License-exempt Wi-Fi complement to 3G
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A B S T R A C T

In this paper we compare and contrast the development of Wi-Fi as a license-exempt wireless broadband technology to access the internet with the licensed regime of broadband cellular networks such as 3G. This exploration is based on an assessment of the two different innovation journeys which resulted from two different underlying communication paradigms and two different regulatory regimes, leading to different business models and different diffusion patterns. In concluding we compare the merits of the two cases and derive recommendations for policy and strategy formation.

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1. Introduction

Today, Wi-Fi has become the preferred means for connecting to the internet – without wires: at home, in the office, in hotels, at airports, at the university campus. Increasingly, Wi-Fi, synonymous with wireless local area networks (WLANs), provides access to the internet for remote communities in developing countries. Even in rural areas of developed countries community-based Wi-Fi initiatives have emerged to provide broadband wireless internet access, as incumbent operators failed to extend the wired infrastructure to less profitable areas. Moreover, local governments in major cities have recognized the added-value in providing municipal Wi-Fi.

The uptake of Wi-Fi resembles the diffusion of digital mobile cellular communication, see Fig. 1 (based on: GSM Association, 2007; Instat, 2007), denoted as 2G – the second generation; analogue cellular being the first generation. Cellular has become the preferred means for voice communication: early 2007 there were 2829 million mobile users worldwide. In roughly a decade wireless has overtaken wireline communication with a deployment history of over 100 years. Although designed and optimized to support voice, the cellular technology and associated standards have evolved to support data communications with increasing data rates; denoted by 2.5G, GPRS and EDGE. Personal multi-media communication with high data rates (originally up to 2 Mbits/s) is denoted as 3G – the third-generation; currently providing packet data rates up to 7 Mbits/s.

The success of Wi-Fi is remarkable, as hitherto the most significant developments in radio frequency technology – radio-relay systems, R-TV broadcasting, cellular – have emerged under a licensed regime, whereby a government agency provides exclusive rights to the use of a specific part of the radio frequency (RF) spectrum, thereby providing the application protection from harmful interference by other radio frequency users. The success of Wi-Fi, however, emerged under a licensed-exempt open access regime, whereby it had to contend with many other applications and users in the same RF band, including microwave ovens.

The success of digital cellular communications, in particular the domination of GSM –80% of the mobile phones are based on the GSM standard (GSM Association, 2007), has been attributed to the leading role of European governments and their
institutions in creating a harmonized market for cellular communication through a standardization effort of digital mobile technology, the allocation of RF spectrum on a regional basis, combined with a coordination effort in the alignment of the underlying business model in the second half of 1980s. The importance of standardization becomes apparent if we compare the uptake of cellular communication in Europe and the USA. In contrast, the success of Wi-Fi must be attributed to the private sector, albeit, it has been triggered by the US Federal Communications Commission (FCC) in setting the example allowing radio communications including Radio-LANs to operate in bands designated for industrial, scientific and medical (ISM) applications from 1985 onward.

In this paper we compare and contrast the development of Wi-Fi as a license-exempt wireless broadband technology to access the internet with the licensed regime of broadband cellular networks. Often one can observe debates about the question which one is better, in terms of data rates being supported, in quality, in utilizing the radio frequency spectrum, in the contribution to welfare, etc. The generic answer to this question is: it depends. We will argue that the systems should be compared on their merits. Based on our insights we conclude this contribution with recommendations for policy and strategy formation.

To evaluate the two systems, an appreciation of the two, distinctly different development trajectories is considered necessary. Hence, we will start with a recap of the historical developments having led to the current day success of these two forms of wireless communication: (1) the genesis and development of cellular communication, originally designed for the transmission of voice and (2) the genesis and development of wireless local area networking, originally designed for the transmission of data. While these different starting points have led to different business models and hence to different diffusion models, the transition from analogue to digital communication and applications becoming based on the TCP/IP protocol stack, allow these development trajectories to converge. Cellular networks are increasingly supporting data and Wi-Fi is increasingly supporting voice.

2. The origin and development of cellular

In 1906 Fessenden transmitted for the first time the human voice using radio technology. In the 1920s and 1930s this led to radio broadcasting and to radio receivers appearing in most homes. In 1946 mobile telephony service was introduced when AT&T, with the permission of the FCC, provided the first commercial car-borne service in St. Louis, Missouri, which quickly expanded to cover the major cities in the US. In 1947 Bell Labs introduced the concept of cellular communications to resolve capacity constraints of these systems through the geographical re-use of frequencies. To make the concept work the principle of ‘switch-over’ between cells had to be realized, a functionality for which the technology was not yet available.

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1 The Federal Communications Commission is an United States government agency, directly responsible to Congress. The FCC was established by the Communications Act of 1934 and is charged with regulating interstate and international communications by radio, television, wire, satellite and cable. The FCC’s jurisdiction covers the 50 states, the district of Columbia, and US possessions (FCC, 2007).

2 Critical to the development of radio communication and broadcasting has been the invention of the vacuum tube by Fleming in 1915.

3 This functionality would be developed in the 1960s–1970s.
2.1. 1G developments in the USA

In 1968 – 21 years later – the FCC initiated proceedings for the deployment of cellular communications. In 1970 it sets aside 75 MHz of spectrum for cellular systems to be operated by wireline carriers. In 1971 this allocation was extended to include non-wireline carriers. However, in 1974 the FCC decision was reversed. Only one system per market (geographical area) would be allowed, and the allocation reduced to 40 MHz. In 1975 as the powers shifted again, both wireline and non-wireline carriers were allowed to participate. In 1977 the building of two so-called developmental systems was authorized, which led in 1981 to the decision to allow two systems in each market (Meurling and Jeans, 1994). In 1982 the FCC started to accept application for licenses. They received 140 applications for the first round of 30 designated markets, each market attracting two to twelve applicants. The selection was to be based on ‘comparative hearings’, using the requested information on marketing, engineering, and roll-out plans, cash-flow projections, etc. For practical reasons this model was quickly abandoned and replaced by an evaluation based on ‘population covered’. The first commercial license was granted in 1983 and the first analogue cellular service based on the AMPS (advanced mobile phone system) specification by Bell Labs was introduced by Illinois Bell in Chicago in the same year. Like earlier systems AMPS uses frequency division multiple access (FDMA) and operates in the 800–900 MHz band (Botto, 2002; Manninen, 2002; Mock, 2005; Rey, 1983).

