajectory*		*Patents contributing to trajectory*		*Patents non-contributing*	*Knowledge position indicator (see text)*
Qualcomm	6	(30%)	63	(10%)	616	39.5%
Interdigital	4	(20%)	34	(5%)	416	25.2%
Lucent	2	(10%)	56	(8%)	641	18.5%
Motorola	0	(0%)	111	(17%)	633	16.8%
Philips	2	(10%)	22	(3%)	165	13.3%
Ericsson	0	(0%)	76	(12%)	714	11.5%
NEC	0	(0%)	66	(10%)	510	10.0%
Nokia	1	(5%)	30	(5%)	602	9.5%
NTT	1	(5%)	28	(4%)	148	9.2%
Alcatel	1	(5%)	14	(2%)	126	7.1%
Matsushita	1	(5%)	7	(1%)	265	6.1%
Samsung	1	(5%)	6	(1%)	328	5.9%
Harris	1	(5%)	0	(0%)	28	5.0%

All in all, we can conclude that the results of the HDA analysis – especially when extended to patent contributing into the trajectory – are to a very large degree consistent with the standardisation roadmap, and are in line with the associated technical challenges identified in the technical literature.

5. Comparison and conclusion

Standardization is an important yet underrated economic alignment mechanism, where the rate and direction of technological change is being negotiated between firms. Therefore an important aspect of standardisation procedure is the knowledge positions that firms occupy have in such technologies. In fact, strong knowledge positions may increase chances for sustainable participation, market success, bargaining power and licensing revenues. In the recent literature, so-called essential patents have been used as an indicator for firms' knowledge positions in standardized technologies.

The aim of this paper was to challenge this and to propose an alternative method based on patent citation networks.

In order to do so Section 2 presents a narrative of the standardisation process occurred in mobile telecommunications. This history clearly highlights the strategies and the knowledge position of the major players. Section 3 presents the patent analysis of the essential patents, whereas section 4 applies network analysis.

Which of the two empirical analyses better match the received history and firms' bargaining power?

Simple patent counts do not well predict actual knowledge positions – as also confirmed by royalty payments. In particular, it signals that the value of essential patents is far from homogeneous and counting essential patents is not enough to understand knowledge positions.

In this respect, the network approach seems to provide a better matching to the receive history highlighting technological leaders and followers. In particular, the uses of traditional and new indicators for the firms' knowledge position help in distinguishing different innovative behaviour.

As a final validation, we compared the patents in the main top path with the list of patents that were declared essential, as well as any of their family members. For the top path in the full time period (and ignoring startpoints and endpoints because of their possible arbitrary nature) we find that 7 out of 13 patents in the top path are claimed

essential (see annex B for details). This makes good sense if one considers the interplay between standardization and technological trajectories. The findings confirm that many important inventions on the top main path are indeed claimed essential (but not necessarily all, because standard might not have employed all the features that are present in the top main path). The opposite, of course, is not true: of all claimed essential patents, only very few are on the top path.
Looking at the other CDMA branches in earlier time periods that later disappeared, we find that only 1 out of 12 patents are claimed essential (again ignoring end points, and ignoring one patent that is at the same time present on the final top path). Also this makes sense: while the trajectory analysis shows that at some point in time these inventions were very important, the standard took another turn and their technologies eventually did not become part of what is defined in the standard.
A bit of a special case is that of the two early trajectories for 2G technologies. Not even one single patent in these two top paths is in fact claimed essential to the 2G GSM standard. This initially seems an oddity, but a closer look at the historical narrative reveals the likely course. As shown in Section 2, the companies that were involved in developing this first 2G standard believed there was an 'gentleman agreement' that one would not patent the technologies to be used in this unique, European standardization effort.

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Annex A. List of Acronyms

AMPS	Advanced Mobile Phone System
CDMA	Code division multiple access
EDGE	Enhanced Data rates for GSM Evolution
FDMA	Frequency-division multiple access
GPRS	General packet radio service
GSM	Global System for Mobile Communications
HSPDA	High-Speed Downlink Packet Access
MC-CDMA	Multi-carrier code division multiple access
NMT	Nordic Mobile Telephone
OFDM	Orthogonal frequency-division multiplexing
TACS	Total Access Communication System
TDMA	Time division multiple access
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband Code Division Multiple Access

Annex B. Trajectory evolution: Analysis of the patents in the top main paths for each time period

