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A study on wireless technologies, technological trajectories, and essential patent claims

Rudi Bekkers and Arianna Martinelli

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Eindhoven Centre for Innovation Studies (ECIS),
School of Innovation Sciences,
Eindhoven University of Technology, The Netherlands

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Rudi Bekkers, Eindhoven Institute for Innovation Studies (ECIS), Eindhoven University of Technology, The Netherlands, r.n.a.bekkers@tue.nl

Arianna Martinelli, Wirtschaftswissenschaftliche Fakultät, Friedrich-Schiller-Universität, Jena, Germany, arianna.martinelli@uni-jena.de

Summary

In many technology fields, standardization is the primary method of achieving alignment between actors. Especially if strong network effects and increasing returns are present, the market often ends up with a single standard that dominates the technical direction, activities and search heuristics, for at least one full technology generation. Although literature has addressed such decision processes quite extensively, relatively little attention has been paid to the way in which standards affect - and are affected by - technological change. Building upon the concepts of technological regimes and trajectories (Dosi, 1982), and on the methodology proposed by (Hummon & Doreian, 1989) to empirically investigate such trajectories, this papers aims to study the interplay between standardisation and technological change.

We conclude that the empirically derived technological trajectories very well match the standardisation activities and the main technological challenges derived from the engineering literature. Moreover, we also observe that the Hummon & Doreian methodology can indeed reveal technological discontinuities. To the best of our knowledge, this has not been the case in earlier studies using this technology, and refutes concerns that this methodology has a (too) strong bias towards incremental, continuous technological paths. Finally, we compare the set of patents in the most important technological trajectories to the set of so-called essential patent claims at standards bodies, and conclude that there is no significant relationship. This confirms earlier arguments that essential patents are not necessarily 'important' patents in a technical sense.

1. Technological trajectories as an indicator of the main paths of technological change

For a long time, orthodox economics has largely neglected the detailed study of technological change and its underlying knowledge. Starting in the 1980s, this gap was addressed by concepts such as technological paradigms (also referred to as technological regimes) and technological trajectories. The underlying theoretical backgrounds were developed by (Nelson & Winter, 1982), (Rosenberg, 1976) and (Sahal, 1981). These works were accumulated in a seminal paper of (Dosi, 1982). Following these theoretical conceptualizations, several efforts have been devoted to empirically study technological paradigms and trajectories. These recent studies generally used patent citations networks in order to construct and understand technological development and knowledge flows. Some of the first studies to use this methodology were on the development of fuel cells (Verspagen, 2005) and on telephony switching equipment (Martinelli, 2008). Others have used a similar approach for studying the medical sector (Mina, Ramlogan, Tampubolon, & Metcalfe, 2007).

Standards, on the other hand, are widely believed to influence technological change, whilst at the same time being the result of technological change. Especially in markets that exhibit strong network effects, standards are an alignment mechanism in which stakeholders negotiate and decide on the direction of technology. As such, they are a mechanism to align technological choices (Schmidt & Werle, 1998). There are several modes in which the market comes to such a widely supported standard. Sometimes this is through negotiation within a single Standards Developing Body (SDO), sometimes through competition between several SDO, consortia or fora and sometimes – though considerably less often - through competition between end user products in the market place (e.g. Blu Ray vs. HD-DVD). An interesting framing is that of (Anderson & Tushman, 1990). These authors see technological development as periods of ferment (with design competition, technological races, and technological discontinuities), followed by long periods of more incremental technological change, with an elaboration of dominant designs. It is likely that, in many cases, standards are in fact the embodiment of such dominant designs.

In many network markets and/or markets with compatibility standards (e.g. colour television, Compact Disc, fax, mobile telephony, bank/chipcards, RFID tags, MP3 players, DVD), the availability and content of the standards affected both the rate and the direction of technological change. One could be forgiven to expect that this relationship would be clear from empirical literature. However, this is not the case. After a stream of literature addressing the role of compatibility standards by ((Katz & Shapiro, 1994) (David & Steinmueller, 1994) (Schmidt & Werle, 1998) (Besen & Saloner, 1989)), few papers actually studied or tested the relationship between standards and the direction of technological change. (A notable exception to this is (Fontana, Nuvolari, & Verspagen, 2009)). With this paper we hope to address this omission. In order to do so, we study the link between standardisation and research in economics on technological development using the concept of technological trajectories. We assume this to be a two-way relationship: technological trajectories open windows of opportunities to create standards, whereas standards influence the further development of these trajectories - and, at one point in time, might be challenged again by new technological opportunities.

This paper continues with a technical account of the area in question, which is wireless technologies. Section 3 briefly introduces our methodology, describes our patent data set, and discusses the empirical result, both at the patent level and at the firm level. In Section 4 we address the relationship between the patent networks and claimed 'essential patents'. Section 5 concludes.