The FCC decided that the following two rounds would be allocated based on a lottery system. Under the threat of the lottery, contenders having filed application came together under the leadership of Aaron of RAM Broadcasting and Sherwin of Graphic Scanning, the major contenders in several markets, to essentially play a game of Monopoly. “For each city, a value was set at, say, 10 US dollars per inhabitant (pop). If there were 500,000 inhabitants, the city would be worth 5 million US dollars. Now, if there were five contenders for this city, each contender was given a card worth one million dollars for the city. In this way, all the contenders accumulated a bunch of cards, or tokens, corresponding to their position in the filings. They were told to sit down in groups and attempt to swap tokens. In some cases, an applicant might decide to offer additional money to fill out a ‘hand’. As soon as somebody had got together a ‘full hand’ for a given city, he would report to Aaron. If they were not through by morning – the lottery! And, by morning, the United States of America had been re-arranged – as far as mobile communications were concerned. . . . With the help of market forces, order emerged from chaos.” (Meurling and Jeans, 1994).

2.2. 1G developments in Europe

In the Netherlands plans for a public mobile phone service were developed in 1947 and led to the introduction of service in 1949, the first in Europe; the connections were set up by an operator. The service proved its value during the flooding in 1953, when the fixed infrastructure was out of service (Schuilenga et al., 1981). In Sweden mobile developments started with a trial system becoming operational in 1950 to be followed by two commercial systems in 1956, in Stockholm and in Gothenburg. In 1965 a newer car-borne system was introduced (Manninen, 2002; Meurling and Jeans, 1994). In 1970, in the context of Pan-Nordic cooperation, the internal study commissioned by Televerket on mobile communication would form the basis for a working party that subsequently recommended the construction of a new, pan-Nordic automatic mobile telephone system, to be based on the cellular concept. The nordic mobile telephone system (NMT) was born. The NMT Group decided upon a standardized approach to be applied across the Nordic countries, including quality of service and ‘roaming’, to be completed in 1975, and to be made available to the industry, essentially as an open standard – free of charge. In 1978 a trial was successfully concluded. In 1977 manufacturers had been invited to bid for the supply of the base stations and the mobile switching equipment with the cut over date to be October 1st 1981. Ericsson was to become the supplier of choice for the switching part and SRA for the base stations. The targeted in-service date was met, but the world’s first cellular system would be inaugurated one month earlier on September 1st 1981 in the Kingdom of Saudi Arabia; also based on NMT. In 1981 to the Kingdom. In 1979 this contract was extended to include a mobile telephone system.

With this initial success other countries followed to introduce mobile telephone service. In the Netherlands the incumbent operator adopted the NMT 450\(^7\) standard, as did the operators in Belgium and Luxemburg. In 1986 Sweden introduced NMT 900 to cater to increasing demand.\(^8\) In the UK the duopoly concept had been introduced and the first license was awarded to Cellnet, an independent subsidiary of the incumbent operator BT. The second license was open to competition and awarded in 1983 to a new entrant, a joint venture of Racal and Milicom (later Vodafone). Subsequently Cellnet and Vodafone had to negotiate the standard to be used, which became known as TACS (total access communication system), a version of the US AMPS, heavily pushed by Vodafone, intending to leverage the larger US market volume. Motorola would become supplier to Cellnet

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\(^4\) Televerket: the Swedish Telecommunication Administration, a state organization having provided the country with telephone service. In 1993 it would become a stock company called Telia AB, still state owned.

\(^5\) The mobile switching system MTX was of the AXE type, the first fully digital switch developed by Ellemtel, a joint company of Swedish Telecom and Ericsson. SRA – Svenska Radio Aktiebolaget – was founded in 1919 by ASEA, AGA and Ericsson. In 1982 it would become a fully owned subsidiary of Ericsson (Meurling and Jeans, 1994).

\(^6\) In 1978 the joint venture between Ericsson of Sweden and Philips of the Netherlands had been awarded the contract to build a new fixed telephone network for the Kingdom. In 1979 this contract was extended to include a mobile telephone system.

\(^7\) NMT 450 referred to the 450 MHz frequency band being used.

\(^8\) Countries applying NMT 900 had to phase out the system to allow the deployment of GSM in the same band.

\(^9\) The main difference is the channel spacing: 25 kHz in Europe and 30 kHz in the USA.
and Ericsson to Vodafone. The in-service date was January, 1st 1985. TACS was also adopted in Hong Kong (Manninen, 2002; Meurling and Jeans, 1994).

National cellular standards were applied in Germany: Netz-C (in-service in 1986), in France: Radiocomm 2000 (1986), and in Italy: RTMI/RTMS (1985), which later introduced TACS. AMPS was, furthermore, deployed in South America, the Far East and the Asia Pacific region. Thailand and Indonesia opted for NMT. In Japan NTTs MCS system was the representative of the – 1G – generation (Botto, 2002; GSM Association, 2004; Manninen, 2002; Meurling and Jeans, 1994).

2.3. The development to 2G

The potential of pan-European mobile communications was observed by the French PTT who convened a meeting with PTTs in 1981 to explore the use of the 900 MHz band, which had been reserved through the CEPT10 for mobile communications in 1978. Only France and the UK appeared to be pushing to exploit the 900 MHz band to address foreseen capacity issues by 1983. This same year the Nordic Administrations initiated the NMT-2 Group to explore ‘mobile communications for the future’.