Patent #	Assignee	Label	1985	1990	1995	2000	Full	Priority year	Main challenge addressed	Claimed essential?
US4028497	NEC	NEC1	1	1				1977	Handling frequency variations	
US4107608	NEC	NEC2	1	1				1979	Burst synchronisation	
US4346470	IBM	IBM1	1	1				1981	Burst synchronisation	
US4715033	NEC	NEC3	1					1985	Burst formatting	
US4797678	NEC	NEC4	1					1985	Time offset / advance timing	
US4574379	Lucent	LUC1	1					1986	Other	
US4644534	ANT Nach-richtentechnik	ANT1	1					1986	Time offset / advance timing	
US4418425	IBM	IBM2		1				1983	Burst synchronisation	
US4835731, US4905302, US5020132	General Electric	GE1 and GE2 and ERIC1		1				1988	Other	
US5131007	General Electric	GE3		1				1991	Other	
US4528656	Harris	HAR1			1	1	1	1985	Frequency allocation	
US4697260	Philips	PHI1			1	1	1	1986	Asymmetric multiplexing for up- and downlink	
US4765753	Philips	PHI2			1	1	1	1987	Handover	x
US5056109	Qualcomm	QUA1			1	1	1	1991	Power control (loop)	x
US5164958	Cylink	CYL1			1			1992	Handover	
US5295153	Ericsson	ERIC2			1			1993	Frequency block allocation	
US5363404	Motorola	MOT1			1			1994	Other	
US5530716	Motorola	MOT2			1			1996	Identification of coded signal	
US5642348	Lucent	LUC2			1			1996	Other	
US5629934	Motorola	MOT3			1			1997	Power control (loop)	
US5768269, US5966376	Terayon	TER1 and TER2			1			1997	Other	
US5950124	Aironet	AIR1			1			1997	Dynamic parameters (e.g. PN codes)	
US6137840	Qualcomm	QUA2			1			1997	Power control (loop)	x
US5805583	Terayon	TER3			1			1998	Modulation/demodulation	
US5267262	Qualcomm	QUA3				1	1	1993	Power control (loop)	x
US5383219	Qualcomm	QUA4				1	1	1995	Power control (loop)	x
US5461639	Qualcomm	QUA5				1	1	1995	Power control (loop)	x
US5570353	Nokia	NOK1				1	1	1995	Power control (loop)	
US5694388	NTT	NTT1				1	1	1996	Modulation/demodulation	
US6034952	NTT	NTT2				1		1997	SIR	
US6385184, US6487188, US6526032, US6590883, US6490263	Matsushita	MAT1, MAT2, MAT3, and MAT4				1		2000	Pilot channel & power control combination	x[a]
US6512931	Samsung	SAM1				1		2000	Power control (loop)	
US6654358	Samsung	SAM2				1		2000	Power control (loop)	
US6831910	Samsung	SAM3				1		2000	Signalling	
US6747969	Philips	PHI3				1		2001	Signalling	
US6868279	Ericsson	ERIC3				1		2001	(power)	
US6999427	NTT	NTT3				1		2001	Power control (loop)	
US6311070	Northern Telecom	NOR1				1		2002	Power control (loop)	

US6795712	Skyworks	SKY1	1		2004	Power control (loop)	
US6055231	Interdigital	INT1		1	1998	Modulation/demodulation	
US6208632	Sharp	SHA1		1	1999	Pilot channel	
US6490263 (same family as US6385184)	Matsushita	MAT4		1	2000	Pilot channel & power control combination	x
US6564067	Alcatel	ALC1		1	2001	Power control (loop)	x
US6748234	Qualcomm	QUA6		1	2002	Power control (loop)	
US7106700	Lucent	LUC3		1	2002	Dynamic parameters	
US6934526	Samsung	SAM4		1	2003	Dynamic parameters / system mode changes	
US7136666	Lucent	LUC4		1	2003	Power control (loop)	
US6907010, US7126922	Interdigital	INTER2 and INTER3		1	2004	Dynamic parameters	
US6985473	Qualcomm	QUA7		1	2005	Dynamic parameters / system mode changes	
US7009955	Interdigital	INTER4		1	2005	Power control (loop)	

[a] The main patent here, patent US6385184, is not claimed essential as such but we found an INPADOC family member that was.

Notes: patents that are members of the same family *and* present in the same trajectory are shown in one column. The years indicate the periods in question, being 1976-1985; 1976-1990; 1976-1995; 1976-2000; and full network.

Annex C: Citation matrix for the whole sample.