2. Technological change and standardisation in wireless technologies

In this paper, we collect and analyze data in the technological field of wireless communications. This sector has experienced substantial technological changes and strong economic growth, and the development and adoption of standards (such as GSM and W-CDMA[1]) are believed to be instrumental in these. Also the use and impact of patenting in this sector have received considerable academic interest (Leiponen, 1985) (Bekkers, Duysters, & Verspagen, 2002) (Lemley & Shapiro, 2006). Wireless and mobile telecommunications involve a wide range of relevant technologies. Here we focus specifically on what is perhaps the most important single technology area: the way radio signals are coded and transmitted (called the radio transmission protocol and the

[1] In Europe also known as UMTS.

modulation techniques) and the way in which larger numbers of users are simultaneously served, sharing common radio spectrum resources (called multiplexing techniques). In order to be able to interpret the technological trajectories in Section 3 below, we will now summarise and discuss the main developments and engineering challenges in mobile telecommunications for various generations (generally referred to as 1G, 2G, 3G, and 4G), and the associated standards. Annex A summarises these generations and their most important aspects.

In the early 1980s, the first cellular mobile telephony systems were introduced (dubbed 1G). For such systems, the coverage area was divided into cells, each with their own capacity, and within every single cell each simultaneous call is assigned its own frequency. Handing over a call from one cell to another for a moving caller was one of the main technological challenges, as well as a mobility management system able to trace users and forward incoming calls to them. Although these first generation systems were much more successful than expected, their total system capacity was limited and the costs per user were high. The technology was also fragmented, with almost a dozen different standards in use.

A breakthrough was reached with the development of a single, harmonised European standard for digital cellular systems, called GSM. This standard was developed by the European Telecommunications Standards Institute, ETSI. Being the dominant second-generation standard, it offered a high system capacity, of up to dozens of millions of subscribers per network. Their TDMA techniques, whereby a number of users share the same transmitters, enabled considerably lower costs per user. The main engineering challenges can be traced in the technical literature during the early development period, in particular by looking at the proceedings of IEEE conferences that brought together researchers in this area (see, for instance, (Fuhrm &
Fremin, 1986), and handbooks (e.g. (Garrard, 1998), (Hillebrand, 2003), (Mouly & Pautet, 1992). Particularly revealing are the proceedings of the '*Nordic seminar on digital land mobile radiocommunication'* (Nordic_Seminar, 1995). The main engineering challenges – identified as such - 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 (see Annex A for more details). GSM eventually became the dominant world standard, now serving more than 3 billion users.

Although the 2G technology was upgraded to support data transmission, its data speeds and other features made it quite unsuitable for many data applications that were becoming popular in fixed networks (e.g. internet access). One of the main design challenges for 3G was much better support for data services. At the same time, 3G systems were supposed to meet many other – often conflicting - design requirements, as shown in Annex A. Perhaps most importantly, given the expected growth of data usage and the limited willingness of subscribers to pay more, the new technology had to reduce considerable the cost price per unit of data (Annex C illustrates how these unit costs decrease per generation). For this paper, again, the technical challenges were identified by studying the technical literature (e.g. (Berruto, 1998),(Evci & Kumar, 1993), (Buitenwerf, 1994)) and (IEEE) conferences proceedings, as well as several handbooks (Hillebrand, 2003), (Holma & Toskala, 2000). Fierce technical discussions took place, both within and outside the relevant standards bodies. The standard that eventually would become most successful came (again) from ETSI and was later aligned with standards bodies around the world. At the decision stage, five different basic technologies were proposed (see (Bekkers, 2001) for a detailed discussion). The CDMA technology, in which the transmissions of different users are identified by very fast, unique codes, finally emerged as the winner. This technology was pioneered by the US firm Qualcomm that had already commercialised a 2G CDMA a few years earlier. Although this system (called IS95/cdmaOne) arrived when GSM had already reached a critical momentum and was not able to win a substantial part of the world market, it did show that CDMA technology could be successfully employed in a real life system. More specifically, it proved that power control, the single biggest engineering challenge for a functioning CDMA system, could be mastered. Qualcomm's patented open and closed loop power control methods proved the critics wrong.[2]

Around 2008, the standards for the latest generation of mobile telecommunications networks (often dubbed 3.9G[3] or 4G) were published. One of the main design was to cater for the ever increasing data speeds per user, and – again - bring costs per data unit down. Initially several technical proposals competed in this field, including Mobile WiMax/IEEE 802.16e, Ultra Mobile Broadband (UMB) and Long-Term Evolution (LTE). Currently it seems as if the latter technology, which evolved from the current W-CDMA, will be the winner. 4G systems, again, turn to a rather different radio technology, in this case OFDM. Howeverm it is till to early to expect these developments to be found in our empirical analysis below as methods based on patent citations require some time lag for such citations to be collected.