The British and French incumbent operators decided to cooperate in specifying a joint system, inviting other operators to participate. Before their scheduled meeting of June 1982, the Dutch announced a recommendation to be made to the CEPT to start procedures leading to “the construction of a pan-European automatic telephone service on the 900 MHz band”; a proposal that appealed to many European administrations. This resulted in a working party being created under the hierarchy of the coordination committee for harmonization of CEPT: the Groupe de travail spécial pour les service mobiles (in short: GSM) to develop a specification. The system would have to resolve capacity shortage of the analogue systems and provide for harmonisation of the European market, resolving the incompatibility between the multiple standards being used. In 1984 the European Commission endorsed the project and it issued a Directive for the launch of GSM by 1991, with a minimum set of services including roaming. In 1986 the decision was taken to opt for a digital system. In 1987 operators from 13 countries signed a memorandum of understanding to commit to the network roll-out and cooperation on commercial and operational matters, such as tariff principles (e.g. calling party pays) and accounting. The validation trials held in 1986 with the support of major equipment suppliers, such as Nokia, Ericsson and Siemens, led to the decision to adopt narrow-band time division multiple access (TDMA) technology. In 1989 the group became a technical committee within the newly created ETSI (European telecommunication standards institute), in which manufacturers, operators, administrations and user groups were represented. A year later Phase 1 of the GSM-900 specifications was released, with open interfaces to foster competition in network deployment. In the fall of 1992 GSM was launched in seven countries by 13 operators (GSM Association, 2004; Manninen, 2002; Meurling and Jeans, 1994).

Variants of GSM include digital cellular systems operating at 1800 MHz (DCS-1800 or GSM-1800) and PCS 1900 deployed in the USA and South America.

In 1988, the US cellular telecommunications industry association (CTIA) published a set of requirements for the industry with the objective to increase the capacity of the analogue network tenfold, in addition improving reliability and quality. AT&T, Motorola and Ericsson setup tests to demonstrate the capabilities of their digital systems. Qualcomm used this opportunity to pitch for a new concept code division multiple access (CDMA), based on spread spectrum techniques, claiming a theoretical capacity increase of 40 times. However, CDMA was considered too complex and not a proven concept, and although only an threefold increase could be demonstrated with good voice quality, the telecommunication industry association (TIA) voted for a TDMA specification to be called IS-54 or D-AMPS. The advantage was that TDMA could be positioned as an upgrade of AMPS using the existing base stations, albeit for this evolution dual-mode analogue/digital handsets were required. In 1989 NTT of Japan introduced PDC, a TDMA-based system modified to fit the Japanese network (Meurling and Jeans, 1994; Mock, 2005).

Late 1989 Qualcomm in close cooperation with PacTel demonstrated a CDMA prototype, with a tenfold capacity increase. Field test executed in the fall of 1991 confirmed their claim. However, in 1992 the CTIA reconfirmed its support for TDMA, but also recommended that the TIA set up a structure to develop a wideband spread spectrum standard. In 1993 the IS-95 CDMA standard was ratified by the TIA. In 1994 the FCC auctioned large blocks of spectrum in the 1900 MHz band for Personal Communication Services. This led in 1995 to CDMA being adopted by PCS PrimeCo, Airtouch and Sprint. By 1997 more than 50% of the PCS licensees had implemented CDMA technology. Other non-US early adopters of CDMA were Hutchinson in Hong Kong, Korea Mobile Telecom and Shinsegii Telecom also in Korea (Manninen, 2002; Mock, 2005).

2.4. The development to 3G

The unexpected but welcome success of text messaging or short message service (SMS) as part of – 2G – had indicated the potential of cellular with respect to data communication. Future growth in traffic was expected to be in data applications, which has stimulated the industry to pursue solutions to provide data-on-the-move and m-commerce. The deployment of WAP (wireless application protocol) in 1998 was an early attempt to link the circuit switched mobile telephony world

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10 CEPT: Conférence des Administrations Européennes des Postes et Télécommunications, an Association of European Postal and Telecommunications Administrations (PTTs).
to the packet switched Internet world. A wireless mark-up language was being used to bridge the differences in terminal
capabilities between stationary and mobile terminals (Botto, 2002). The introduction of GPRS (general packet radio service)
is providing for a packet overlay and is increasing the user data rate to a maximum of 171 kbits/s. GPRS supports applications
such as e-mail, internet browsing, as well as value added services. GPRS and EDGE (enhanced date rates for global evolution)
have been denoted as -2.5G-, or the intermediate step towards broadband mobile communication, i.e. the third-generation
of mobility: – 3G – or in Europe UMTS (universal mobile telecommunication service).

In Japan the introduction of I-mode by NTT DoCoMo in February 1999 showed the potential of mobile communication
beyond plain voice. Within six month the one million subscriber level was achieved, by August 2000 the 10 million mark,
and by October one third of DoCoMo’s mobile subscribers had signed up for I-mode. I-mode offers Internet access and email,
as well as access to third-party provided fee-based services (Natsuno, 2000).

'True' broadband communication with data rates in the range of Mb/s, referred to as the next generation or – 3G –
started in 1986 under the heading of future public land mobile telecommunication system11, and started to generate tangible
results as a collective effort to standardize the Universal Terrestrial Radio Access radio interface and the evolved GSM core net-
work under the 3rd Generation Partnership Project, involving standards and industry organizations from Europe, USA, Japan
and Korea. In 1997 Lucent Technologies, Motorola, Nortel and Qualcomm set out to develop the next generation standard
CDMA2000. The European Commission funded the advanced communications technologies and services (ACTS) group to pre-
pare for the next generation of Wideband-CDMA for Europe. To reach a global deployment the new -3G- equipment would
have to interface with the existing – 2G – equipment, primarily GSM, D-AMPS and CDMA. In 1999 the dispute over intellectual
property rights that had emerged in 1995 between Ericsson and Qualcomm was settled and a – 3G – standard that had three
modes of operation, one for each major – 2G – variant, could be supported (Mock, 2005).

