UNLICENSED INNOVATION: THE CASE OF WI-FI*

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Abstract

In this paper we describe the genesis and development of Wi-Fi as a combined result of (1) a change in the US communications radio spectrum policy in the 1980s, (2) the industry leadership provided by NCR, its corporate successors and collaborators, to create a global standard and to deliver compatible products under the Wi-Fi label, and (3) the influence of the users that moved the application of Wireless-LANs from the enterprise to the home, from indoor to outdoor use, from a communications product to a communications service, and from operators to end-users as the provider of that service. In concluding we assess the implications of this case for the formation of government policy and firm strategy. The case exploration and analysis is based on contributions by experts from the field, having been involved 'first hand' in the innovation journey of Wi-Fi.

Keywords: WLAN; IEEE 802.11; Wi-Fi; spectrum policy; firm strategy; sources of innovation; technology diffusion

1. INTRODUCTION

To-day, 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.

* This paper draws upon a research project being executed within the Faculty Technology, Policy and Management at the Delft University of Technology (TUDelft) aimed at documenting the genesis and development of Wi-Fi. This is a multi-disciplinary and multi-national research project with a wide range of contributions from the academic community and the industry at large.
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Increasingly Wi-Fi provides access to the Internet for remote communities in developing countries, e.g. in the Himalayan mountains and in the Andes. Even in rural areas of developed countries, for instance, in Denmark a community based Wi-Fi initiative emerged to provide broadband wireless Internet access, as the incumbent operator failed to extend the infrastructure to less profitable areas in a timely manner.

This is a remarkable result as wireless local area networking (WLAN) was not on the radar screen of the US Federal Communication Commission (FCC) when in 1980 it initiated a market assessment that would lead to its landmark decision of 1985, whereby it decided to open up three radio frequency bands designated for Industrial, Scientific and Medical (ISM) applications for the use by radio communication systems, including WLANs.

In hindsight, this should not come as a surprise. The Ethernet, which would become the standard for wired-LANs, was still subject of a major standardization battle within the IEEE in 1980. Moreover, recall that the Apple II had been launched in 1977, while the IBM PC would be introduced in 1981, and the Internet would be named in 1984. Mobile computing equipment like laptops and notebooks still had to be conceived.

The current success of Wi-Fi is remarkable in more ways. Hitherto, the most significant developments in radio frequency technology—radio-relay systems, radio and television broadcasting—had emerged under a licensed regime, whereby a government agency provides exclusive rights to the use of a specific part of the radio frequency spectrum, thereby providing the application protection from interference by other radio frequency applications and users. The success of Wi-Fi, however, emerged under a license-exempt regime, whereby it had to contend with many other applications and users in the same radio frequency band, including micro-wave ovens and radar equipment.

In this paper we will explore the innovation journey that has resulted in the global success of Wi-Fi, in the form of a descriptive longitudinal case study. The case starts in 1980 when the US Federal Communications Commission initiates a study into the public use of spread spectrum techniques leading to its rulemaking in 1985. We describe how this opportunity is used by the industry, thereby focusing on the developments at NCR and its corporate successors to develop, market and sell a new Wireless-LAN product. The choice of NCR stems from the leading role it assumed in the creation and adoption of a global Wireless-LAN standard: IEEE 802.11. Subsequently we will explore how Wi-Fi is being deployed and shaped by the users, as part of commercial service offerings by "hotspot" operators and through deployment as part of community initiatives and municipal networks. We conclude with a discussion of the implications of this case for government policy and firm strategy.

2. TRIGGERED BY US POLICY

A critical input to the development, production and application of any wireless device is the permission to use the radio frequency spectrum. This permission has typically to be granted by a government agency, as in the current spectrum management paradigm the national governments have taken ownership of the frequency spectrum as a natural resource and assign parts of the spectrum to certain applications and users upon request or as a result of policy it executes (Hazlett, 2006). In the case of Wi-Fi the first permission is the Report and Order of May 9, 1985 of the US Federal Communication Commission[1] to "[authorize] spread spectrum and other wideband emissions not presently provided for in the FCC Rules and Regulations" (FCC, 1985).

The political climate was set by the Carter Administration and FCC Chairman Charles Ferris intended to extend the deregulation spirit to the radio frequency spectrum. He would like to end the practice whereby numerous requests for spectrum would be brought forward, based on special cases of technology application. The adagio was 'let us unrestrict the restricted technologies' (Marcus, 2007; 2008). Dr. Stephen J. Lukasik the first Chief Scientist of the FCC, was requested to identify new communications technologies that were being blocked by anachronistic rules. It was Dr. Michael J. Marcus, employed at the Institute of Defense Analysis, who suggested that spread spectrum was such a technology and as a consequence was invited to join the FCC to follow up on the idea. In December 1979 the MITRE Corporation was invited to investigate the potential civil usage of spread spectrum. Their report of 1980 started the public consultation process on the use of spread spectrum technology.[2]

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 U.S. possessions (FCC, 2007).

2 When the FCC receives petitions for new rule making, or if they see themselves a need to make a rules change, they have to organise a public consultation in the form of a "Notice of Inquiry, NoI". The public at large is invited to comment within a set period after which the public is requested to provide comment on comments, the so-called Reply Comments.
All comments have to be addressed in the subsequent consultation round, the so called "Notice of Proposed Rule Making, NPRM". In this document, the FCC also provide the proposed new rules with the reasons for their choices. This round is also followed by a comment and reply comment period.
Again, the FCC has the obligation to address all comments and reply comments and publishes the results in a "Report and Order, R&O". Sometimes, a "Further Notice of Proposed Rulemaking, FNPRM" is included when the Order is only partially completed. A comment and reply comment period automatically follows the FNPRM.
Issues found in the Order can only be appealed in Petitions for Reconsideration.

2.1. THE ORIGIN OF SPREAD SPECTRUM

In the Notice of Inquiry the FCC proposed the civil use of spread spectrum (FCC, 1981). Until 1981 this technique had remained officially classified as military technology (Mock, 2005). 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: U.S. Patent # 2,292,387, issued on August 11, under the title: "*Secret Communications System*". Lamarr, born as Hedwig Eva Maria Kiesler in 1913 in Vienna, had been married to Friedrich Mandl, an Austrian arms manufacturer, which had exposed her to discussions on the jamming of radio-guided torpedo's launched from submarines. In 1937 Kiesler left Austria for America, under a contract with MGM. Here, 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 U.S. military as a contribution to the war effort. However, the first practical application was after the war, in the mid 1950s, in sonobuoys used to secretly locate submarines (Mock, 2005 p11–7). The first serial production of systems based on direct sequence spread spectrum were most probably the Magnavox AN/ARC-50 and ARC-90 airborne systems. There are most probably other early systems that have remained classified (Marcus, 2007).

2.2. THE FCC REPORT & ORDER

Interestingly, the MITRE report that investigated the potential benefits, costs, and risks of spread spectrum communications did not identify a strong requirement or need from the industry to assign spectrum for spread spectrum applications. The report concludes that "many potential spread spectrum applications are likely to be economically unattractive", other potential applications "...may be economically feasible, but may make poor use of the spectrum resources that they would require" and "[i]n certain applications, spread spectrum techniques can make more efficient use of the spectrum than the usual implementation of narrowband techniques... ...when the information bandwidth per user is low and the operating frequency is high" (Mitre Corp., 1980 p6–1 to 6–2). In the analysis it was recognized that spread spectrum is inherently more resistant to interference. The MITRE report had identified the bands designated for Industrial, Scientific and Medical applications (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 p6–4). Typical applications in the ISM bands were garage door openers, retail security systems, cordless telephones and includes the operation of microwave ovens. Hitherto no communications applications were permitted in the ISM bands.[3]

The FCC Notice of Inquiry proposed to use spread spectrum as an "underlay" within other bands, i.e. sharing the frequencies with other services.[4] The Notice triggered comments expressing fear of interference and the difficulty of tracing the source of interference. 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 overlay on the spectrum above 70 MHz at very low power (below –41 dBm) and one for unspecified power limits in the 3 bands designated for ISM applications (Marcus, 2007). The Further Notice and Notice of Proposed Rulemaking triggered more comments, whereby many of the respondents favoured the proposed authorization (FCC, 1984). Subsequently the FCC deferred all actions on all but the Police radio service and the use of spread spectrum in the three bands designated for ISM applications: the 902–926 MHz, the 2400–2483.5 MHz and the 5725–5850 MHz bands (FCC, 1985).[5]

This FCC rulemaking that would ultimately lead to the global success of Wi-Fi had an interesting final twist. After the release of the spread spectrum authorization, the whole top leadership of the FCC Office of Science and Technology was exiled, possibly as a result of actions by the industry being concerned about the deregulation that would make the FCC less responsive to major manufacturers who wanted new technology only made available when it was convenient to them. An attempt was made to fire one deputy, and the name of the Office was changed into Office of Engineering and Technology. The position of Marcus was eliminated and an attempt was made to dismiss him from the FCC. According to Marcus: "In the months following the spread spectrum decision three top manager of the Office of Science and Technology were removed and the new organisation took no similar bold initiatives for almost a decade." (Marcus, 2007; 2008).

3. DEVELOPED BY INDUSTRY, WITH NCR IN THE LEAD

Some FCC staff members had opposed the rule changes out of fear that the new rules to be adopted would never be used. The reality proved otherwise. The authorizations

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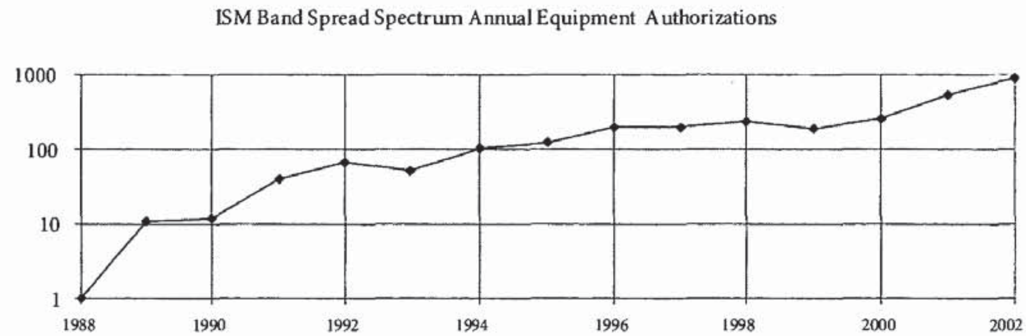
3 In Europe, some communication services were permitted in the ISM bands: video surveillance by police, and news gathering services such as the video connections between mobile cameras on motorbikes and helicopters to follow the Tour de France.

4 This underlay approach was similar to the approach the FCC adopted in 2003 for Ultra Wide Band (UWB), but in 1981 it was an idea ahead of its time (Marcus, 2007).