3. Empirical analysis of technological trajectories

The dataset for this paper 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) while the so-called manual code and re-phrased abstracts help to adequately assess the scope of patents. On the basis of a combination of a keyword search and a technological classification search, aiming at a focussed set yet having a high recall, we identified 17,402 patent families that contained at least one US patent. A number of patent families contained more than one US patent; this can happen with patent continuations or divisional patents; for a discussion see (Hegde, Mowery, & Graham, 2007). After recalling these patents[4], we constructed a database of 19,196 unique US 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 12,288 patents, with granting dates up to 2006.[5] Assignee matching was, however, not done via the Compustat concordance table, but rather via

[2] This scepticism is 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.'* Source: Bill Frezza, Wireless Computing Associate, "Succumbing to Techno-Seduction," Network Computing, April 1, 1995. http://www.networkcomputing.com/604/604frezza.html

[3] The term '3.9G' has been coined because the current version of the most promising standards, LTE, does not met yet the criteria that the International Telecommunications Union (ITU) defined for fourth generation networks.

[4] 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.

[5] 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 analyze the technological field up to and including 3G.

the DII database[6], as this proved to be more appropriate in our context. In cases where patents were assigned both to individual persons and to companies, we attributed the patent to the company in question. Finally, the data on essentiality claims for standards (see Section 4 below) was retrieved from the public ETSI IPR database (www.etsi.org/ipr) and cleaned using the OECD/EPO PatStat database.

In order to see the changes over time, we analysed five distinct periods, each starting in 1976 and ending in 1985, 1990, 1995, 2000, and 2003 respectively. We assigned patent to these periods according to their priority dates, as we believe this data comes closes to the actual invention. Table 1 shows all firms owning 100 or more in our data set, in their presence in the various networks (i.e. all patents that are not isolates). Note the relatively long tail; there are another 1350 patent owners in the data set, of which 1130 own 5 patents or less. Slightly more than 10% of the 1350 entities are individual owners (i.e. patents for which only one or more individuals are mentioned as assignees).

Table 1: 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	Network 1976-2003
Ericsson	877		12	140	663	790
Motorola	869	4	49	214	576	744
Lucent	804	18	38	113	570	699
Qualcomm	762		6	61	414	685
Nokia	712			47	454	633
NEC	672	28	61	143	475	576
Interdigital	444			33	156	413
Samsung	394			5	230	335
Northern Telecom	326		2	15	240	294
Matsushita	312			31	197	273
Philips	231	5	27	55	154	189
Sony	228		1	18	147	191
Fujitsu	223	6	11	33	129	178
NTT	193	3	5	31	118	177
Siemens	191	2	3	19	129	158
Alcatel	161			35	123	141
Toshiba	156		2	30	83	131
Mitsubishi	136		2	17	74	120
LG	124			2	70	103
Hitachi	121		4	14	69	97
Other	4352	84	230	821	2450	3435
Total	12288	150	453	1877	7521	10362

The networks were analysed using the method proposed by (Hummon & Doreian, 1989), which we will refer to as HDA (Hummon and Doreian Approach). The results are depicted in Figure 1. The top path of the earliest network (1976-1985) includes seven patents, starting with US 4,028,496. This patent can be found at the top left side of the smaller of the two components shown in the figure. From Annex B, which summarises the main focus of each of the patents in this figure, 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

[6] 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.

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.[7]