The success story of – 2G – combined with the success of the Internet, raised the expectation for mobile broadband com-
 munications. This was reflected in the initial willingness to pay by operators at the auctions for 3G-licenses.12 The first auc-
tion was held in the UK, where five licenses were on offer. The gross proceeds of the auction amounted to US$ 33.3 billion, or
US$ 650 per inhabitant (Lennin and Paltridge, 2003; OECD, 2005). The auction principle was also applied in Germany yielding €
613, Italy € 240 and the Netherlands € 171 per inhabitant. The level of proceeds was determined largely by the auction design,
but also fed by the promise of the mobile internet during the peak of the telecom boom, see e.g. Melody (2001) and Van Damme

In October 2000 the first commercial offering of – 3G – services was introduced by SK Telecom in Korea, based on CDMA
1X. NTT DoCoMo of Japan followed in October 2001. In 2002 Verizon launched – 3G – services, and by the end of the first
quarter 2006 deployment had reached 61 million users. By October 2007 132 operators had deployed 3.5G high speed packet
access, with data rates between 1.8 and 7.2 Mb/s on the down link (HSDPA), and 56 operators were providing high speed
uplinks (HSUPA) of 1.4 to 5.7 Mb/s (GSM Association, 2007; Lehr and McKnight, 2003; Mock, 2005).

3. The origin and development of Wi-Fi

The transmission technique used in Wi-Fi is called spread spectrum, denoting that the signal is spread over a wider frequency
range than is strictly necessary when a single carrier frequency would be used. The invention of spread spectrum, in
the form of frequency hopping, dates back to 1942 when a patent was granted to actress Hedy Lamarr and composer George
Antheil: US Patent # 2,292,387, issued on August 11, under the title: “Secret Communications System”, Hedy Lamarr, was born
as Hedwig Eva Maria Kiesler in 1913 in Vienna and had been married to Friedrich Mandl, an Austrian arms manufacturer.
This marriage had exposed her to many discussions on the issue of jamming of radio-guided torpedos launched from sub-
marines. In 1937 Kiesler left Austria for America, under a contract with MGM, where she met with the composer George
Antheil. Their combined insights in technology and music generated the idea to change the carrier frequency on a regular basis,
akin to changing the frequency when striking another key on the piano. They presented their idea to the National Inventors Council and subsequently donated their patent to the US military as a contribution to the war effort. Given the technical complexity involved, the first practical application occurred in the mid 1950s, in sonobuoys used to secretly locate submarines (Mock, 2005).

3.1. The landmark decision by the US Federal Communications Commission

The use of spread spectrum techniques remained restricted until 1985 when the FCC through its Report and Order of May
9 decided to allow the public use of spread spectrum for communication purposes (FCC, 1985). This decision followed an
investigation by the MITRE Corporation, initiated by the FCC in 1980 in response to the Carter administration pushing for
deregulation.

Interestingly, the MITRE report that investigated the potential benefits, costs, and risks of spread spectrum commu-
nications did not identify a strong need from the industry to assign RF spectrum for spread spectrum applications. The

11 The ITU abandoned the original objective of one global standard to develop a framework for 3rd generation mobile communications under the heading of
IMT-2000.

12 The UK auction was preceded by awards in Finland in 1999 and Spain in 2000 based on a beauty contest (Financial Times, 2002).
report concludes that the technology is inherently more complex and thus more costly (Mitre Corp., 1980). The report did identify spread spectrum as inherently more resistant to interference. Moreover, it identified the ISM bands as bands “…in which spread spectrum techniques may be able to improve the utilization of the spectrum…”as these bands) are relatively unsuitable for applications requiring guaranteed high levels of performance. Indeed, since users of the ISM bands are not nominally protected from interference, it can be argued that any productive use of these bands frees other spectrum resources that are needed by applications requiring protection from interference” (1980). Typical applications in the ISM bands were garage door openers, retail security systems, cordless telephones and microwave ovens.

The FCC Notice of Inquiry13 proposed to use spread spectrum as an “underlay” within other bands, i.e. sharing the frequencies with other services. The Notice triggered comments expressing fear of interference and the difficulty of tracing the source. Based on the responses, the FCC proposed two rules changes: one for licensed use of spread spectrum in the police bands and one for unlicensed use. The unlicensed proposal called for an underlay on the spectrum above 70 MHz at very low power (below –41 dBm) and one for unspecified power limits in the three bands designated for ISM applications (Marcus, 2007). The Further Notice triggered more comments, whereby many of the respondents favoured the proposed authorization. Subsequently the FCC dropped the proposal for an underlay and issued a ruling on the police radio service and on the use of spread spectrum in the three bands designated for ISM applications: the 902–926, the 2400–2483.5, and the 5725–5850 MHz bands.14

This 1985 FCC decision is the trigger for the industry to start the development of wireless local area networks (WLANs).

3.2. NCR taking the lead in WLAN development

A leading role in the development of WLANs has been played by NCR15 as a nagging issue for the sales force had been the lack of ‘mobility’ in the cash register product portfolio. Retail department stores, a major client group, reconfigured the sales floor on a regular basis and the cost of rewiring the transaction terminals was significant. To address this issue NCR had conducted a study into the use of infrared light technology, but quickly recognized that radio technology would be a much better option: “…if it was permitted, if we could make it work, and if we could turn it into affordable products” (Johnson, 2007). The seed money from NCR head quarters in Dayton Ohio kicked off a development process whereby the Dutch based engineering center started a feasibility study to assess whether a wireless device could be developed for cash registers under the rules set by the FCC.

In the summer of 1987, after the feasibility study had ended with a positive result, the team set out to create a wireless network interface card (Wireless-NIC) to build a Wireless-LAN with an over-the-air data rate of 1–2 Mbits/s. The NIC would have to operate in the 900 MHz band, to provide the maximum possible range and to reduce the cost of the electronics. The creation of a new medium access control (MAC) protocol became the focus of the product development effort. The MAC provides the functionality required to access a particular physical medium, in this case the radio waves. To limit costs and reduce development time the team intended to leverage as much as possible existing MAC designs and to make use of existing protocol standards.