5 The limitation on peak power was set at a level of 1 Watt for the three ISM bands. No limitations on the antenna gain were specified.

opened the way for innovation, because with the regulation in place companies were more willing to allocate investment capital to research and development. In 1988 the first real civil applications of spread spectrum appeared in the form of a Local Area Networks, e.g. Telesystems and one year later the Gambatte[6] MIDI LAN, which became very popular with top rock musicians. A derivative of this system was used in nuclear power plants, under the name of Midistar – Pro. From 1990 onward the number of equipment authorizations by the FCC expanded significantly, see Figure 1 (Marcus, 2000).[7]

Figure 1. Spread spectrum equipment authorizations



3.1. THE LEADING ROLE OF NCR AND ITS CORPORATE SUCCESSORS

A leading role in the development of WLANs has been played by NCR.[8] A nagging issue for their sales force had been the lack of mobility in the cash register product portfolio. Retail department stores, one of the main client groups of NCR, reconfigured the sales floor on a regular basis and the cost of rewiring the transaction terminals was a significant expense. 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

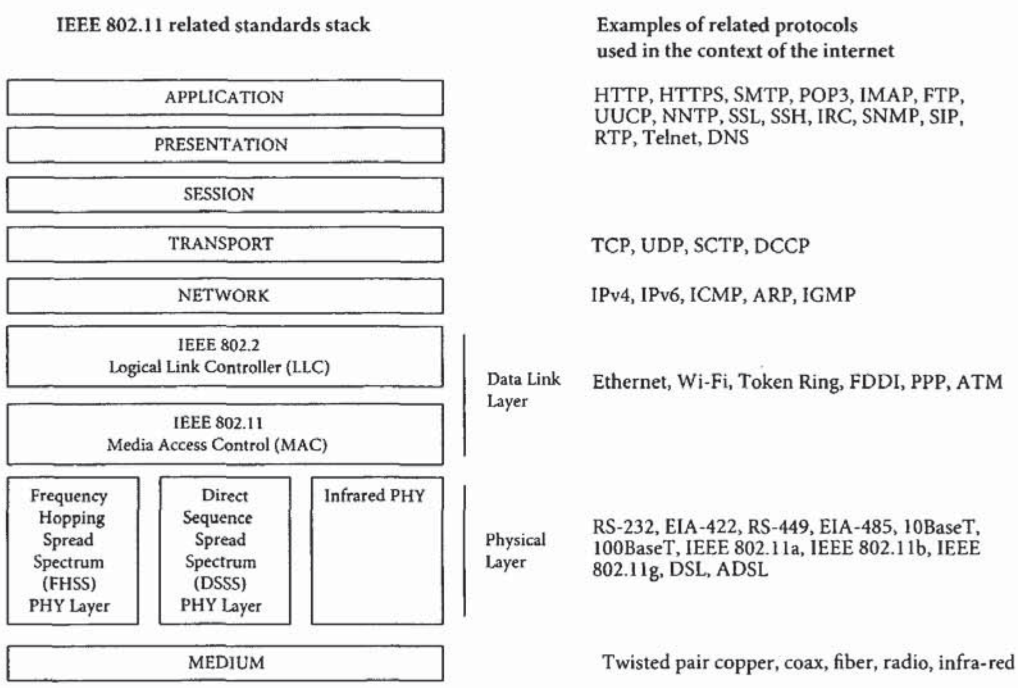
6 Gambatte became Digital Wireless Corp. and then Cirronet. It was acquired by RFMonolithics in Texas in 2006.

7 By bringing spread spectrum techniques into the civil domain, the FCC not only opened the way for Wi-Fi to emerge, but also facilitated the developments towards spread spectrum application in the field of mobile telephony in the form of CDMA, promoted by Qualcom, a company established by Jacobs and Viterbi c.s., a month after the FCC decision (Mock, 2005).

8 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).

if we could turn it into affordable products" according to Don Johnson at the NCR Corporate R&D organisation (Johnson, 2007). The purpose and mission of Corporate R&D in Dayton Ohio was to (1) recognize emerging technologies and (2) to promote advanced development and study in areas which would benefit multiple operating units. All advanced development was performed in the individual operating units. Following the FCC Report & Order NCR Corporate initiated a feasibility study into the use of a wireless technology in local area networking. Copper wires, coax and (shielded) twisted pair, differ from radio frequency spectrum in their transmission properties and in the way the medium can be accessed. In terms of the Open System Interconnection (OSI) model this implied that new designs were required at the physical layer (PHY) and at the medium access layer (MAC), see also Figure 2, which shows the layers of the OSI protocol stack in relation to examples of current day protocols used in the context of the Internet (Based on Ohrtman and Roeder, 2003). Any possible further impact on the higher layers of the stack (network through application) would also have to be assessed.

Figure 2. IEEE 802.11 standards mapped to the OSI reference model



3.2. INVOLVEMENT OF THE DUTCH R&D CENTRE

The seed money from Head Quarters in Dayton Ohio kicked off a development process whereby a Dutch-based Systems Engineering centre started a feasibility study for an American company to assess whether a wireless device could be developed for cash registers to be sold in the USA.

The Systems Engineering centre was established to adapt the NCR products to the specific European requirements. The centre included a significant software development team working on integration of financial systems into the IBM-world, and another group of experts working on adapting the telephone modem technologies to the European Standards. The Utrecht Centre had become a skill centre in modem communication designs. One of the designs was a wired Local Area Network (MIR-LAN); which NCR deployed to wire up their Cash Machines in stores before Ethernet became a standard.

The choice of the Utrecht Engineering Centre for the execution of the technology investigation was based on their signal processing expertise, hardware design experience related to wired Local Area Networks, and the recent acquired radio technology knowledge from Philips Electronics.

The first part of the feasibility project was to determine what power levels were needed and under what rules such products could be certified by the FCC. One of the issues was the so called "processing gain" requirements. This was the factor that had to be used in a spread spectrum system to "expand" the bandwidth above the bandwidth you would "normally" need just to get your information data signal transmitted. The logic here is that the more "spread" or processing gain the system has, the more the signal looks like "noise" to others – the more capable the system is in rejecting other signals, so more coexistence would be possible in a unlicensed band (Tuch, 2007).[9] Of course there is a trade off between the data rates to be achieved and the complexity of the total system and thus the costs. Interactions with the FCC suggested that a signal with a code sequence of length 10 or greater was required. This information implied that a WLAN could be realized operating at 1 Mbit/s or more. The team set to work to get the processing gain parameters set, and established a code which had a length of 11 with the required properties that were determined from indoor propagation studies.[10] The feasibility study resulted in a Wireless-LAN Demo unit and a set of related product specifications.

3.3. THE START OF PRODUCT DEVELOPMENT

After the feasibility study had ended with positive results, the development team in Utrecht convinced the Retail Systems Division that product development was also best carried out by the same team. In the summer of 1987 the team set out to create a Wireless Network Interface Card (Wireless-NIC) to build a Wireless-LAN with an

9 At the time, Bruce Tuch was leading the wireless R&D efforts of the Utrecht centre.

10 The code's property: The periodic and aperiodic autocorrelation function of this 11 length code is "bounded" by one. Actually it turned out that this was a "known code" called the Barker Sequence used in Radar Systems that was "rediscovered".

over-the-air data rate of 1–2 Mbit/s, to be used in the retail markets that NCR was serving. The NIC would have to operate in the 902–928 MHz band, the lower ISM band as specified by the FCC. This lower band was selected to provide the maximum possible range, as opposed to the ISM bands at 2.4 and 5 GHz which have higher levels of attenuation. Another reason was to reduce the cost of the electronics.

The creation of a new Medium Access Control (MAC) protocol, as part of the Data Link Layer (DLL), was the focus of the product development effort. To limit costs and to reduce the development time the team intended to leverage as much as possible existing MAC designs and to make use of existing protocol standards where possible.

3.4. THE ROLE OF STANDARDS WITHIN NCR

Within NCR de-facto standards had been a curse rather than a blessing, as they were of a proprietary nature. Although the company was a leading provider of point-of-sale terminals, most of the time these terminals had to be connected to a back office computing system, mostly supplied by the leading mainframe provider IBM. Having a dominant position in this market IBM used proprietary protocols to connect terminal equipment to its mainframes and mini-computers. As a result much of the protocol expertise of the Utrecht development team originated from the analysis and subsequent emulation of IBM protocols. Where NCR had the opportunity it promoted the use of open standards.

3.5. FINDING AN EXISTING MAC PROTOCOL

Finding a related MAC was in essence a search for a MAC protocol already being implemented using a wireless medium, or to find a MAC implemented for another medium, such as twisted pair copper or coax cable, that could be adapted to wireless use. This search led to "ALOHA", which was one of the first Wireless Radio protocols, and derivates of this protocol which morphed into Ethernet and later the IEEE 802.3 standard. While looking at the standards for LANs, another possible choice emerged: the Medium Access Control used in the Token Bus standard, which was very recently approved as IEEE 802.4. It became clear that the standards body to focus on was IEEE and in particular the "802" committee. The development team recognized that having an already established group within IEEE 802 to sponsor a new physical layer was a much faster process than trying to start a new standard from scratch. The IEEE 802.4l Task Group was already working on a wireless variant driven by General Motors, but it seemed it was "losing steam".[11]

11 According to the PAR this taskgroup is denoted 802.4c which through a transcription error became 802.4l.

The Chair of the 802.4l Task Group did not attend anymore, but the Executive Secretary was available and willing to convene on request of NCR a meeting in July 1988. In the following meeting in November Vic Hayes of NCR was elected to take over the chair of this Task Group. However, as Tuch observed: "Making the 802.4 protocol fit with the wireless medium was like trying to use a boat to get across a swamp instead of a hovercraft." (2007). Having concluded that the Token Bus MAC protocol was not suitable for the purpose, the MAC used as part of 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. A solution developed by NCR and Inland Steel was presented to the IEEE 802.3 Ethernet standards group, to solicit interest to start a new wireless working group (Tuch and Masleid, 1991). They were apparently too busy on the evolution of the Ethernet standard towards higher speeds to support this initiative. With a negative vote for the proposal the political stage was set to "start from scratch" with a new Wireless MAC standard. Under the leadership of Bruce Tuch of NCR, the companies interested in establishing a wireless local area network standard quickly generated the necessary paperwork for the establishment of a new standardization project within IEEE. At the July Plenary meeting, the IEEE 802 Executive Committee approved the request. With the subsequent approval by Standards Board the new "802.11" Working Group was born, and Vic Hayes of NCR was appointed as the interim chairperson.

3.6. NCR TAKING THE LEAD IN IEEE 802.11

September of 1990, at the first meeting of the 802.11 Working Group Vic Hayes was elected as the Chair.[12] At the November 1991 meeting of the Work Group two Sub Groups were established, the MAC group and the PHY group. On a case by case basis the sub groups made their own rules for what materials the proponents had to submit for the "802.11" membership to make a well informed decision. Once the proposals would be available, the two groups had the daunting task of selecting the appropriate technology for the project. In most of the cases the Task groups used a process of selection whereby in each round of voting the proposal with the lowest number of supporting votes would be removed from the list, until a proposal would reach majority support. The proposal reaching majority support would be submitted to the Working Group for approval as the technological basis for the draft standard.