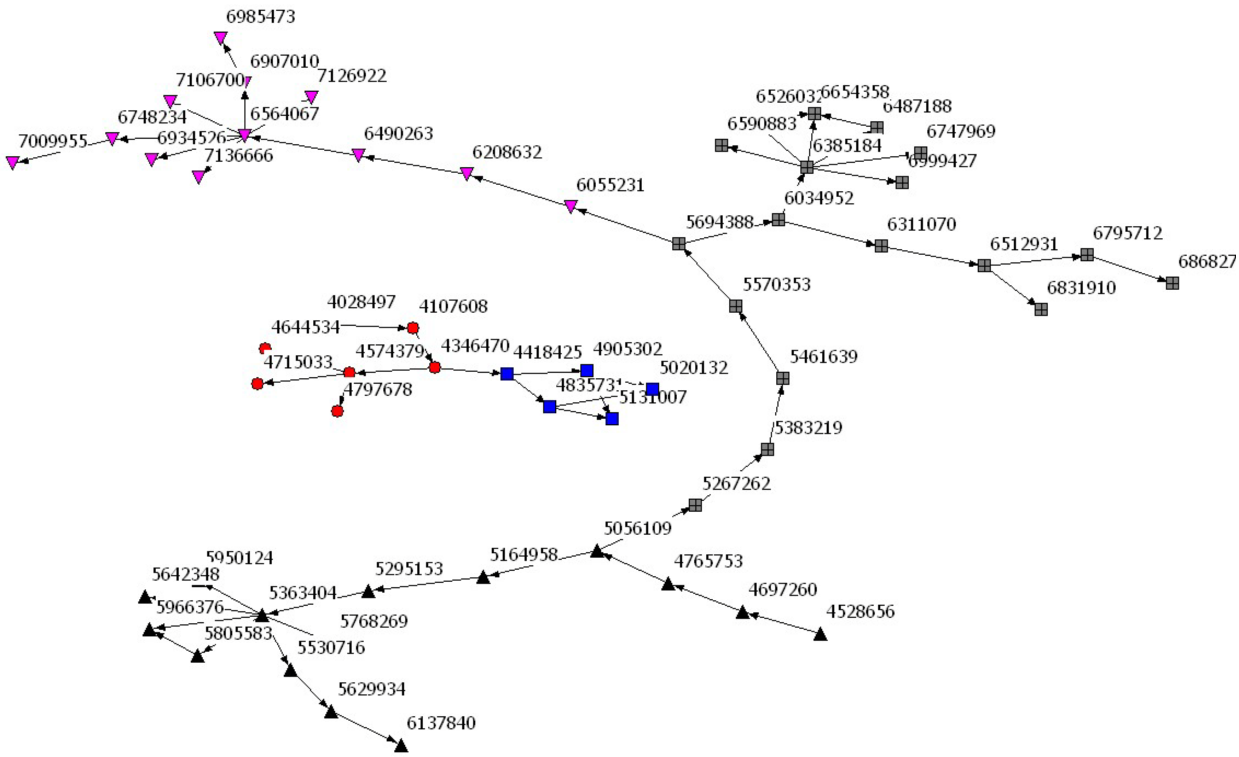

Figure 1: Trajectories for the five time periods

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 right corner in Figure 1 and ends at the bottom left corner, coinciding in time with the development of the third generation CDMA systems. Indeed, 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[8] and assigned to Qualcomm. This is the fourth patent in the trajectory, preceded by a patent from Harris, an American company that produces

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[7] 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.

[8] K. Gilhousen is a 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.

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. 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.

All in all, we can conclude that the results of the HDA analysis 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.

Analysis at the firm level

Up to this point, we have basically taken individual patents as the unit of analysis. Now, we move one abstraction level higher and take *firms* as the unit of analysis. In order to do so, we aggregate the full, relevant patent stock to the firm level. Annex D shows the statistics of this operation for each of the periods we distinguish. Firstly, we address the question whether there are clear-cut relations between various indicators that, over time, have been taken by authors as proxies for the importance of firms in such networks. More specifically, we focus on received citations (which we corrected for the average yearly citation rate as well as for self-citations), the SPL as specified in the Hummon & Doreian methodology, and the betweenness centrality (as known from Social Network Analysis). Table 2 reports on the rank correlation between these indicators and shows that they are all strongly and significantly related, in each of the time periods. In other words: firms that are supposedly 'important' in the technology field score high on all indicators.

Table 2: Rank correlations for (corrected) citations, SPLC, and betweenness

Variables	1976-1985	1976-1990	1976-1995	1976-2000	1976-2003
Rank citations	0.7124*	0.6207*	0.6988*	0.7744*	0.6131*
Rank SPL	0.6209*	0.5172*	0.6346*	0.7451*	0.7434*
Rank betweenness	0.5359*	0.5616*	0.6381*	0.7085*	0.6242*
Observation	18	29	34	41	45

Note: Tau Kendall Rank Correlation. Citations are corrected for self-citations and for the average number of citations of patents in the same year. '*' indicates 5% significance level.

Next, we have examined the citation network between firms (Figure 2 to Figure 6). Detailed data of the citation behaviour of each of the firms can be found in Annex E, which also reports on the self-citing. Not surprisingly, given our earlier findings, these networks grow and get more intertwined over time. Especially the network in the latest period can be characterized as a dense network, not dominated by a single party from which knowledge flows to others (as far as patent citations do represent knowledge flows at all) but rather a network in which a about a dozen of central players regularly draws upon each other's knowledge.