This search led to the MAC used in the token bus standard, recently approved as IEEE 802.4. The IEEE 802.4l Task Group was already working on a wireless variant driven by General Motors, but it seemed it was “losing steam”.16 However, as Tuch of NCR observed: “Making the 802.4 Token Bus protocol fit with the wireless medium was like trying to use a boat to get across a swamp instead of a hovercraft.” (Tuch, 2007). Having concluded that the Token Bus MAC was unsuitable, the MAC used in the IEEE 802.3 Ethernet standard still might be adapted. One of the key issues was how to get “collision detect” implemented using a wireless medium.17 A solution developed by NCR and Inland Steel was presented to the IEEE 802.3 group to solicit interest to start a new wireless Task Group, albeit, without success. Subsequently, under the leadership of Tuch the companies interested in establishing a WLAN standard quickly generated the necessary paperwork for the establishment of a new standardization project. At the July Plenary meeting, the IEEE 802 Executive Committee approved the request.

The new IEEE 802.11 Working Group was born, and Vic Hayes of NCR was appointed as the interim chairperson.

At the November 1991 meeting of the work group the MAC and PHY18 sub groups were established. The groups had the task of selecting the appropriate technology for the standard; proposal reaching majority support would be submitted to the

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13 When the FCC receives petitions for new rule making, or they see themselves a need to make a rules change, they have to organize public consultation in the form of a “Notice of Inquiry, NoI”. All comments have to be addressed in the subsequent consultation round. This round is also followed by a comment and reply comment period. The FCC has the obligation to address all comments and reply comments and publishes the results in a “Report and Order, R&O”. Issues found in the Order can only be appealed in petitions for reconsideration.

14 The limitation on peak power was set at a level of 1 W. No limitations on the antenna gain were specified. The 1 W was determined on the basis of a coverage area of one mile.

15 NCR Corporation was founded in 1879 as the National Manufacturing Company of Dayton, Ohio, to manufacture and sell mechanical cash registers. In 1884 it was renamed National Cash Register Company. The company was acquired by AT&T in 1991. A restructuring of AT&T in 1996, led to its re-establishment as a separate company in 1997 (NCR, 2007).

16 According to the PAR this Task Group is denoted 802.4c which through a transcription error became 802.4l.

17 If two stations simultaneously are accessing a shared medium the resulting “collision” needs to be detected and a re-send procedure initiated to assure the proper transfer of information.

18 The PHY is the layer concerned with the physical transport of a raw bit stream, subject to the type of medium being used.
working group for approval. In the meeting of November 1993 the foundation technology of the MAC was selected. The first letter ballot on the draft standard was started at the November 1994 meeting.

Much more contentious was the standardization of the PHY. The FCC had specified two different spread spectrum modulation techniques that could be used: frequency hopping (FH) and direct sequence (DS). When put to a vote neither of the two modulation techniques obtained the required 75% level of support. Proponents of FH claimed it was easier to implement, while DS had the promise of a more robust system with a higher data rate. The individuals in the FH camp feared that the required investment in silicon would be significant, while the DS camp tried to refute the argument based on their experience in the implementation of pilot versions in silicon. As neither of the two groups could obtain the required level of support, the only way out was to include both modulation technologies in the standard.

The main driver for an alternative standard called HomeRF, being pushed by an industry consortium involving Proxim and Intel, was the perceived inadequate support in the draft specification for isochronous services, i.e. telephony (Negus et al., 2000). The consortium adopted the FH method to support a data rate of 1.6 Mbits/s. HomeRF was positioned as a low cost solution having a relaxed PHY specification supporting both isochronous and asynchronous traffic. When the IEEE adopted the “802.11b” project for an 11 Mbits/s extension of the standard, the HomeRF consortium announced a second release of the specification for speeds of 6–10 Mbits/s (Negus et al., 2000). This required the HomeRF consortium to request the FCC for a change in the interpretation of the existing rules to widen the sub-channels from 1 MHz to 3 and 5 MHz. On August 31st 2000 the FCC released a Report and Order changing the frequency hopping rules (FCC, 2000).

The HomeRF battle in the 802.11 working group was fierce. Despite the support of major payers in the industry the HomeRF initiative failed. According to Lansford the reasons for the failure were twofold (Lansford, 2007):

1. Because none of the consortium members were developing PHY silicon, they were forced to abandon a PHY that was similar to 802.11 FH and switch to the OpenAir PHY developed by Proxim. Many companies in the HomeRF consortium felt this made the standard a proprietary system, and
2. The adoption of 802.11b in 1999 and its support by several silicon vendors (Harris, Lucent Technologies, etc.) drove down prices relatively quickly compared to the single silicon source for HomeRF. The HomeRF consortium had assumed that FH products would always be cheaper than DS products, but market competition invalidated that assumption.

The voting for the IEEE 802.11b PHY was very contentious. The main contenders were Harris and Lucent Technologies, and a proposal from an outsider Micrilor. There was a degree of truth in a 3Com statement that most of the Lucent Technologies supporters had decided to side with Micrilor to avoid that Harris would have an unfair advantage, as they had progressed substantially in their development efforts. In the same week representatives of Lucent Technologies and Harris sat together and acknowledged a compromise was needed. Subsequently they worked out a new radio transmission scheme, different from anything that had been proposed before, called complementary code keying (CCK). Because this proposal gave no advantage to any party it was accepted in the next meeting of the Working Group, resulting in the IEEE 802.11b standard.

3.3. Formal approval of the IEEE 802.11 standards

In September 1997, the standards activities board (SAB) approved IEEE 802.11 – 1997 edition, to be published on December 10th 1997 covering frequency hopping at a data rate of 1 Mbits/s and direct sequence at 2 Mbits/s.

Project 802.11a for an extension of the standard to support data rates up to 54 Mbits/s in the 5 GHz band, and Project 802.11n for an extension of the standard to support data rates up to 11 Mbits/s in the 2.4 GHz band were balloted at working group level in November 1998 and re-circulated twice to start the sponsor ballot in April 1999. After two recirculation ballots, both were submitted to the SAB in August 1999. IEEE 802.11a was officially published on December 30th 1999 and IEEE 802.11n was published on January 20th 2000. In 2003 the specification for data rates up to 54 Mbits/s in the 2.4 GHz band was released as IEEE 802.11g. Higher data rates of 100 Mb/s and more making use of antenna diversity with MIMO (Multiple Input – Multiple Output) technology are being pursued as part of Task Group 11n. In 2007, Dutch based Airgo provided the technology for the first commercially deployed IEEE 802.11n based products with a data rate of 300 Mbits/s (Van Nee, 2007).