12 Hayes would serve as Chairperson of the IEEE 802.11 Working Group for 10 years, the maximum period allowed.

3.6.1. *The first battle ground: IBM vs NCR / Symbol Technologies / Xircom*

The first point of contention emerging in the MAC Task Group was about the principle to be used in assigning capacity to a terminal based on the shared use of the radio spectrum. A similar issue in the Wired-LAN arena had split the industry and led to three different incompatible standards having been approved by the IEEE: Ethernet, Token Bus and Token Ring. For WLAN IBM proposed a centralized approach while NCR together with Symbol technologies and Xircom submitted a proposal that supported a decentralized mechanism. The merits of the two proposals were intensely debated.[13] In the end the proposal for a decentralized approach won the vote; one of the reasons being that this protocol would support "ad hoc" networking, whereby a terminal would be able to independently coordinate communications with another terminal.

3.6.2. *The second battle ground: Frequency Hopping vs Direct Sequence*

The second area of contention was related to the PHY. In its 1985 Rule & Order the FCC had specified two different spread spectrum modulation techniques that could be used: Frequency Hopping (FHSS) and Direct Sequence (DSSS). When put to a vote in the PHY Task Group neither of the two modulation techniques obtained the required 75% level of support. Proponents of FHSS claimed it was easier to implement, while DSSS had the promise of a more robust system with a higher data rate. The individuals in the FHSS camp feared that the required investment in silicon would be significant, while the DSSS camp tried to refute the argument based on their experience in the implementation of pilot versions. As neither of the two groups could get the required level of support, the only way out was to include both modulation technologies in the standard.

3.6.3. *The third battle ground: HomeRF*

The initiative for an alternative standard called HomeRF is said to originate with Proxim, and led to the establishment of an industry consortium (HRFWG) in early 1997 (Negus, Stephens et al., 2000). The main driver for this development was the perceived inadequate support for isochronous services, i.e. the use of telephony, in the IEEE 802.11 draft specification.[14] The consortium adopted the Frequency Hopping

13 To reach agreement within the IEEE Working Groups and Task Groups individuals opposing a proposal in a vote have to explain the reasons for their opposition. By making these reasons explicit the group as a collective is invited to find ways to resolve the issue and if successful it has broadened the support for the resulting proposal.

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

method as the basis for their standard.[15] The HomeRF Shared Wireless Access Protocol – Cordless Access (SWAP-CA) combined portions of the OpenAir frequency hopping PHY as developed by Proxim, CSMA/CA packet data derived from the 802.11 Frequency Hopping standard, and TDMA-based voice support from the Digital Enhanced Cordless Telecommunication (DECT) standard. The FH method adopted by the consortium supported a data rate of 1.6 Mbit/s (Negus and Petrick, 2008). HomeRF was positioned as a low cost solution having a relaxed PHY specification supporting both isochronous (connection oriented) and asynchronous (connectionless) traffic. In April 2000 Intel announced its Anypoint wireless home networking and in November Proxim unveiled its Symphony HRF (Palo Wireless, 2003).

When the IEEE adopted the "802.11b" project for an 11 Mbit/s WLAN, the consortium announced a second release of the specification for speeds of 6 Mbit/s up to 10 Mbit/s (Negus, Stephens et al., 2000). Therefore, they filed a letter at the FCC asking for a change of the Frequency Hopping in the form of an interpretation of the existing rules to widen the channel width from 1 MHz to 3 and 5 MHz. However, the FCC disagreed and started a rules change procedure with a Notice of Proposed Rules Change (FCC, 1999). On August 31, 2000, the FCC released the 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 (2007)[16]:

1. Because none of the consortium members were developing PHY silicon, they were forced to abandon a PHY that was similar to 802.11FH and switch to the OpenAir PHY developed by Proxim. Many companies in the HomeRF Industry 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[17], 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.[18]

15 According to Marcus, a consideration for choosing FH might have been that the 11 chip PN code defined in IEEE 802.11 Direct Sequence was questioned by some members of the FCC Office of Engineering and Technology to be in full compliance with the FCC rules.

16 Lansford has been Co-Chair of the Technical Committee for the HomeRF Industry Working Group and wireless system architect with Intel Corporation.

17 With the 1996 tri-vestiture of AT&T, the WLAN activities moved to Lucent Technologies.

18 This notion was said to be confirmed in a personal statement by King, the CEO of Proxim, admitting that the deal of Lucent Technologies with Apple was the real blow to HomeRF.

3.6.4. *The fourth battle ground: HIPERLAN*

Following the decision making by the FCC, an ad-hoc group on Radio-LANs within the CEPT, the body responsible for the harmonization of spectrum use in Europe, recommended that the 2.4 GHz band destined for ISM applications to be opened for the license-exempt use of RadioLAN devices, and it requested ETSI, the body responsible for the development of telecommunication standards in Europe, to develop the necessary standard to define the technical characteristics and the test method (ETS, 1996).[19] In 1991 the European Radio Commission 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 (CEPT, 1991). This paved the way towards a global assignment of spectrum for Wireless-LANs.

The ad-hoc group continued with searching the spectrum for the next free band to accommodate RLANs by studying the allocation rules from 2.5 GHz upwards. The first opportunity occurred at 5150–5300 MHz with an optional extension to 5350 MHz (CEPT, 1992). As often happens in Europe, this allocation of the spectrum would be tied to devices adhering to a specific standard, in this case the standard tagged HIPERLAN for High Performance Local Area Networks, yet to be developed. HIPERLAN was aimed at providing high speed (24 Mbit/s typical data rate) radio local area network 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 asynchronous and synchronous applications. The specification included the PHY and MAC, and a new sub-layer called Channel Access and Control managing the access request to the channels based on priority.

Following the establishment of the IEEE 802.11 Working Group for wireless local area networks in July 1990, Vic Hayes had been invited to participate as an industry representative in the ad-hoc RLAN committee of CEPT, and in the Technical Committee ETSI-RES 10. This provided the NCR Team, and upon the 1991 acquisition the AT&T Team in Utrecht with a rather unique position to leverage its activities in IEEE and ETSI, and to align as far as (politically) possible the activities in the two standard-setting bodies. Again the company volunteered to provide the chair person; Jan Kruys became the second chair of ETSI-RES 3. The Committee published its first technical specification HIPERLAN/1 in 1997.

A second version HIPERLAN/2 was developed as part of the ETSI-BRAN Broadband Radio Access Networks project to provide much higher speeds (up to 54 Mbit/s data rate) for communication 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) aspects.[20]

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19 Note that in Europe the 900 MHz band is used for GSM.

20 A HIPERLAN2 Global Forum was established to support its deployment, supported by e.g. Bosch, Dell, Ericsson, Nokia, Telia and TI (Palo Wireless, 2003).

Neither the HIPERLAN/1 standard completed in 1997 nor HIPERLAN/2 standard completed in 2004 have become a success. Alvarion, Motorola and SICE Communications were involved in early product introductions, but, as was the case with HomeRF, also 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.

3.6.5. The fifth battle ground: Lucent Technologies vs Harris vs Micrilor

Following the approval of the 100 Mbit/s Ethernet standard in 1993, high speed wired-LAN products had been introduced in the market and during the final editing of the IEEE 802.11-1997 it was becoming clear to everybody in the "802.11" community that also higher speeds Wireless-LANs would be required. The goal set was to extend the performance and the range of applications in the 2.4 GHz band, and specify a higher speed wireless access technology suitable for data, voice and image information services in the lower 5 GHz band. The decision to keep the MAC the same for a multitude of PHYs to accommodate future spectrum opportunities was made early in the development of the standard. The PHY would have to be different given the different bands, moreover other constraints applied to the use of the 5 GHZ band.

The least contentious was the 802.11a variant in the 5 GHz band. There were two main proposals, one from Breezecom (later Alvarion) on a single carrier modulation method and one from Lucent Technologies and NTT, based on OFDM. The voting was won by the Lucent Technologies and NTT combination, leading to a 54 Mbit/s standard.

The voting for the IEEE 802.11b PHY was very contentious, and almost a war on the brink of tearing the 802.11 Working Group apart. The main contenders were Harris (now Intersil[21] and Lucent Technologies, and a proposal from an outsider Micrilor, a start-up company with a proposal having some significant technical advantages (Negus and Petrick, 2008). There was a degree of truth in a 3Com statement that most of the Lucent Technologies supporters had decided to side with Micrilor in the voting to avoid that Harris and their supporters would have an unfair advantage in the market, as they already had progressed substantially in their development efforts. In the same week the IEEE meeting took place representatives of Lucent Technologies and Harris sat together and acknowledged a compromise was needed. Subsequently Harris and Lucent Technologies 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 the joint proposal was

21 The Wireless LAN part of the business was sold to Conexant, which discontinued the WLAN business in November 2007.

accepted in the next meeting of the Working Group six weeks later, resulting in the IEEE 802.11b standard.[22]

3.7. FORMAL APPROVAL OF THE IEEE 802.11STANDARDS

At 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. In total four ballots were needed to reach the required level of 75% support.

The Sponsor Letter Ballot was issued on August 1996 and after two recirculation ballots the draft standard was submitted to the Standards Activities Board (SAB) in August 1997, to be approved at their September meeting and to be published on December 10, 1997 as IEEE 802.11 – 1997 edition, covering Frequency Hopping at a (mandatory) data rate of 1 Mbit/s (the optional 2 Mbit/s was never implemented) and Direct Sequence at 1 and 2 Mbit/s (both mandatory).[23]

3.7.1. Approval of the first extensions IEEE 802.11a and 11b

With a group now experienced in developing a standard and all members eager to increase the supported data rate, a Study Group was established at the November 1996 meeting. Two projects were established to make extensions to the standard: Project 802.11a for an extension of the standard to support higher data rates in the 5 GHz band which received its SAB approval in August 1997, and Project 802.11b for an extension of the standard to support higher data rates in the 2.4 GHz band to be approved in December 1997.[24]

Both were balloted at Working Group level in November 1998 and re-circulated twice to start the Sponsor ballot in April 1999. After 2 recirculation ballots, both were submitted to the SAB in August 1999. IEEE 802.11a was officially published on December 30, 1999 and covered data rates up to 54 Mbit/s in the 5 GHz band. IEEE 802.11b was published on January 20, 2000, covering a 11 Mbit/s data rate in the 2.4 GHz band.

In parallel with the 802.11a and 11b project the group undertook to revise the 802.11–1997 standard, to lead it through the ISO/IEC process to become adopted as an International Standard. After carefully synchronizing the processes within the two organisations, the revision of IEEE Std 802.11, 1997 edition was published on August 10, 1999 designated ISO/IEC 8802–11:1999.

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22 Two years later Micrilor would be acquired by Proxim, thereby obtaining a strong patent portfolio.

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

24 Note that 802.11a and 802.11b were included into a consolidated standard in 2005.

3.8. INTRODUCING THE WLAN PRODUCTS IN THE MARKET

The decision by NCR to exploit the new business opportunity through the development of an open standard in cooperation with others was an important step in realizing its WLAN vision. While manufacturing partners can be aligned through the standardization process, real products are required to convince potential customers of the benefits that Wireless LANs can provide. Market research initiated by NCR to establish the right product positioning strategy indicated that LAN (re-)wiring was cumbersome and expensive, estimated at US$200–1500 per 'drop'. Also the lack of expertise was mentioned as an issue. The connection of PC adaptors to the coax cable and localizing faults in the early Ethernet systems was know to be cumbersome. Lower overall cost was identified as the key feature of Wireless-LANs.