Cited → Citing ↓	Luc	Fuj	NEC	Phi	NTT	Sie	Mot	Nor	Int	Mit	Tos	Eri	Alc	Qua	Hit	Mat	Son	Nok	Sam	*Tot*	% Self
Lucent	532	23	88	27	35	25	148	70	382	21	11	215	21	276	25	35	20	114	91	*2159*	25%
Fujitsu	13	32	50	4	9	1	9	6	11	18	3	23	5	19	5	13	2	13	19	*255*	13%
NEC	80	67	299	29	44	18	86	27	145	27	28	120	33	78	35	83	28	100	42	*1369*	22%
Philips	43	5	26	32	6	16	42	6	106	10	5	70	14	83	6	10	11	55	6	*552*	6%
NTT	35	29	98	7	84	2	18	12	81	38	9	68	13	52	38	102	15	46	36	*783*	11%
Siemens	16	4	14	4	5	28	10	7	56	16	1	12	3	36	6	2	2	18	7	*247*	11%
Mototrola	317	45	112	36	58	41	544	88	186	58	33	383	47	330	30	74	64	213	114	*2773*	20%
Northern	79	12	23	11	7	6	35	69	40	4	1	77	3	76	19	9	7	47	51	*576*	12%
Interdigital	58	11	39	10	7	6	52	15	762	22	4	90	15	72	20	27	7	49	46	*1312*	58%
Mitsubishi	16	7	19	2	4	4	14	2	19	40	3	20	0	9	3	6	8	22	5	*203*	20%
Toshiba	22	16	39	6	3	6	23	8	21	5	64	29	9	14	8	29	15	41	20	*378*	17%
Ericsson	293	28	134	61	54	69	206	92	453	47	14	844	75	195	31	100	33	360	92	*3181*	27%
Alcatel	26	1	8	5	7	17	16	10	22	6	6	56	29	19	5	3	0	44	6	*286*	10%
Qualcomm	305	37	164	35	74	22	405	166	772	30	16	371	35	1622	84	122	44	206	242	*4752*	34%
Hitachi	9	6	30	6	9	6	10	6	38	0	2	14	3	19	42	17	5	11	25	*258*	16%
Matsushita	35	13	77	4	18	12	12	3	24	21	16	31	14	16	21	91	11	31	21	*471*	19%
Sony	13	8	23	6	3	5	9	1	29	4	4	23	4	21	13	17	65	16	11	*275*	24%
Nokia	122	28	72	28	52	51	96	66	133	29	11	244	32	129	38	52	31	569	96	*1879*	30%
Samsung	42	4	25	5	3	2	31	24	26	18	2	28	8	41	6	5	4	18	95	*387*	25%
Tot	*2056*	*376*	*1340*	*318*	*482*	*337*	*1766*	*678*	*3306*	*414*	*233*	*2718*	*363*	*3107*	*435*	*797*	*372*	*1973*	*1025*		

Annex D: Summary of key measures for the analysis of the knowledge network

Variable	Definition
Density	The density for a valued network is defined as the sum of all the values divided by the number of possible ties.
Average distance	The average of geodesic distances between nodes in the network. The distance is the length of a geodesic between them, which is measured as the shortest path.
Fragmentation	Proportion of nodes that cannot reach each other.
Reciprocity	Percentage of reciprocated ties on total ties in the network.
GINI Coefficient for firms' outdegree centrality	Distribution of forward citations linkages measured by the GINI coefficient applied to outdegree centrality. Outdegree is the number of citations received by a firm's patent portfolio.
GINI Coefficient for firms' indegree centrality	Distribution of backwards citations linkages measured by the GINI coefficient applied to indegree centrality. Indegree is the number of citations received by a firm's patent portfolio.

Annex E: Core/periphery model fit

This annex reports the results obtained in fitting a core/periphery model. The procedure here used maximizes the correlation between the permuted data matrix and an ideal structure matrix consisting of ones in the core block interactions and zeros in the peripheral block interactions.

		Density of the linkages		Final fit
		Core	Periphery	
1995	Core	23.595	5.06	0.734
	Periphery	1.866	0.373	
2000	Core	139.024	18.657	0.807
	Periphery	10.525	1.52	
tot	Core	275.45	33.6	0.820
	Periphery	21.071	3.419	

Annex F. List of the companies in the periphery.

Period	Disconnected Firms
1975-1995	Fujitsu NTT Thompson Siemens ITT GE IBM Northern Harris BT Toshiba Hughes Alcatel OKI Hitachi Mitsubishi Canon FT Matsushita Sony Nokia StanfordTelec Omnipoint Bosch Arraycomm NipponDenso Samsung LG LSI Sanyo Hyundai
1975-2000	Fujitsu Philips NTT Siemens Thompson ITT IBM GE Northern Harris BT Mitsubishi Toshiba Hughes Bosch Alcatel OKI Hitachi Canon Matsushita FT Sony StanfordTel Omnipoint Arraycomm NipponDenso Samsung Hyundai ETRI Sanyo LG LSI Intel TRW TexasInstr Conexant Tantivy Cisco Sprint Broadcom
Full network	Fujitsu NEC Philips NTT Siemens Thompson ITT IBM GE Northern Harris BT Mitsubishi Toshiba Hughes Bosch Alcatel OKI Hitachi Canon Matsushita FT Sony Nokia StanfordTel Omnipoint Arraycomm NipponDenso Samsung Hyundai ETRI Sanyo LG LSI Intel TRW TexasInstr Conexant Tantivy Cisco Sprint Broadcom