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19 In a direct sequence system the incoming information is modulo 2 added to a higher speed code sequence. The combined result is then used to modulate a radio frequency carrier. Since the high speed code sequence dominates the modulating function, it is the direct cause of the wide spreading of the transmitted signal. In a frequency hopping system the carrier is modulated with the coded information in a conventional manner. However, the frequency of the carrier changes at fixed intervals under the direction of a pseudorandom coded sequence. The wide RF bandwidth needed is required to accommodate the range of frequencies to which the carrier frequency can hop.

20 Companies that were involved in product development included: Butterfly Communications, Compaq, HP, IBM, Intel, iReady, Microsoft, Motorola, Proxim, OTC Telecom, RF Monolithics, Samsung and Symbionics (Lansford, 1999).

21 Lansford has been co-chair of the technical committee for the HomeRF industry working group and wireless system architect with Intel Corporation.

22 In 1991 NCR is acquired by AT&T. In the 1996 tri-vestiture AT&T, continues as the (inter)national telecom services operator, NCR becomes an independent company again, and the equipment activities become part of the newly established Lucent Technologies. The WLAN activities move to Lucent Technologies.

23 Soon after the SAB approval, conforming products with either 1 Mbits/s FH and 2 Mbits/s DS appeared on the market. The third option, based on infrared, never made it into products.
3.4. Developments in Europe

Following the decision making by the FCC, an ad-hoc group on Radio-LANs within the CEPT, the organization responsible for the harmonization of spectrum use in Europe, recommended that the 2.4 GHz band designated for ISM applications be opened for the use of RadiolAN devices, and it requested ETSI, the organization responsible for the development of telecommunication standards, to develop the necessary standard. In 1991 the European Radio-communications Committee assigns the 2.4 GHz ISM band for WLAN use; on a non-protective and non-interference basis, without the need for an end-user license. This paved the way towards a global allocation of spectrum for Wireless-LANs.

The ad-hoc group also assigned 5150–5300 MHz with an optional extension to 5350 MHz to accommodate RLANs. As often happens in Europe, this assignment of the spectrum would be tied to devices adhering to a specific standard, HIPERLAN for high performance local area networks, yet to be developed. HIPERLAN was aimed at providing high speed (24 Mbits/s typical data rate) communications in the 5 GHz band compatible with Wired-LANs based on Ethernet and Token Ring standards. HIPERLAN was aimed to cover a range of 50 m and to support (a)synchronous applications. The committee published the HIPERLAN/1 specification in 1997. A second version was developed as part of the ETSI-BRAN Broadband Radio Access Networks project to provide data rates up to 54 Mbits/s in the 5 GHz band between portable computing devices and broadband ATM and IP networks. This version supported multi-media applications, with emphasis on quality of service (QoS).

Neither the HIPERLAN/1 nor the HIPERLAN/2 standard, which were completed in 2004, have become a success. Motorola and other firms were involved in product developments, but, as was the case with HomeRF, HIPERLAN/2 had to compete with a much more matured IEEE 802.11 standard for which devices had been developed that had already reached a price point too low to compete with effectively.

4. Subject to different paradigms and regimes

In interpreting the two different “innovation journeys” (Van de Ven et al., 1999), and with reference to Teece and Pisano (1994), we should recognize that innovation strategies of firms are strongly constrained by their current position and by the specific opportunities open to them in future: in other words, they are path dependent (Tidd et al., 2001). From the notion of path dependence, Tidd et al. argue, comes the notion of technological trajectories as introduced by Nelson and Winter (1977) and elaborated by Dosi (1982). A technological trajectory is defined by Dosi as: “the pattern of ‘normal’ problem solving activity (in the Kuhnean sense) on the ground of a technological paradigm.” The two different communication paradigms and the two different regulatory regimes provide different starting positions with respect to the business models that can be exploited.

4.1. Two different communication paradigms

The two innovation journeys described relate to two different communication paradigms. A technological paradigm is being defined as: “a ‘model’ and a ‘pattern’ of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies.” (italics in original, Dosi, 1982 p. 152). As such the paradigm determines broadly the trajectory a firm or an industry is following in its development. Cellular communication is the logical wireless extension of the circuit-mode voice-driven paradigm, which originated with the invention of the telephone in 1876 and evolved from the setup of analogue wireline circuits of 3 kHz bandwidth to the transmission and switching of the digital representation of the voice signal using 64 kbits/s channels. In 1960 packet switching was introduced as a more appropriate way of handling computer communication. Each message is thereby cut in fixed length packets, and to each packet addressing information is added to facilitate the routing through the network. In 1965, recognizing the vulnerability of hierarchically network structures for outages through hostile acts, the US Department of Defence started to fund the advanced research projects agency (ARPA) to develop a more robust network topology. Using a fully interconnected (mesh) network, multiple routes would be available for the transport of packets. With the ARPA research efforts becoming the basis of the internet, the resulting packet-mode paradigm would become leading in data communication using the public network. The development of local area networks to interconnect computers and peripherals at high data rates using packets occurred in parallel. The first LAN was introduced in 1971, Ethernet in 1975, to become the IEEE 802.3 standard in 1985 (Von Burg, 2001).

4.2. Two different regulatory regimes

The two wireless communication systems show similarities in the way they use the RF spectrum, but more important are the differences. Both systems are assigned to operate in a specific RF band to avoid interference with other applications and

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24 Note that in Europe the 900 MHz band is used for GSM.
25 A HiperLAN2 Global Forum was established to support its deployment, supported by e.g. Bosch, Dell, Ericsson, Nokia, Telia and TI (Palo Wireless, 2003).
26 See for a more extensive elaboration of the two communication paradigms Lemstra (2006).
27 In the air interface encoding schemes at 16 Kbits/s or less are used to increase the capacity of cell sites.
users. However, in the case of cellular, operators vie for exclusive usage rights within the band, while Wi-Fi users share usage rights to the band with an unknown number of other users. In the cellular model, following Hazlett, the state has awarded exclusive spectrum usage rights to operators who effectively re-assign use rights in negotiated agreements with select third-party vendors, such as handset makers, and re-assign spectrum access rights on a national level and on a mass-market scale to subscribers (Hazlett, 2006). The equivalent spectrum usage statement for Wi-Fi should read: the state has assigned a part of the RF spectrum on a non-exclusive basis for use by equipment subject to a set of related requirements. Hence, manufacturers of compliant equipment allow end-users to access the spectrum for their own (data) communication use, free of charge. Hence, cellular operators are able to define and maintain a certain quality of service level, until the number of available channels is exhausted, while Wi-Fi users are subject to graceful degradation of the service, lowering the effective data rates. This limits the QoS that Wi-Fi operators can provide.