Ahead of a formal standards approval, NCR launched its first WaveLAN product for the US market at Networld in Dallas, in September of 1990. The product operated at 915 MHz and used one communication channel providing a bandwidth of 2 Mbit/s. It was a desktop PC plug-in board, essentially a radio-based Network Interface Card (NIC), and required an external antenna. The general product release was in May 1991, after radio certification and manufacturing start-up issues had been cleared and resolved. Prospective customers appeared to be fascinated by the technology, but the benefits were perceived as marginal and the price as too high. At the product launch the price was set at US$1,390 per card, which included the Novell Netware driver. In comparison an ARCNet card was sold at US$300, an Ethernet card at $495, and a Token Ring card at $645. However, giving the difference in implementation only a Total Cost of Ownership calculation would provide for a fair comparison. Although this improved the business case significantly, within short NCR would lower the price of the PC plug-in to $995.

In the course of 1991 it became clear that the product was incomplete in the view of prospective customers. Multiple Access Points (AP) would be needed to cover larger buildings, to be connected to the wired-LAN infrastructure; plus the capability of roaming (also called hand-off) between the APs. The concept was easily described and readily adopted, given its similarity with cellular communication. The implementation looked relatively easy as the client stations, PC/laptop, could keep track of the signal strength of each AP within reach and switch the connection to the AP with the best transmission performance. However, the R&D efforts increased significantly when the system had to be 'scaled-up', and became comparable to the efforts involved in the development of the NIC.

3.8.1. Security concerns

As it is much easier to eavesdrop on a wireless system than on a wired system the level of security provided by WLANs raised doubts in the minds of prospective customers, which in turn frustrated its adoption. From the outset WaveLAN included as an option a Data Encryption Security (DES) chip. This chip was used until the IEEE standard was implemented, which included the so-called Wired Equivalent Privacy (WEP) algorithm, providing a basic authentication and encryption method.[25]

In 1993 AT&T was successful in closing the first contract for large scale deployment of WaveLAN at the Carnegie Mellon University (CMU) in Pittsburgh, Pennsylvania. The project involved the deployment of Access Points to serve 10,000 students, faculty and staff moving about the university campus (Hills and Johnson, 1996; Hills, 1999). The acquisition of CMU as a client would provide a perfect test bed for a large scale deployment of WLANs.

3.8.2. *Crossing the Chasm*

In the course of 1998 the Lucent Technology senior management started questioning the results of the Wireless LAN project. This was after only two years of involvement and with limited visibility of what had been spent in the preceding decade. Slowly but surely resources were moved to other more promising radio projects, such as Wireless Local Loop (WLL). Nonetheless, the sales team kept pushing WaveLAN. The fortune of WaveLAN and for that matter WLANs would take a turn for the better following an unexpected call from Apple Headquarters, simply stating: "Steve Jobs wants to have a meeting with Rich McGinn about wireless LANs." Apparently Steve Jobs, who had returned to Apple as 'interim CEO' to reinvigorate the company, had decided that Wireless-LAN had to be the key differentiating feature for the iBook which was scheduled to be launched in 1999.[26] The meeting in the Apple Boardroom was an interesting one, with Steve Jobs concluding the meeting with: "We need the radio card for

25 The security of Wireless LANs has remained an ongoing concern. With the approval of the IEEE 802.11-1997 standard the Wired Equivalent Privacy (WEP) algorithm was introduced, providing a basic authentication and encryption method. WEP was designed in the 1990s and was purposely weak, to remain within the confines of existing export requirements (Ohrtman and Roeder, 2003p61-85). In late 1999 and early 2000, initial attacks on WEP were identified and made public, just at the time when WLAN technology was becoming popular, and thus a fertile area of investigation for security researchers and an attractive target for hackers. Papers by Borisov, Goldberg, and Wagner (1999), and Walker (2000) discussed the vulnerabilities of WEP. While some businesses deployed WLAN technology in combination with Virtual Private Network and proprietary security solutions, the response by the industry was the development of an IEEE 802.11 standard-based solution, with interoperability certification developed by the WECA – later Wi-Fi Alliance.

26 Apple had considered wireless connectivity as essential to the success of its laptops and PDA business. In early 1990 Apple petitioned the FCC to allocate 40 MHz of spectrum in the 1850–1990 MHz band earmarked for new technologies, in particular PCS, for a new radio service called Data-PCS. In the fall of 1993 this request was accommodated, albeit, the band was used by microwave users. Although relocation with compensation was agreed upon, there was no effective model for managing the relocation. Apple also filed a petition for rule making in 1995 for an allocation of 300 MHz in the 5GHz band, linked to the National Information Infrastructure initiative in the Clinton-Gore period. In 1997 the FCC created the Unlicensed-NII band within the existing 5 GHz ISM-band. (Goldberg, 2008).

US$50, and I want to sell at $99." Then Steve apologizes, he has to leave – stands up, says "Hi!" and goes. The room falls silent (Links, 2007). [27]

For Steve Jobs the job was done, for Lucent Technologies the work started. The target was audacious, because early 1998 the cost level of the cards was still above US$ 100. The chipsets for the next round of cost reductions had been designed, but it was not clear whether the target set by Apple could be met by spring of 1999. In the following months several rounds of negotiations took place to obtain agreement on the product definition. Apple wanted a special interface, moreover, they wanted three versions of the Access Point: a low, medium and high-end version. Also the price was subject of some tough negotiations. A complicating matter was that the initial agreement had been based on the existing 2 Mbit/s product. However, the standards making process had advanced substantially and the 11 Mbit/s version was expected to become available in 1999. Apple wanted to go directly to the 11 Mbit/s, but did not want to accept a higher price for the increased bandwidth. It became an all or nothing negotiation. The product was launched as the Apple Airport in the summer of 1999, with the PC card priced at $99 and the Access Point at $299. At this price level the 11 Mbit/s Wireless LANs could compete effectively with the 10 Mbit/s wired Ethernet. The industry was shocked. Cees Links recalls: "We were accused of "buying" the market and that we were losing money on every card sold. But we were not. The mechanism we used was to 'forward' price the product. With the volume going up quickly the costs would also come down quickly, and the market share gained would bring in the margin. That is the theory – well, it worked in practice, and it worked very well as would turn out in the following years." (Links, 2007).

Dell was the first PC vendor to follow the trend set by Apple. However, the cooperation with Dell had an additional complicating factor: they used the Microsoft Operating System. As a consequence Lucent was faced with another hurdle to overcome. As Microsoft had become overloaded with requests to resolve interface issues, they had installed a new certification procedure called Wireless Hardware Quality Labs. Unfortunately some requirements in the certification program were incompatible with the operation of Wireless-LANs. This required Lucent to work closely with Microsoft to resolve these issues. Initially some compromises were made and waivers obtained to expedite market deployment. Eventually the cooperation involved creating new software to support Wireless-LANs proper, to be included in the upcoming release of XP in 2001.

With this effort done, the two world leading PC operating systems had in-built features to support Wireless-LANs, and hence another dimension of the "whole product" concept had been resolved. The Apple Airport had become the beachhead, or in the terminology of Geoffrey Moore: the head pin on the bowling alley (Moore, 1995). With the success of the Apple Airport the "chasm" had been crossed effectively, the

27 At the time Cees Links was Product Line Manager of WaveLAN.

company was entering the "tornado zone". Within a year all other PC vendors had followed the example set by Apple. Agere Systems[28], had almost a clean sweep of the Wireless-LAN market for PCs.[29] This success is replacing the business user as the main target of WLAN applications by the home user.

This new period posed new challenges. Ramping up volume in manufacturing became the key challenge, which implied lead time reduction, improving inventory management, optimizing test capabilities. In the early days the radio part of the card had about 15 test points and involved manual calibration. Now, the cards are fully tested through software. The early cards had about 300 components, which has come down to 30 and would go down further to 10. All the result of moving from a production level of 100 cards per week in 1991 to 100,000 cards per week in 2001 (Tuch, 2007).

3.8.3. *The Wi-Fi Alliance*

With the approval of the IEEE 802.11 standard a number of implementation variants were allowed, in part a result of the FCC Report & Order that included the two spread spectrum variants, frequency hopping and direct sequence. This could in practice lead to two companies claiming to be compliant while the products would be incompatible. This situation forced the leading Wireless LAN companies to collaborate. The Wireless Ethernet Compatibility Alliance (WECA) started operation in 1999 as a non-profit organisation driving the adoption of a single DSSS-based world-wide standard for high-speed wireless local area networking, focussing on IEEE 802.11b compliance. Governed by a small Board WECA quickly established an interoperability testing procedure and a seal of compliance, the Wi-Fi (Wireless Fidelity) logo. In 2002 it changed its name to the Wi-Fi Alliance to acknowledge the power of the Wi-Fi brand. As of July 2007 the organisation had certified the interoperability of over 3,500 products (Wi-Fi Alliance, 2007).

3.8.4. *The ultimate success*

By early 2001 Agere had reached the summit as supplier of Wi-Fi products with an approximately 50% market share, inclusive of the OEM channel. By that time the market had grown to an US$ 1 billion annual level. By the end of 2001 it became clear that the industry was moving into another phase. With the broad acceptance of Wi-Fi it was clear that the Wireless-LAN functionality would be progressively integrated into the various computer and networking products. The competition would shift

28 In 2000 Agere Systems was established as a subsidiary of Lucent Technologies, the WLAN activities moved to this entity.

29 Note that in another episode of corporate transformation Agere Systems had been incorporated in 2000 as subsidiary of Lucent Technologies, assuming the activities of the former Micro-Electronics Division, and including WaveLAN.

from the plug-ins toward the chipsets, as was confirmed by the moves of e.g. Intersil, Broadcom, Infineon, and AMD. As a consequence the ORiNOCO brand (as successor to WaveLAN) and the related infrastructure products, Access Points, Residential gateways and Outdoor Routers, were separated organisationally from the chip activities. In 2002 Agere sold the ORiNOCO business unit to Proxim in a friendly take-over valued at US$ 65 mln. Agere Systems continued to develop the Wireless LAN technology and turned it into new chipsets. They also sold the technology to other chipset providers to allow the integration with other I/O technologies.

Meanwhile Intel had expanded its WLAN expertise by acquiring Xircom in 1999. In 2003 Intel launched the Centrino chipset with built-in Wi-Fi functionality for mobile computers. This launch was supported with a US$ 300 mln marketing campaign, essentially moving the success of the "Intel inside" campaign to a "Wi-Fi inside" campaign. This marks the ultimate success of Wi-Fi, having moved from PC adaptors, through plug-ins and integrated chipsets, to functionality that has become part of the hardware core of laptop computers. This also moved the industry into another era and ends the period of the specialty suppliers. As a result Agere Systems discontinued its Wireless LAN activities in 2004. The remaining WLAN expertise transitioned 'in person' to other firms, in particular to Motorola, a company active in the field of WiMAX, another member of the Wi-Family.