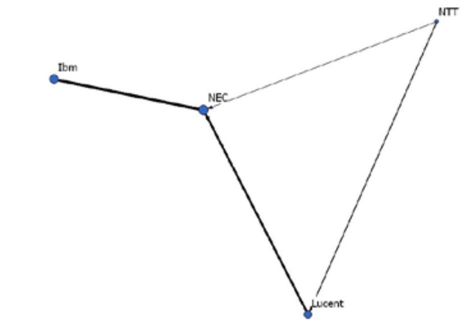


Figure 2: Firm network, 1976-1985

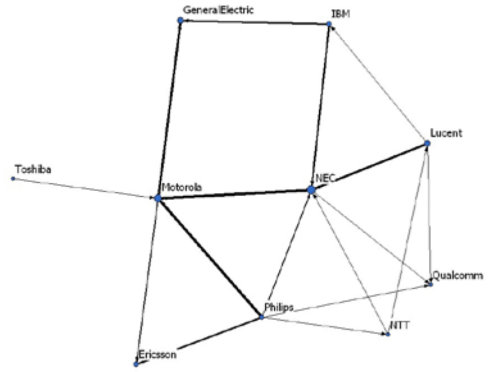


Figure 3: Firm network, 1976-1990

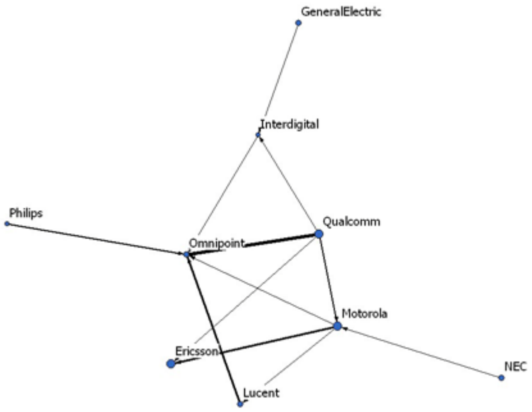


Figure 4: Firm network, 1976-1995

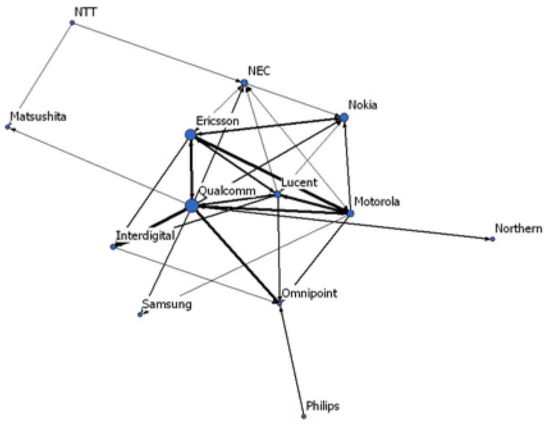


Figure 5: Firm network, 1976-2000

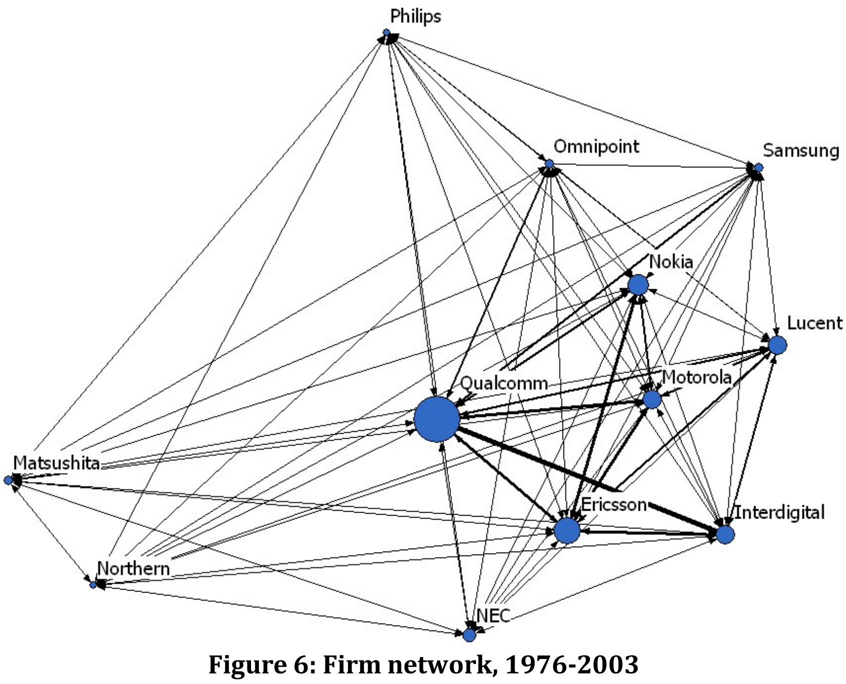


Figure 6: Firm network, 1976-2003

Note: In the figures above, the thickness of the lines represents the strength of the ties (as the sum of incoming & outgoing citations) and the arrows represents the direction in which the knowledge is flowing. The size of the node is proportional to the number of self citations.

4. The relationship between patent networks and claimed 'essential patents'

Standards bodies face the challenge of ending up in situations whereby 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-obligatory) 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[9]). 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 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 fascinating question is whether the claimed essential patents are also the technically most important or valuable patents in the particular field of technology. Whether this is the case will depend, among other things, on the technical inclusion process: on the basis of what considerations do the committees that draft standards include patented technology? Recent work presented evidence that both patent quality and the bargaining position of its owner are significant determinants of this inclusion, though the effect of the latter is stronger (Bekkers, Bongard, & Nuvolari, 2009).

For this paper, we compared essential patent claims with our data set. Data on essentiality claims were taken from the public ETSI IPR database. After cleaning up and harmonising the entries, we identified 538 USPTO patents. Of these, 219 also appear in our sample. (Note that essential patents may cover all different aspects of a standard, and since our study focuses on radio interface technologies only, patents in areas such as signalling, compression, human interface, etc. will not be present). We can observe that the ownership of essential patents is – roughly speaking – in the hands of the same group of firms that are central in both the patent data set and in the top main paths (Table 3), but that their relative shares differ considerably.[10] More specifically, Interdigital and Qualcomm have a much higher share in essential patents than in the other measures.