While the principle of geographical re-use is applied in both cellular and Wi-Fi, the coverage range of cellular is measured in kilometres while Wi-Fi access points are measured in metres, as the transmission power is severely limited by regulation. This limit has been set to facilitate the simultaneous use of multiple WLANs within the same frequency band. For the same reason the FCC specified the use of spread spectrum transmission technique being more resilient to interference. While the lay-out of cell sites is planned by operators, the location of WLAN resembles a pseudo random process, both are directly related to population density.

4.3. Two different business models

Generically business models can be compared using the resource base of the firm, the activity system and product offering (De Wit and Meyer, 2004). For wireless operators important distinctions can be made in the way RF spectrum is exploited, and how that affects the financing of the business.

From the above it becomes clear that the environment in which cellular communication has emerged and matured is dominated by the telecommunication operators. For incumbent operators wireless services are an extension of the business model applied for voice services provided over wired lines. Albeit, the gradual opening of the market provided for the entry of new players with a pure wireless business model. Both categories of network operators exploit the RF spectrum for a profit, based on the construction of a cellular network infrastructure to provide end-users with mobile voice communication service.

The origin of Wi-Fi as a Wireless-LAN reflects a different business model. In connecting the WLAN to the “public” wired communications infrastructure Wi-Fi has become a wireless access technology. By using WLANs in public environments in the form of hotspots, Wi-Fi has moved into the realm of service provisioning for a profit, or when offered for free it is intended to improve the core business of the hotspot operator. Through the deployment as community or citizens network,

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28 In this section we address in summary form the business model implications resulting from the two different innovation journeys. For a more general discussion of business models and business strategy see e.g. De Wit and Meyer (2004), for telecom specific aspects Lemstra (2006) and for mobile services in particular Bouwman et al. (2008) and Van de Kar (2004).
or in the form of Wi-Fi zones and municipal Wi-Fi networks, Wi-Fi has become an infrastructure in pursuit of economic and social objectives,\textsuperscript{29} including efforts to close the “digital divide”.\textsuperscript{30}

What sets cellular systems and Wi-Fi apart as access technologies is the cell site or access point coverage area, the data rates, and the degree of mobility being supported. Wi-Fi stations can move around freely as the ‘hand-over’ from one access point to another is supported. However, this movement is assumed to take place at low speed, while cellular communication is designed to support car speeds. For a comparison of the application areas see Fig. 2 (adapted from: Briso et al., 2004).

What sets them further apart is the exclusivity of RF spectrum use provided to cellular operators, allowing them to attract significant amounts of capital for the acquisition of a RF license and for the construction of a cellular network infrastructure; and to recover these investments over an extended period of time. Similar investments, it is argued, would not have occurred under an open access regime, as applicable to Wi-Fi, given the uncertainties such a regime presents with respect to potential competition and the quality of service that can be guaranteed.

Notwithstanding the open access regime, the adoption of Wi-Fi suggests that the underlying business model can be exploited successfully. This can be attributed to the power restrictions for Wi-Fi, which makes the relatively small WLAN coverage area virtually exclusive. Moreover, the investment in the transmitting and receiving equipment required rests on the individual user (private or corporate), through which the equipment manufacturer is able to recover its R&D investments.

4.4. Two different diffusion trajectories\textsuperscript{31}

In the diffusion of wireless technologies standards play an important role. In the USA, the first – analogue – generation that emerged under the “Bell System” led to the application of one standard: AMPS. In Europe, different standards were deployed, with the Nordic NMT standard being adopted by a large number of countries, but having a relatively small market size. In the second – digital – generation the European actors – operators, manufacturers and regulators – coordinated their efforts and introduced one harmonized standard and operations model: GSM.\textsuperscript{32} In the USA, following the break up of the “Bell System” the operators coordinate the selection of cellular technologies through the TIA and CTIA, however, they retain individual freedom in the technology selection, applications, network architectures, and price schedules. This resulted in different – almost reversed – adoption curves for the two generations of cellular systems as depicted in Fig. 3 (adapted from: Ericsson, 2007).\textsuperscript{33}

The diffusion model of cellular communications is based on a for profit exploitation of the RF spectrum assigned to telecom operators. Although the assignment is on an exclusive basis, the service is provided in competition, and the acquisition of the RF spectrum may be costly, as the – 3G – auctions have shown. The broad and fast diffusion of cellular technology has shown that personalized communications is responding to a deep social need of human beings. Moreover, it has shown that (flat fee) pricing and bundling play an important role in forging success. The introduction of pre-paid services has unlocked market segments that hitherto had been closed due to uncertain or unacceptable credit standing of the prospective user. In the process cellular has become a substitute for wireline access.

\textsuperscript{29} For an assessment of the rational of municipalities to engage in infrastructure provisioning through Wi–Fi, see Ballon and Van Audenhove (Ballon et al., 2007; Van Audenhove et al., 2007).

\textsuperscript{30} While (prepaid) cellular communication has largely closed the “analogue divide” for voice communication, many Wi-Fi based community projects are aimed at closing the “digital divide”, in developing countries (e.g. http://www.regulateonline.org/content/view/949/63/ and http://drupal.airjaldi.com/) as well as rural areas in developed countries (Nielsen, 2007).

\textsuperscript{31} For a general treatise of innovation diffusion see e.g. Rogers (2003). For the process of IT adoption see, e.g. Moore (1991, 1995).