4. SHAPED BY OPERATORS AND USERS

While the initial application of WLANs had been targeted by its manufacturers to be in the corporate domain, Apple had opened up the home networking market. The massive adoption by the users shaped the emerging market. This triggered another set of entrepreneurs, including telecom operators, to use Wi-Fi to provide (semi-)public access to the Internet at "hotspots".

4.1. HOTSPOTS

According to a popular account, Wi-Fi access in public places has been first conceived in 1993 by Stewart while working on the IEEE 802.11 MAC at AMD (Fleishman, 2002). Most likely others have come up with the same idea in that same time frame considering the many start-ups that emerged pursuing wireless access services in public places or "hotspots". To implement his idea the company Plancom was established in 1995, to become Wayport in 1996. In the same year Wayport equipped its first hotel lobby and bar with wireless access.[30] By 2003 Wayport was serving some of the major hotel brands: Embassy, Four Seasons, Sheraton, Summerfield, Westin and Wyndham.

30 They used Breezecom equipment, which was based on Frequency Hopping.

4.2. STARBUCKS

"Travel at blazing speeds on the Internet – all from the comfort of your favorite cozy chair" (Starbucks, 2007). It has been the Starbucks initiative to provide wireless access to the Internet in their coffee shops that has set off Wi-Fi as the preferred means of accessing the Internet in public areas in general. For Starbucks it was the prospect of attracting more customers and keeping them longer in the coffeehouse, in particular after the rush hour, that made investments in the new service an interesting proposition. In January 2001 Starbucks, MobileStar and Microsoft announced their strategic relationship to create a high-speed, connected environment in Starbucks locations across North America. The service would be provided by MobileStar, a wireless ISP established in 1996 with a focus on providing high-speed Internet access for business travellers in 'hotspots' such as airports, hotels, convention centres, restaurants and other public places in the US. MobileStar would install Access Points in the Starbucks locations and connect these locations to the Internet using T1-lines.[31] Microsoft was to provide the portal facilitating an easy log-on procedure (Microsoft, 2001). MobileStar set out using a proprietary frequency hopping spread spectrum product supplied by Proxim, and subsequently moved to an IEEE 802.11 compliant direct sequence based product. By the end of the year MobileStar had equipped some 500 Starbucks locations, but also had ran into financial difficulties. In the aftermath of the telecom market crash the private equity market had become very constrained, and the events of September 11th had severely limited business travel. The company seized operation in October 2001 and subsequently the assets were acquired by VoiceStream, a cellular communications company to be acquired by T-Mobile in 2001. By February 2002 the service at Starbucks was operating under the T-Mobile Hotspot brand. This acquisition made T-Mobile the largest hotspot provider in the USA.

In early 2002 Starbucks launched a major expansion plan to provide wireless access at "T1" speed in 800 coffee shops in the USA and 400 in Europe, to be extended to 2000 in total by the end of the year 2002. In this extension plan Starbucks cooperates with T-Mobile as service provider and HP to provide access software, in particular the Wireless Connection Manager, which facilitates easy configuration management for notebooks or PDAs not running on the Microsoft XP operating system (Arar, 2002; Singer, 2002).[32] In 2003 Schultz, the CEO of Starbucks, claimed that the partnership with T-Mobile contributed to a 27% increase in revenue June 2003 over June 2002, and claiming that customers spend approx. 45 minutes per session using hotspot

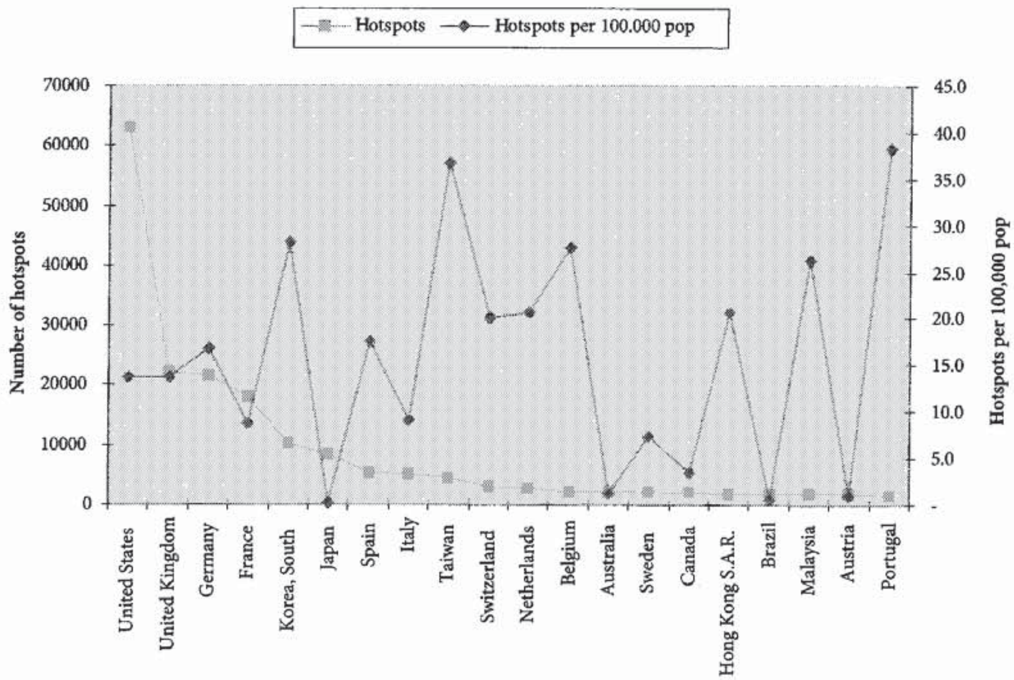
31 T1-lines are digital links at a data rate of 1.5 Mbit/s.

32 The service was offered after a free trial for US$49.99 per month with unlimited national access to a flat fee of $2.99 for a 15-minute session. Also prepaid plans were available at $ 20 for 120 minutes nationwide or $50 for 300 minutes.

access (O'Shea, 2003).[33] In the face of increasing competition and to stimulate usage the prices of the T-Mobile Hotspot service were sharply reduced in 2003 (Griffith, 2003).[34] In July 2004 Starbucks announced further successes: 3,100 coffeehouses are offering Wi-Fi based Internet access[35], T-Mobile HotSpot subscribers visit Starbucks more often – on average eight times per month – and spend on average one hour per session, while 90% of accesses are during off-peak hours. In a next step exclusive access to entertainment content is being provided at the Starbucks locations (Starbucks, 2004), which was expanded through an exclusive partnership between Starbucks and Apple to preview, buy and download music from the iTunes Wi-Fi Music Store to launch on October of 2007 (Apple, 2007).

In 2007 according to Jiwire the top three countries in terms of number of hotspots were the USA, the UK and Germany, albeit in terms of hotspots per inhabitant Portugal was leading with 38 hotspots per 100,000 inhabitants followed by Taiwan 37 and South Korea with 28. See also Figure 3 (based on U.S. Census Bureau, 2006; Jiwire, 2007).

Figure 3. Hotspots by country



33 By 2003 T-Mobile operated 2100 Wi-Fi hotspots in the USA, the lion's share being the Starbucks outlets, further including Kinkos copy shops and Borders book stores.

34 Unlimited access to US$ 29.99, without a cap on data transfer, based on a subscription of one year. The pay-as-you-go plan comes at $2.99 for 15 minutes and $0.25 per minute thereafter and $0.10 per minute after the hour.

35 Out of 4,700 T-Mobile Hotspots in the USA, covering Borders Books and Music, FedEx Kinko's Office and Print Centers, Hyatt Hotels and Resorts, airport business lounges of American, Delta, United Airlines and US Airways.

4.3. AN ALTERNATIVE BUSINESS MODEL – FON

Between the use of Wi-Fi for-free in the home and for-a-fee in hotspots a new model has been introduced by Varsavsky in 2006 as FON. The company has its headquarters in Madrid, Spain, and is funded by Sequoia Capital, Index Ventures, Google and eBay.[36] The business model of FON is aimed at establishing privately owned hotspots worldwide under the slogan: "Make a little money with your Wi-Fi and roam the world for FREE". It is based on acquiring a wireless router and access point called "La Fonera", which splits the capacity into two streams, one for personal use and one for public use.[37] FON distinguishes three types of users: "Bills", "Linuses" and "Aliens". The "Bills" charge for providing access while also paying for obtaining access to any other Foneros network. The revenue from opening-up the FON Access Point is split 50/50 between the FON organisation and the "Fonera" owner. The "Linuses" open their network for free, also to visiting "Bills". "Aliens" are non-Foneros or customers from outside the community who may use the FON-spots by signing-up through eBay's PayPal online payment service.[38] Additional revenues can be made through advertising as part of the sign-in. (Crane, 2007; FON, 2007)

4.4. COMMUNITY INITIATIVES – WIRELESS NEIGHBOURHOOD AREA NETWORKS

Wireless Internet Service Providers typically exploit Wi-Fi technology to provide Internet access services for-a-profit, or in the case where the location owner exploits the 'hotspot', the objective may be to stimulate the revenues of the core business. Next to these commercially oriented organisations, groups of volunteers have emerged that are providing Internet access for free or at very low cost. The shared Internet Access and often also direct communications among community members is provided based on Wi-Fi Access Points being interconnected forming a wireless Neighbourhood Area Network (WNAN).

These communities of volunteers are mostly motivated by their enthusiasm to explore the possibilities of new technologies and their wish to demonstrate their technological savvy to others. These groups of Wi-Fi volunteers are in many ways similar to the early members of the 'Homebrew Computer Club' that emerged in Silicon Valley when the first do-it-yourself computer kits came on the market in the mid 1970s (Freiberger and Swaine, 1984). Members would come together to trade computer

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36 Varsasky was also the founder of Viatel and Jazztel, new entrants in the telecommunications market.

37 In 2007 "La Fonera" is advertised at US$39.99. In a dedicated campaign "La Fonera" was offered for free when living next to a Starbucks coffeehouse.

38 In 2007 the advertised rate for "Bills" and "Aliens" was US$3 for a 24 hr connection.

parts, exchange schematics and programming tips.[39] A typical example of a Wi-Fi community in the Netherlands is 'Wireless Leiden', a group of volunteers that started in the year 2001 and has built a Neighbourhood Area Network that includes 60 nodes and is covering most of the Leiden city and is being linked to neighbouring towns to cover an area of about 500 km^2 (Vijn and Mourits, 2005). Through the organisation of volunteers the 'Wireless Leiden' network is strongly embedded in the economic and social structure of the Leiden city. Companies that e.g. like to link their offices across the city or to their home sponsor the network by providing the equipment for a network node at their premises that will subsequently operate under their name. Other firms provide communication equipment in kind, or provide facilities for the group of volunteers to meet on a regular basis. The municipality supports the group by providing locations to place nodes and antennas. For a local church the 'Wireless Leiden' network provides live broadcast of the church service, and in return is allowed to place an antenna on the church tower.[40] The network also provides inexpensive communication among schools in the city and provides access to the Internet at the library and at the library busses that serve the city neighbourhood.