Table 3: Patent essentiality claims share vs. other patent shares

	Data set	Claimed essential at ETSI?	Network 2003	Toppath trajectory 2003
Ericsson	7%	2%	8%	
Motorola	7%	5%	7%	
Lucent	7%	1%	7%	1
Qualcomm	6%	24%	7%	29%
Nokia	6%	8%	6%	5%
NEC	5%	2%	6%	
Interdigital	4%	41%	4%	19%
Samsung	3%		3%	5%
Northern Telecom	3%	3%	3%	
Matsushita	3%		3%	5%

[9] 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.

[10] Please note that these numbers may differ considerably from those presented in other papers, as they reflect essential patent claims *on radio interface technologies* only. Firms that score low here might, in fact, have a considerable overall share in essential patents because of patents in other technological areas.

Philips	2%		2%	1
Sony	2%		2%	
Fujitsu	2%		2%	
NTT	2%		2%	5%
Siemens	2%		2%	
Alcatel	1%		1%	5%
Toshiba	1%		1%	
Mitsubishi	1%		1%	
LG	1%		1%	
Hitachi	1%		1%	
Other	34%	14%	31%	7%

We performed an analysis on the individual patent level: does the fact that a patent is in the top main path increase the likelihood to be claimed as being essential? Our results show that essentiality claims do show a significant relation to any of the indicators we tested (overall patent share, patent share in network, patent share in toppath trajectory). This generates further evidence for the view that essential patents are included in a standard often for other reasons than merely their importance in the technical field.

5. Conclusion and discussion

Our understanding of standardisation has grown far off that of being a narrow, technical issue, interesting for engineers only. It is increasingly recognised as a core alignment mechanism, in which the interest of various types of stakeholders are being negotiated. It has major economic and political consequences, and covers not only technical but also many social, economic and legal aspects. Especially in ICT and other sectors in which network effects reign, dominant compatibility standards can be expected to determine the rate and direction of technical change. Despite considerable attention that has recently been paid to the investigation of technological trajectories by analysing patent networks, few papers have explored the link between technological change and standardisation. This paper aims to address that gap.

Studying one of the prominent ICT topics, wireless communications, this paper uses a large patent data set in order to analyse technological trajectories. In a data set based on over 17,000 patent families within the 'wireless mutiplexing' technology (a narrowly defined but nevertheless one of the most important technological areas for wireless systems) we find that the discovered technological trajectories correspond by and large with standardisation processes. More specifically: we observe that the major engineering challenges, as identified by examining the technical literature, are indeed central to the trajectories found by applying the Hummon & Doreian methodology. This confirms the usefulness of this method in identifying the main technology contributions in a given field. Having no intention to hypothesise a causal link from patenting networks to standards, or the other way around, we would like to characterise our finding as evidence of the interplay between both.

Another finding is that when analysing the patent network for different time periods, the so-called top path does not only bend but also breaks. To the best of our knowledge, this has not been the case for published studies using this methodology to date. This dismisses concerns that this methodology has a (too) strong bias towards incremental, continuous technological paths and would therefore not be a proper representation of the real flow of technical development. Our network structure of firms is much less concentrated than one might tend to think, in the context of 'tipping' markets and strong positive externalities. After careful name cleaning (using a 'who owns who' type of data base), we still count almost 1400 different patent owners in our narrowly defined technological area. (Consistency checks on the titles have assured that all patents belong to the selected technology area.) A little less than 10% of these are (only) assigned to individual owners. With the largest patent owners not having more than 6% of the total patent stock in this field, we calculate an HHI of only 0.026. The largest 20 patent owners are part of a dense network in which all companies cite each other's knowledge, without apparent domination. Measures such as (corrected) received citations, SPL, and betweenness centrality are all strongly correlated for the firms in our sample.

In most formal standard setting environments, companies are obliged to adhere to an IPR policy requiring them to report the ownership of patents that are essential to the standard (i.e. patents that are indispensible in order to make products that comply with the standards). Interestingly, there is little or no relationship between patents being claimed as 'essential', and the position of these patents in the knowledge network. This is in line with recent arguments that these claimed essential patents are more the result of strategic manoeuvring by the parties drafting the standard than due to their technical merit.

Annex A. Summary of main technological generations / standards

	1G	2G	3G	4G
Most successful standard(s), main decision	AMPS/TACS (1970s) NMT (1970s)	GSM (1986)	W-CDMA/UMTS (1998)	3.9G: LTE (frozen December 2008) 4G: LTE-A
Commercial services[11]	1983 (US), NMT (1981)	1992	2002	2009 (small scale)
Sub-standards /improvements		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 base stations and terminals. - Low power consumption at terminals - Up to 300 km/h - Cost-efficient coverage in both urban and rural areas - Handoff to 2G systems - Minimizing required number of cell cites / antenna towers	- 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)	FDMA (analogue) *TDMA CDMA	TDMA (A-TDMA) TDMA/CDMA hybrid *W-CDMA OFDM/ODMS	CDMA *OFDM[12]
Main technological challenges	Various, including handover and handsets	- Synchronisation and timing within a cell (solved by 'timing advance') - Multipath fading (solved by the channel equalizer ('Viterbi equaliser') and frequency hopping) - 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)	Signal to noise ratio