\textsuperscript{32} Harmonisation through government facilitation does not guarantee success as the case of Hermes in Europe shows.

\textsuperscript{33} The adoption in Europe of the ‘calling party pays’ principle is considered an important factor in the uptake of cellular communications (Häikiö, 2001). King and West argue that the break-up of the “Bell System” in 1983 has been a contributing factor to the developments in the USA (King and West, 2002).
In the license-exempt domain of Wi-Fi the use of the RF spectrum is free, but not exclusive. The optimal use of the spectrum resource has to come from geographical diversification, the use of robust modulation techniques, and intelligent protocols. The diffusion of Wi-Fi based access depends on the availability and adoption of communication devices equipped with Wi-Fi functionality. The availability of an open standard proved to be essential. Although the industry pushed initially in-door use and corporate applications, the success of Wi-Fi resulted from important changes in the application: a shift to private and to public networking. Firstly, the agreement between Lucent Technologies and Apple made the wireless solution price competitive with Wired-LAN alternatives. The cooperation with Microsoft on the XP software assured that also MS-OS users could benefit. The Wi-Fi Alliance in driving towards the adoption of the direct sequence form of spread spectrum, and by assuring interoperability among competing products, removed the remaining uncertainty from the market. Secondly, telecom operators started to compete to provide Internet access for a fee at “hotspots” based on Wi-Fi. Most notable was the agreement between VoiceStream (later T-Mobile) and Starbucks. As a result Wi-Fi has moved from in-door to outdoor applications and from stationary to nomadic use.

Through this shift Wi-Fi became competitor and complementor to digital cellular technology.

The assignment by the FCC of the ISM bands for the use by Radio-LANs has been followed by assignments by national regulatory agencies in most other countries, thereby creating a global market for Wi-Fi products and the economies of scale that was part of the forward pricing strategy deployed by Lucent Technologies in its agreement with Apple Inc. In the process Wi-Fi moved from functionality that was being added to a PC or laptop by way of an external plug-in, to functionality that is being built-in every laptop. The combined effect was a rapid take off starting in the year 2000, following a gestation period of 15 years.

5. Wi-Fi complement to 3G

As cellular technologies provide increasing data rates, from 52 kbits/s with GPRS, up to 7.2 Mbits/s with HSPA, they become more and more at par with IEEE 802.11b supporting a shared data rate of up to 11 Mbits/s. However, also Wi-Fi capabilities are evolving and IEEE 802.11a/g already support data rates up to 54 Mbits/s, and through MIMO data rates in excess of 100 Mbits/s are supported, while 300-600 Mbits/s are targeted in the IEEE 802.11n standard.

From traffic engineering studies and the initial deployment experience of – 3G – it has become apparent that the capacity of – 3G – cellular networks will be quickly exhausted if the majority of users would require true broadband connectivity. This notion has pushed the idea of reducing the cell size even further, to the point that every home is equipped with a so-called “femto cell” connected to the wired infrastructure, akin to the current Wi-Fi access point being connected to ADSL or cable modem (Rood, 2007).

Also Wi-Fi based networks have a limited capacity as the RF spectrum is being shared. One often speaks of the “Tragedy of the Commons” if the access to a common resource can not be restricted to safeguard the availability and quality of the service provided. What may be of even greater concern to the future success of Wi-Fi is that this potential tragedy may not be revealed as prospective users defect without the ‘system’ being aware of these defections, and hence, do not result in incentives to improve the situation.

Despite all differences, the two development trajectories are coming together through various forms of convergence. The use of the TCP/IP stack decouples in principle applications from the underlying physical medium, the availability of ample bandwidth makes this a practical reality. The functionality of Wi-Fi has been expanded to support voice and mobility, e.g. through QoS support as part of the 802.11e extension, the addition of advanced power saving options and protected access (Wi-Fi Alliance, 2006). Equipment vendors are increasingly providing multi-mode terminals with interoperability between cellular and Wi-Fi (De Leeuw, 2007). Pricing plans are designed to remove differences, the data-driven flat fee models are prevailing (Beming, 2007). Operators compete and benefit at the same time on the basis of providing seamless communication. From a technological perspective the trajectories may come together through the use of increasingly more intelligent radios. Whether the regulatory regimes will come together in practice will depend on whether we can resolve legacy issues.

6. Conclusions

The comparison of the two wireless communication cases has shown that important innovations can result from a combination of different communication paradigms and regulatory regimes. Results that are both competing and complementary in providing broadband wireless access. The following conclusions may inform the process of policy and strategy formation in the field of wireless communication:

- The cases show that the two innovation journeys are very distinct and shaped by the underlying technological paradigms and constrained by the applicable regulatory regime.

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34 Interoperability is provided through unlicensed mobile access (UMA) the 3GPP generic access standard first published in 2004 and deployed in Europe by e.g. BT in 2005, TeliaSonera in 2006; and in the USA by Cincinnati Bell and T-Mobile in 2007. (http://en.wikipedia.org/w/index.php?title=Generic_Access_Network (accessed 2008-08-13).
− Cellular and Wi-Fi are competitors and complimentors. Through convergence the ‘best of both worlds’ is increasingly being made available to wireless end-user.
− The cases show the importance of communication standards in the diffusion of technology.
− The Wi-Fi case reflects the first large scale deployment of radio communication on a license-exempt basis and demonstrates that RF spectrum can be used effectively using a license-exempt regime.
− The potential of an unrevealed “tragedy of the commons” should motivate regulatory agencies to closely monitor the use of Wi-Fi to assist the industry in making timely decisions regarding an accelerated migration towards the 5 GHz band, where spectrum is set aside for unlicensed use.
− For government policy the Wi-Fi case illustrates that innovation can be triggered by a change in policy, by lowering the barriers to the use of RF spectrum.
− Both cases illustrate that gestation times are decades rather than years. Hence, policy and strategy formation in the RF domain have to assume a long term horizon.

From our research we conclude that both forms of wireless communication, licensed and unlicensed, cellular and Wi-Fi, have made significant contribution to economic and social development, as competitors and as complimentors.

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