Based on an investigation of spring 2006 there were approx. 30 NAN initiatives in the Netherlands, of which the 'Wireless Leiden' NAN is the largest (Schreurs, 2006). The investigation revealed that there are or have been many more initiatives than there are networks providing actual service. One plausible reason is that it concerns mostly a loosely organised group of volunteers being involved in the Wi-Fi community initiative next to their day job. Without strong economic incentives projects tend to take much longer to realize, if at all. Nevertheless, there is ample evidence that these Wi-Fi based NANs are important from an economic and social perspective in particular in (1) areas where incumbent telecom operators fail to provide broadband Internet access in developed countries, a typical example is the peninsula of Djursland in Denmark[41], and (2) in developing areas where often the investment capital is lacking to provide the inhabitants with the very basic communication services such as telephony, typical examples are the rural areas in developing countries such as India, Latin America, and Africa.[42] The Case of 'Wireless Leiden' is of interest because of its early start and its significant size, but also for the software development that was done

[39] From the community came the founders of many computer companies, including Bob Marsh, George Morrow, Adam Osborne, Lee Felsenstein, and Apple founders Steve Jobs and Steve Wozniak (Freiberger and Swaine, 1984).

[40] Church service had been provided by the incumbent operator for many decades, but had been discontinued.

[41] It should be noted that use is made of the available fibre based backhaul provided by the incumbent operator TDC.

[42] These applications will be discussed in more detail in a forthcoming publication Lemstra, W. Groenewegen, J.P.M and Hayes, V. (eds.). "The genesis of Wi-Fi and the road toward global success".

to make Wi-Fi networking possible and for the entrepreneurial activities that it generated.

4.5. MUNICIPAL NETWORKS

Since the foundation of 'Wireless Leiden' in 2002 there have been important changes in the environment: broadband internet access through ADSL and CATV-cable and the use of domestic Wi-Fi have become ubiquitous. Moreover, the objectives of the techno-enthusiasts of the early hour have been fulfilled by establishing the network. Keeping the network running requires a different attitude and motivation of volunteers. Meanwhile 'Wireless Leiden' has also become highly visible and according to Michel van der Plas, economic advisor at the Leiden City Office, it has become a highly valuable asset in the positioning of Leiden as a high-tech city. Continuity of the 'Wireless Leiden' network has become important to the municipality. Moreover, professional parties have shown an interest in using the network for developing new, wireless applications like 'location based services'. The Wi-Fi network of 'Wireless Leiden' offers an unique possibility to develop and test new techniques and applications. That is the reason a close working relationship has developed with several research institutions, such as the 'Centre for Technology and Innovation Management', the Institute for Societal Innovation, the 'Hogeschool Leiden' and the Leiden University.

Wireless municipal broadband access has become a major item in the USA with highly visible initiatives in e.g. Philadelphia, San Francisco (involving Google) and Silicon Valley.[43] The provisioning of city-wide Wi-Fi based connectivity is seen as a way for local governments to improve the availability and affordability of broadband access. Municipalities have thereby the opportunity to leverage their role as consumer when considering to become a supplier of broadband access. Reasons that are being stated for municipalities to pursue the opportunity to enter the market for wireless broadband service provision include: (1) opportunity to fill the gap in available and affordable (wired) broadband access, where private firms fail to provide service or offer services at a price considered to be too high; (2) to create a 'third pipe" next to DSL and cable to improve competition; (3) making the city more competitive in attracting business; (4) improving intra- and intergovernmental communications, improving quality of work life for employees; (5) the availability of wireless technology at low cost, without the need for a license; (6) the opportunity to offer services at lower costs of deployment e.g. through ownership of rights-of-way, the use of municipal premises and leveraging internal use of the network (Tapia, Stone et al., 2005; Hudson, 2006; Weiss and Huang, 2007). The role of local government in providing wireless broadband access is subject to intense debates whether public funds may be

43 Tapia indicates that in 2005 over 100 cities have announced plans for municipal wireless (Tapia, Stone et al., 2005).

used and whether these public initiatives infringe on private interests of the incumbent telecom and cable operators. This interest of municipalities in Wi-Fi deployment has resulted in additional law making at US State level to regulate if and how municipalities can enter the wireless service provider sphere (Tapia, Stone et al., 2005).

In a comparative study including European initiatives Van den Audenhove et al. conclude that local government motives to engage in wireless network deployment include policies related to the 'digital divide', city renewal, stimulating innovation, stimulating tourism, and improving the 'economic fabric' of the city.[44] In comparison the European initiatives are more oriented towards "hotspots" and "hotzones" and not necessarily aim at full city coverage; an attitude that may be influenced by uncertainty on the critical position of the European Commission regarding these initiatives with respect to distortion of competition (Van Audenhove, Ballon et al., forthcoming). In addressing these concerns they have analyzed the underlying business models with varying degrees of public and private involvement with respect to network ownership and service provisioning. Six combinations emerge in the study of 28 initiatives: (1) private concessions for the network ownership and service provisioning applied in Bristol, Cardiff, Paris and London; (2) private concession of the network combined with a wholesale based service provisioning used mainly in the USA in Philadelphia, Portland, Sacramento and San Francisco; (3) public ownership of the network combined with wholesale provisioning is applied in Stockholm and Boston; (4) a fully public model is applied only in the case of St. Cloud USA. In addition two more open models can be discerned (5) an "open site" model in Paris and Bologna where the city grants open access to public sites and/or to its backbone network for private providers to exploit; and (6) the community model as it applies in different flavours to Wireless Leiden in the Netherlands and Turku in Finland (Ballon, Van Audenhove et al., 2007).

These studies illustrate that Wi-Fi has evolved from its intended use in wireless corporate networking, with a market breakthrough in wireless home networking, to a wide variety of private entities and public-private partnerships exploiting its potential. The cases described also show that Wi-Fi based broadband access should not be considered a replacement of wired broadband access, but rather as complementary access reaching out to places and users that other networks cannot reach.

5. SUMMARY, REFLECTIONS AND IMPLICATIONS

The current day success of Wi-Fi can be traced back to a change in government policy intended to simplify the rules for the use of radio frequency spectrum and the idea to allow public use of spread spectrum technology. The 1985 decision of the FCC to allow

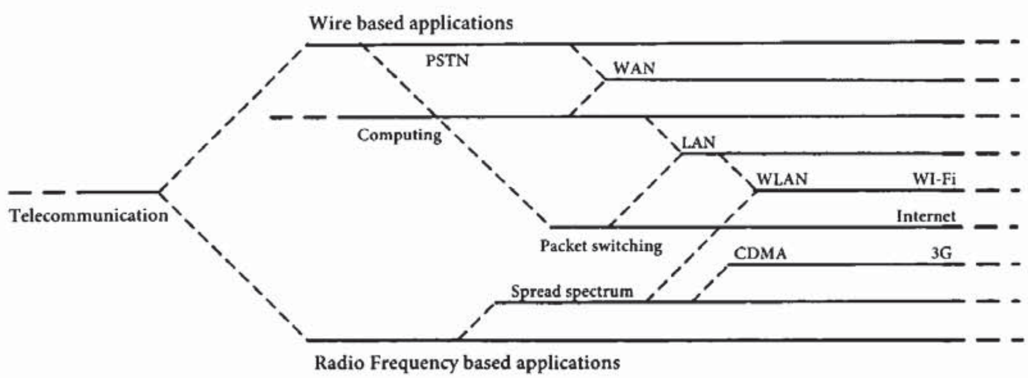
44 The study includes the European cities of Bologna, Bristol, Cardiff, Düsseldorf, Leiden, London, Paris, Stockholm, and Turku.

spread spectrum based radio communication in the three bands designated for Industrial, Scientific and Medical applications triggered communication firms to innovate and develop new short range data communication products. NCR recognized the need to leverage existing standardized communication protocols and became the driving force in the development and adoption of a Wireless-LAN standard - IEEE 802.11, as were its corporate successors AT&T, Lucent Technologies, and Agere Systems. In contracting with Apple and subsequently cooperating with Microsoft the product reached the mass market. In the process the product moved from its intended use as WLAN in the corporate environment to application in the home. Subsequently the home and business use was extended through Internet access services being provided at 'hotspots', 'hotzones', and more recently through city-wide Wi-Fi networking. The low-threshold technology resulted also in networks being created by communities of volunteers in developed as well as developing countries to provide alternative network access and in filling a void left by the incumbent telecommunications operators. The case story of Wi-Fi is an illustration of how innovation can be triggered by policy, developed by the industry and shaped by the users.

5.1. REFLECTING ON INNOVATION

The Wi-Fi case is a good example of an 'innovation journey' (Van de Ven, Polley et al., 1999) and it illustrates how a new 'innovation avenue' (Sahal, 1981, 1985) emerges as a fusion of two existing avenues: LANs and Spread spectrum; see also Figure 4.

Figure 4. Relationship between Wi-Fi related innovation avenues



It is also a good illustration of the different sources of innovation that play a role in the shaping of a product or service as argued by Von Hippel (1988, 2005). In our case the emphasis has shifted from the more traditional role of the manufacturer, to the operator as supplier of a service, to the users building Wi-Fi based community networks.

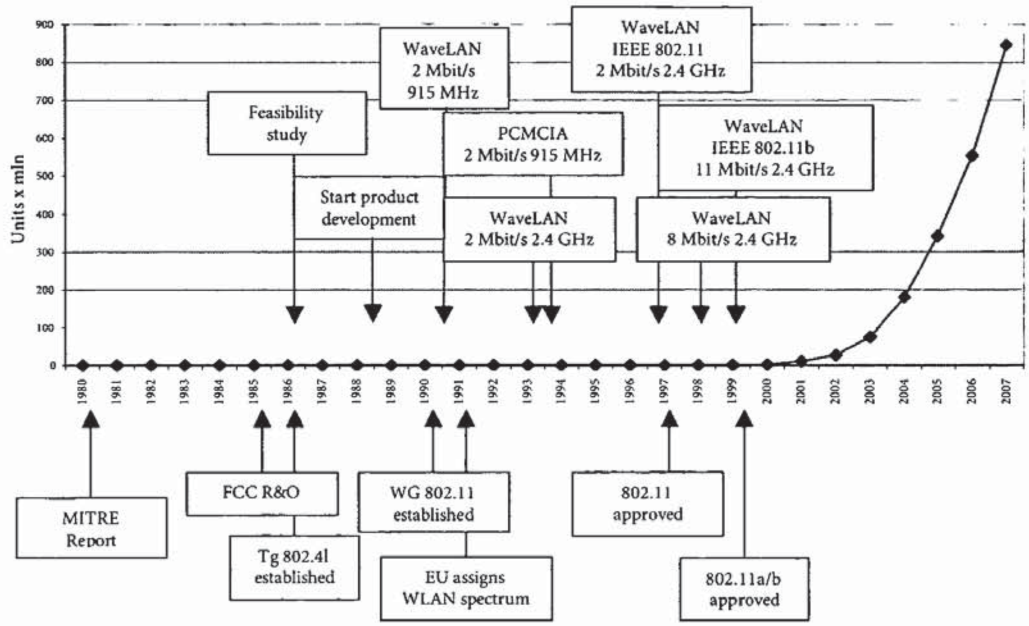
In the Wi-Fi case we can also recognise the notions of evolutionary theory, i.e. novelty generation, transmission and selection, as well as retention. The Wi-Fi development can be related to Nelson and Winter (1977, 1982) who argue that technical advance is an evolutionary process in which new technological alternatives compete with each other and with prevailing practice, whereby *ex-post* selection is determining the winners and losers, usually with considerable *ex-ante* uncertainty regarding the outcome. Thereby we recognise the Lamarckian metaphor of economic evolution which allows acquired characteristics based on learning to be passed on and which acknowledges purposeful intention with respect to changing behaviour. This is in contrast to the Darwinian metaphor whereby change can only take place through mutations at birth and which is considered to be random (Lemstra, Hayes et al., Forthcoming).