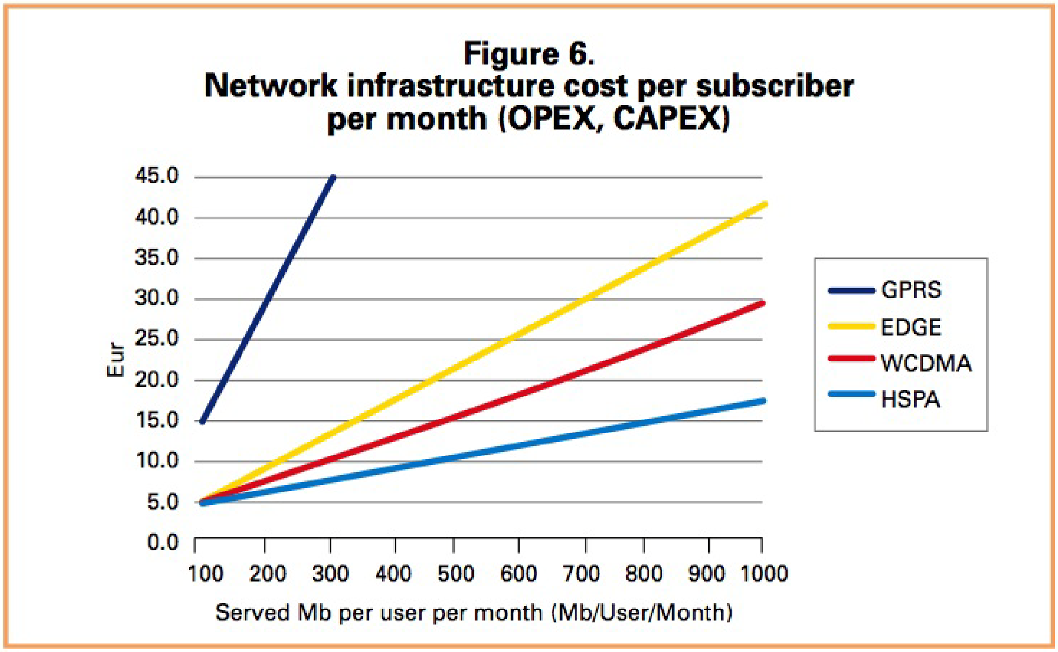
11 It is often hard to determine when the actual introduction of commercial services takes place, as technology demonstrators and trials gradually become commercial services. This row aims to indicate the date when which the first real commercial services with a substantial geographical coverage were offered.
12 Combined with SC-FDMA uplink and with MIMO/ SDMA.

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

Patent #	Assignee	1985	1990	1995	2000	2003	Priority year	Main challenge addressed
US4028497	NEC	1	1				1977	Handling frequency variations
US4107608	NEC	1	1				1979	Burst synchronisation
US4346470	IBM	1	1				1981	Burst synchronisation
US4715033	NEC	1					1985	Burst formatting
US4797678	NEC	1					1985	Time offset / advance timing
US4574379	Lucent	1					1986	Other
US4644534	ANT Nach-richtentechnik	1					1986	Time offset / advance timing
US4418425	IBM		1				1983	Burst synchronisation
US4835731, US4905302, US5020132	General Electric		1				1988	Other
US5131007	General Electric		1				1991	Other
US4528656	Harris			1	1	1	1985	Frequency allocation
US4697260	Philips			1	1	1	1986	Asymmetric multiplexing for up- and downlink
US4765753	Philips			1	1	1	1987	Handover
US5056109	Qualcomm			1	1	1	1991	Power control (loop)
US5164958	Cylink			1			1992	Handover
US5295153	Ericsson			1			1993	Frequency block allocation
US5363404	Motorola			1			1994	Other
US5530716	Motorola			1			1996	Identification of coded signal
US5642348	Lucent			1			1996	Other
US5629934	Motorola			1			1997	Power control (loop)
US5768269, US5966376	Terayon			1			1997	Other
US5950124	Aironet			1			1997	Dynamic parameters (e.g. PN codes)
US6137840	Qualcomm			1			1997	Power control (loop)
US5805583	Terayon			1			1998	Modulation/demodulation
US5267262	Qualcomm				1	1	1993	Power control (loop)
US5383219	Qualcomm				1	1	1995	Power control (loop)
US5461639	Qualcomm				1	1	1995	Power control (loop)
US5570353	Nokia				1	1	1995	Power control (loop)
US5694388	NTT				1	1	1996	Modulation/demodulation
US6034952	NTT				1		1997	SIR
US6385184, US6487188, US6526032, US6590883, US6490263	Matsushita				1		2000	Pilot channel & power control combination
US6512931	Samsung				1		2000	Power control (loop)
US6654358	Samsung				1		2000	Power control (loop)
US6831910	Samsung				1		2000	Signalling
US6747969	Philips				1		2001	Signalling
US6868279	Ericsson				1		2001	(power)
US6999427	NTT				1		2001	Power control (loop)
US6311070	Northern Telecom				1		2002	Power control (loop)
US6795712	Skyworks				1		2004	Power control (loop)
US6055231	Interdigital					1	1998	Modulation/demodulation
US6208632	Sharp					1	1999	Pilot channel
US6490263 (same family as US6385184)	Matsushita					1	2000	Pilot channel & power control combination
US6564067	Alcatel					1	2001	Power control (loop)
US6748234	Qualcomm					1	2002	Power control (loop)
US7106700	Lucent					1	2002	Dynamic parameters
US6934526	Samsung					1	2003	Dynamic parameters / system mode changes
US7136666	Lucent					1	2003	Power control (loop)
US6907010, US7126922	Interdigital					1	2004	Dynamic parameters
US6985473	Qualcomm					1	2005	Dynamic parameters / system mode changes
US7009955	Interdigital					1	2005	Power control (loop)