The development of Wi-Fi was triggered by a major shift in the institutional arrangements: the assignment by the FCC of unlicensed radio frequency spectrum for communication purposes. The technology to be applied had been developed in the military domain and was now prescribed for use in the private domain. This can be characterised as a change in the institutional selection environment. Although the FCC ruling prescribed a certain type of technology, firms generated a broad variety of initial products using proprietary protocols. From a theoretical perspective, the FCC opened the possibility for novelty generation. The incompatibility resulted in a fragmented product market, increasing the risk for the users with respect to future developments. Through NCR taking a leadership role in establishing a coalition the novelty generation in the product market moved to the selection mechanism of the standardization process. The standardization process has been a process of retention and learning of the various firms involved in the development of Wi-Fi. A strong contribution to the development of the content of the standard, a high degree of participation, as well as skilful negotiation and manoeuvring are the major ingredients determining the outcome of this process. A process being facilitated through well-established formal procedures within the IEEE.[45] Wi-Fi emerged as the winner of the battle against HomeRF and HIPERLAN. This connects to the economic literature describing how a dominant design emerges (Abernathy and Utterback, 1978). Once resources come to be largely focused on the leading technology further improvements may soon make it and its further developments the only economic way to proceed because competing designs are left so far behind (Nelson and Winter, 1977, 1982). Implicitly the case shows the importance of software platforms in forging the successful adoption of this hardware oriented product (Gawer and Cusumano, 2002).

The product life cycle of Wi-Fi reflects a long gestation period of almost 15 years, followed by a rapid take off in the last 5–6 years, see also Figure 5.

[45] The IEEE for instances use the Robert's Rules of Order (Roberts, 2000).

Figure 5. Wi-Fi standards and NCR products



The aspect of retention can best be illustrated by characterizing the Wi-Fi based eco-system that has emerged and is evolving (based on: Kamp, 2005; De Leeuw, 2006, 2007):

- In 2004 the Wi-Fi related product market was estimated at US$ 3.5 bln, In the third quarter of 2007 over 43 million WLAN NICs were shipped from Taiwan, 37% more than the previous year,
- The portfolio included: chips and chipsets, PC-adapters (PCI, USB, CF/SDIO), networking devices (access points, bridges, gateways and routers), as well as antennas and boosters,
- A market scan executed in 2007 identified 180 end-product vendors, providing 3289 different products,
- Client devices that include Wi-Fi functionality include: notebooks, PDAs, mobile phones, streaming music and video players, digital camera's, printers, video beamers, gaming devices, and home audio-systems,
- Hotspots worldwide are well in excess of 206,567 in 135 countries,
- Major hostspot/roaming operators are: iPass, T-Mobile, WeRoam, Trustive, Swisscom, Boingo, BT Openzone, Orange, GoRemote (GRIC), GBIA, and NTT,
- Community initiatives have sprung up in developed and developing countries; in a small country as the Netherlands 30 networks are in operation or being constructed; the largest network being the Neighbourhood Area Network of "Wireless Leiden". In the USA over 400 cities and counties are reported with operational

municipal networks, networks under deployment, or tenders issued for Wi-Fi networks.

5.2. REFLECTING ON THE STANDARDISATION PROCESS

Following the success of the IEEE wired-LAN standard, in particular the Ethernet (see Von Burg, 2001), Wi-Fi represents the success of the wireless-LAN standardisation process within IEEE as a standards developing organisation.[46] While the wired-LAN standardization process was rife with conflict, ultimately three version were standardized (Ethernet, token bus, and token ring), issues over intellectual property (IP) in Working Group IEEE 802.11 have remained relatively minor.

The position of the IEEE vis-à-vis the use of patents in standards changed over the life time of the project. Until the end of 1995 the preferred policy was to avoid the use of patented material in the standard, and "if the committee intends to use patented material it must explain the reasons why." (Bylaws of the IEEE Standards Board). By the end of 1995 the Bylaws were changed to: "IEEE standards may include the known use of patent's, including patent applications, if there is compelling technical justification ... and provided the IEEE receives assurance from the patent holder that it will license applicants under reasonable terms and conditions for the purpose of implementing the standard."[47] In 1996 the IEEE 802.11 Chair collected out of the 63 firms actively participating in the standardization process: 16 FRAND usage statements (fair, reasonable, and non-discriminatory), 1 firm listing an IP claim without a use statement, 5 firms stating no IP was being claimed, and 43 firms did not respond to the query.[48]

The more contentious issue related to the perceived advantages of one firm over others in the implementation of the standard in silicon as discussed in section 3.6.5.

5.3. IMPLICATIONS FOR GOVERNMENT POLICY

For government policy the Wi-Fi case is important as it reflects the first large scale deployment of radio communication on an unlicensed basis. The worldwide adoption of Wi-Fi demonstrates that RF spectrum can be used effectively using a licensed-exempt regime. As the initial RF assignment has been based on the use of the existing bands designated for the use of Industrial, Scientific and Medical applications, the use can be considered to be highly efficient as no new spectrum had to be allocated.

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46 See for a comparison of the cellular standardisation with Wi-Fi Lemstra & Hayes (Forthcoming-a) and for an expansion on the standardization process (Forthcoming-b).

47 Doc: IEEE P802.11-96/14, V. Hayes, Changes in IEEE's Patent Policy Rules, January 9, 1996.

48 It should be noted that copyrights automatically transfers to the IEEE when copyrighted material from submissions and added into the standard.

The common understanding that open access regimes lead to a 'tragedy of the commons' is shown not to be applicable to this case. Although access is not restricted and no protection is offered under this unlicensed regime, the limitations set to the power levels used appear to be effective in creating a localized use that resembles the characteristics of a private property regime. The adoption and use appears not to be restrained by the lack of protection. Albeit the regime does not provide any indicators that signal congestion or deterioration of service leading to users abandoning the use of Wi-Fi. Hence, there may be an undisclosed albeit very localized 'tragedy of the commons'.

The relative low power levels do represent a limitation to the deployment of Wi-Fi as in the case of community Wi-Fi networks or municipal Wi-Fi, as the signal does not penetrate deeply enough, without antenna boosters, into homes and offices to provide an acceptable quality of service.

The 'free rider' phenomenon also associated with open access regimes has shown to be less of an issue in this case. Multiple product vendors and later service providers have shown to be willing to invest in the development of products and services to exploit the unlicensed part of the RF spectrum. One could argue that this is the result of the return on investment largely being based on the sale of the Wi-Fi equipment, and not in the exploitation of a service requiring complementary and deep investment in the creation of a network infrastructure, as is the case in cellular based communications.

For government policy the case illustrates that innovation can be triggered by a change in policy, by lowering the barriers to the use of radio frequency spectrum as an input to the production function. The Wi-Fi case illustrates the innovation potential of a license-exempt RF spectrum regime. It also shows the constancy of purpose required to ultimately reap the economic and social benefits: the original idea going back to 1980 while the large scale deployment of Wi-Fi starts in the year 2000.

In terms of innovation policy the case shows the global nature of to-day's ICT industry: whereby the locus of invention (USA) or of innovation (the Netherlands) is not necessarily the locus of manufacturing (Taiwan) or the locus where ultimately most of the value is being appropriated. Nonetheless the case illustrated the contribution by a Dutch entity to innovation in the field of ICT, moreover, it shows that this contribution is not incidental. While the entity that is associated with the emergence of Wi-Fi may have been dissolved, the individuals involved continue to contribute to the process of innovation, through enhancing the product and/or expanding in adjacent application areas, such as Wi-MAX, Zigbee and Bluetooth.

5.4. IMPLICATIONS FOR FIRM STRATEGY

The case story of Wi-Fi is a good example of how the innovation process works in practice. It shows the linkage to corporate strategy; it shows the role of individuals in various parts of the organisation in driving the course of events. It shows the importance of teamwork, of personal commitment and dedication. The extensive period required for the standardization illustrates the commitment, the tenacity and the resources required from an emerging industry leader involved in 'rule breaking' (De Wit and Meyer, 2004). Moreover, it shows the importance of institutions in technology and product development. For examples, the FCC as national regulatory agency in providing the governance of the radio spectrum; the IEEE providing the ICT industry with a platform to develop standards.

The behaviour of NCR can be connected to the role of the entrepreneur as in the view of Casson: "an entrepreneur is someone who specializes in taking judgmental decisions about the coordination of scarce resources" (Ricketts, 2002). A particular challenge for the entrepreneur is to move the business beyond the early adopter phase into the mass market phase, i.e. from selling successfully to the technology enthusiast and visionaries to selling to the pragmatists. To reflect this difficulty Moore uses the metaphor of 'crossing the chasm' (1991). To cross the chasm successfully he argues that it is important to target the right initial product segment. If properly selected and executed the attack moves to adjacent segments. Thereby the success in the first market segment will work as the head pin at a bowling alley, ultimately leading to mass market success (Moore, 1995). In the terms of Moore, the 'chasm' was crossed in 1999 through a strategic cooperation of Lucent Technologies with Apple and subsequently Microsoft. While Wi-Fi started as a technological innovation, its development became characterized by subsequent releases of enhancements to the IEEE 802.11 standard. These standards were translated into chipsets which became incorporated in products, which in turn became part of communications systems. This connects to the economic literature as for instance Nelson argues that once a dominant design comes into existence, radical product innovation slows down, and product design improvements become incremental. The attention shifts to the improvement of the related process technology. The growth in the number of people who own and use a particular technology variant plays an increasing role as skills develop that are particular to a certain variant, as are investments in complementary products designed to fit with a particular variant (Katz and Shapiro, 1985, 1994; Arthur, 1996). In our case-study, we observe that first these WLAN systems were applied in the corporate domain, subsequently in the private domain, followed by the public domain. As a result the industry evolved from a component and product focus to a product and service focus. An expanding value network has been the result.

With the emphasis shifting from invention to mass production, the industrial activities within NCR/AT&T/Lucent Technologies shifted from the Netherlands and the USA to Taiwan and China. Lucent Technologies, severely affected by the downturn in telecommunication spending in the aftermath of the telecom bubble, divested its WLAN activities through the spin-off of Agere Systems in 2001. In 2004 Agere discontinued its WLAN development activities and the team in Utrecht has been dissolved.