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 1976-2003.

Annex C. Illustration of costs per data unit dropping per generation



This figure is taken from a report by the Global mobile Suppliers Association (GSA, 2005).

Annex D. Partitioning the network into companies

	Raw Network			*Company Partitions*					*Reduced Company Partitions*		
	Patents	*Citations*	*No Isolates*	*Companies*	*Arcs*	*Loops*	*Min*	*Max*	*Cutpoints*	*Companies (reduced)*	*Links (reduced)*
1985	333	153	150	11	32	6	1	40	2	7	17
1990	734	713	453	21	103	9	1	138	4	11	40
1995	2375	6058	1877	36	423	24	1	811	42,54	11	32
2000	8660	31185	7521	45	1030	36	1	2934	76,21	19	74
2003	12288	43861	10362	45	1173	40	1	4061	105,1	18	71

Annex E. Citing patterns between the 20 largest firms, 1976-2003

The table below shows for each company in a row how often it is cited by the companies in the columns. The grey cells report the number of self-citations, whereas the last column ('self-cites') expresses the percentage of the total number of citations received.

cited → ↓ citing	eri	mot	luc	qua	nok	NEC	int	sam	not	mat	phi	son	fui	NTT	sie	alc	tos	mit	hit	Other	*Total*	*self-cites*
Ericsson	844	206	293	195	360	134	450	92	92	100	61	33	28	54	69	75	14	47	24	800	*3971*	*21%*
Motorola	383	544	317	330	213	112	170	114	88	74	36	64	45	58	41	47	33	58	29	891	*3647*	*15%*
Lucent	215	148	532	276	114	88	348	91	70	35	27	20	23	35	25	21	11	21	24	935	*3059*	*17%*
Qualcomm	371	405	305	1622	206	163	770	241	166	122	35	44	37	74	22	35	16	30	83	934	*5681*	*29%*
Nokia	244	96	122	129	569	72	133	95	66	52	28	31	28	52	51	32	11	29	34	376	*2250*	*25%*
NEC	120	86	80	78	100	299	139	42	27	83	29	28	67	44	18	33	28	27	28	494	*1850*	*16%*
Interdigital	66	29	48	65	45	31	506	45	13	23	7	4	11	7	5	14	2	21	18	253	*1213*	*42%*
Samsung	28	31	42	41	18	25	26	95	24	5	5	4	4	3	2	8	2	18	4	85	*470*	*20%*
Northern	77	35	79	76	47	23	40	51	69	9	11	7	12	7	6	3	1	4	17	170	*744*	*9%*
Matsushita	31	12	35	16	31	77	23	21	3	91	4	11	13	18	12	14	16	21	20	87	*556*	*16%*
Philips	70	42	43	83	55	26	92	6	6	10	32	11	5	6	16	14	5	10	6	208	*746*	*4%*
Sony	23	9	13	21	16	23	29	11	1	17	6	65	8	3	5	4	4	4	10	67	*339*	*19%*
Fujitsu	23	9	13	19	13	50	11	19	6	13	4	2	32	9	1	5	3	18	3	66	*319*	*10%*
NTT	68	18	35	52	46	98	81	36	12	102	7	15	29	84	2	13	9	38	36	132	*913*	*9%*
Siemens	12	10	16	36	18	14	47	7	7	2	4	2	4	5	28	3	1	16	6	84	*322*	*9%*
Alcatel	56	16	26	19	44	8	22	6	10	3	5	0	1	7	17	29	6	6	4	104	*389*	*7%*
Toshiba	29	23	22	14	40	39	21	20	8	29	6	15	16	3	6	9	64	5	6	79	*454*	*14%*
Mitsubishi	20	14	16	9	22	19	19	5	2	6	2	8	7	4	4	0	3	40	2	42	*244*	*16%*
Hitachi	13	10	9	19	11	28	38	25	6	17	6	5	5	8	4	3	2	0	39	42	*290*	*13%*
Other	517	365	451	482	272	212	790	135	117	147	117	109	63	86	72	68	56	58	74	n/a		
Total	*3210*	*2108*	*2497*	*3582*	*2240*	*1541*	*3755*	*1157*	*793*	*940*	*432*	*478*	*438*	*567*	*406*	*430*	*287*	*471*	*467*			

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