However, as the original radio expertise moved with the people from Philips to NCR, the success of Wi-Fi developments has triggered new start-ups by former staff of Lucent Technologies, continuing the innovation process. For instance Airgo was established in the Netherlands in 2001. Airgo, recently acquired by Qualcom, continues to lead developments in the Wi-Fi space, in particular with MIMO (multiple inputs multiple outputs). Airgo designed chips which have resulted in the first ever MIMO consumer products being introduced in the market by a number of suppliers. Following in the footsteps of NCR, Airgo is contributing extensively to IEEE 802.11 Task Group 'n', aimed at achieving high throughput extension (Van Nee, 2006).

Next to knowledge diffusion through start-ups, former Agere staff has moved to other (leading) companies in the wireless industry including Motorola, and they continue to push the envelope in terms of innovation in wireless communications.[49]

NCR survived the acquisition by AT&T and continues to be a successful independent company in the field of transaction processing with an increasing focus on services.

5.5. CONCLUSIONS

The case of Wi-Fi has shown that policy makers not necessarily have to wait until representatives of the industry request the allocation and assignment of radio spectrum for a particular use. Pro-active allocation can provide opportunities for innovation, and an unlicensed regime can result in highly successful products and services. The case does illustrate the need for the industry to provide leadership in the development of standards, the harmonization of spectrum use, and the compatibility of products to facilitate the creation of a mass market. It shows that significant lead times are involved, and hence, constancy of purpose is required by the governments and the firms involved. Ultimately the end-users extend the deployment of the product in unforeseen directions, in this case in providing voice and data services to areas that hitherto have remained unserved.

49 Other areas in the wireless domain where the Dutch have been leading are Bluetooth and Lofar. Bluetooth development was triggered in 1994 by the desire to replace the wires between mobile phones and auxiliary devices with a radio connection. Jaap Haartsen, working at Ericsson at the time, led the development. LOFAR started as a new and innovative effort to force a breakthrough in sensitivity for astronomical observations at radio-frequencies below 250 MHz. LOFAR is the first telescope using an array of simple omni-directional antennas spread out over an area of ultimately 350 km in diameter. The electronic signals from the antennas are combined in software to emulate a conventional antenna. (Astron, 2006).

6. REFERENCES

ABERNATHY, W.J. and UTTERBACK, J.M. (1978) "Patterns of industrial innovation", *Technology Review*, 80 (7): 40–47.

APPLE (2007) "Apple and Starbucks announce music partnership" (accessed on 2007-09-26).

ARAR, Y. (2002) "Starbucks expands wireless internet offering" (accessed on 2007-08-29).

ARTHUR, W.B. (1996) "Increasing returns and the new world of business", *Harvard Business Review*, 74 (4): 100–109.

ASTRON (2006) "LOFAR" (accessed on 2006-07-22).

BALLON, P., VAN AUDENHOVE, L. et al. (2007) "Business models for wireless city networks in the EU and the US: Public inputs and Returns", 18th European Regional ITS Conference. Istanbul.

BORISOV, N., GOLDBERG, I. et al. (1999) "802.11 Security" (accessed on 2007-01-30).

CEPT (1991) *Recommendation T/R 10-01 (Oslo 1991, revised in Madrid 1992), Wide band data transmission systems using spread-spectrum technology in the 2.5 GHz band. Superseded by T/R 70-03.*

CEPT (1992) *Recommendation T/R 22-06 (Madrid 1992, revised at Nicosia 1994), Harmonised radio frequency bands for high performance radio local area networks (HIPERLANs) in the 5 GHz and 17 GHz frequency range. Superseded by T/R 70-03.*

CRANE, M. (2007) "Stealing Starbuck's Wi-Fi customers", available at Forbes.com (accessed on 2007-08-28).

DE LEEUW, G.J. (2006) "Wi-Fi in the Netherlands", 9th Annual International Conference Economics of Infrastructure. Delft, the Netherlands.

DE LEEUW, G.J. (2007) *A snapshot of the Wi-Fi world in 2007.* Delft, the Netherlands: TUDelft.

DE WIT, B. and MEYER, R. (2004) *Strategy: process, content, context – An international perspective.* London: Thomson.

ETS (1996) *European Telecommunications Standard 300 328, Radio Equipment and Systems (RES); Wideband transmission systems; Technical characteristics and test conditions for data transmission equipment operating in the 2,4 GHz ISM band and using spread spectrum modulation techniques, Second Edition November 1996.*

FCC (1981) "GEN Docket 81-413, Authorization of spread spectrum and other wideband emissions not presently provided for in the FCC rules and regulations. Notice of Inquiry, June 30, 1981." (accessed on 2008-01-30).

FCC (1984) "GEN Docket 81-413, Authorization of spread spectrum and other wideband emissions not presently provided for in the FCC rules and regulations.

Further Notice of Inquiry and Notice of Proposed Rulemaking, April 26, 1984." (accessed on 2008-01-30).

FCC (1985) *Report and Order, Gen Docket No. 81-413 in the matter of: Authorization of spread spectrum*. Washington, D.C.: Federal Communications Commission.

FCC (1999) "ET Docket 99-231, Amendment of Part 15 of the Commission's rules regarding spread spectrum devices. Notice of Proposed Rulemaking, released June 24, 1999." (accessed on 2008-02-08).

FCC (2000) "ET Docket 99-231, Amendment of Part 15 of the Commission's rules regarding spread spectrum devices. First report and order, released August 31, 2000." (accessed on 2008-02-08).

FCC (2007) "About the FCC" (accessed on 2007-01-05).

FLEISHMAN, G. (2002) "Wi-Fi timeline" (accessed on 2006-05-31).

FON (2007) "What's Fon?", available at FON (accessed on 2007-08-30).

FREIBERGER, P. and SWAINE, M. (1984) *Fire in the Valley: The making of the Personal Computer.* Berkeley, CA: Osborne/McGraw-Hill.

GAWER, A. and CUSUMANO, M.A. (2002) *Platform leadership: How Intel, Microsoft and Cisco drive industry innovation*. Boston: Harvard Business School Press.

GOLDBERG, H. (2008) "Grazing on the commons: The emergence of Part 15", The genesis of unlicensed wireless policy. Arlington, VA.

GRIFFITH, E. (2003) "T-Mobile cut price of Wi-Fi", available at wi-fiplanet.com (accessed on 2007-08-29).

HAZLETT, T.W. (2006) "The spectrum-allocation debate: an analysis", *IEEE Internet computing*: 68-74.

HILLS, A. (1999) "Wireless Andrew", *IEEE Spectrum*, 36 (6): p49-53.

HILLS, A. and JOHNSON, D.B. (1996) "A wireless data network infrastructure at Carnegie Mellon University", *IEEE Personal Communications*, 3 (1): 56-63.

HUDSON, H.E. (2006) *Municipal wireless broadband: Lessons from San Francisco.* San Francisco: University of San Francisco.

JIWIRE (2007) "Hospot directory" (accessed on 2007-09-12).

JOHNSON, D.B. (2007) Personal communication. Personal Communication.

KAMP, D. (2005) *Analysis of the emergence of Wi-Fi.* Delft: TUDelft.

KATZ, M.L. and SHAPIRO, C. (1985) "Network externalities, competition, and compatibility", *American Economic Review*, 75: 424-40.

KATZ, M.L. and SHAPIRO, C. (1994) "Systems competition and network effects", *Journal of economic perspectives*, 40: 93-115.

LANSFORD, J. (1999) *HomeRF: Bringing wireless connectivity home*: Intel.

LANSFORD, J. (2007) Personal communication. Personal Communication.

LEMSTRA, W. and HAYES, V. (Forthcoming-a) "License exempt: Wi-Fi complement to 3G", *Telematics & Informatics.*

LEMSTRA, W. and HAYES, V. (Forthcoming-b) "The shaping of the IEEE 802.11 standard – The role of the innovating firm in the case of Wi-Fi", In K. Jakobs (ed.), *Information and Communication technology standardization for e-business: Integrating supply and demand factors*. Hershey, PA: IGI Global.

LEMSTRA, W., HAYES, V. et al. (Forthcoming) "Network modernization in the telecom sector – The case of Wi-Fi", in R. W. Künneke (ed.), *The governance of network industries: Redefining rules and responsibilities*. Cheltenham, UK: Edward Elgar.

LINKS, C. (2007) Personal communication. Personal Communication.

MARCUS, M. (2000) "Commercial spread spectrum" (accessed on 2007–06–28).

MARCUS, M. (2007) Personal communication. Personal Communication.

MARCUS, M.J. (2008) "Wi-Fi and Bluetooth – The path from Carter and Reagan-era faith in deregulation to widespread products impacting our world", The evolution of unlicensed wireless policy. Arlington, VA.

MICROSOFT (2001) "MobileStar to provide high-speed wireless Internet access and infrastructure", available at Microsoft (accessed on 2007–08–29).

MITRE CORP. (1980) *Potential use of spread spectrum techniques in non-government applications*. Springfield, VA: National Technical Information Service.

MOCK, D. (2005) *The Qualcomm equation*. New York: AMACOM.

MOORE, G.A. (1991) *Crossing the chasm*. New York: Harper Business.

MOORE, G.A. (1995) *Inside the tornado*. New York: Harper Business.

NCR (2007) "About NCR – History" (accessed on 2007–01–05).

NEGUS, K.J. and PETRICK, A. (2008) "History of Wireless Local Area Networks (WLANs) in the unlicensed bands", The evolution of unlicensed wireless policy. Arlington, VA.

NEGUS, K.J., STEPHENS, A.P. et al. (2000) "HomeRF: Wireless networking for the connected home", *IEEE Personal Communications*, Feb.

NELSON, R.R. and WINTER, S.G. (1977) "In search of a useful theory of innovation", *Research Policy*, Vol. 6: p36–76.

NELSON, R.R. and WINTER, S.G. (1982) *An evolutionary theory of economic change*. Cambridge, MA: The Belknap Press of Harvard University Press.

O'SHEA, D. (2003) "Starbucks says Wi-Fi's a hit", available at TelephonyOnline (accessed on 2007–08–29).

OHRTMAN, F. and ROEDER, K. (2003) *Wi-Fi Handbook – Building 802.11b wireless networks*. New York: McGraw-Hill.

PALO WIRELESS (2003) "HomeRF overview and market positioning" (accessed on 2007–08–07).

RICKETTS, M. (2002) *The economics of business enterprise – An introduction to economic organisation and the theory of the firm*. Cheltenham, UK: Edward Elgar Publishing.

ROBERTS, H.M. (2000) *Robert's rules of order – Newly revised*. Cambridge MA: DaCapo Press.

SAHAL, D. (1981) *Patterns of technological innovation*. Reading, MA: Addison-Wesley.

SAHAL, D. (1985) "Technology guideposts and innovation avenues", *Research Policy*, 14: 61–82.

SCHREURS, M. (2006) *Wi-Fi netwerk initiatieven in Nederland*. Delft: TUDelft.

SINGER, M. (2002) "Starbucks serves up Wi-Fi access", available at Internetnews.com (accessed on 2007-08-29).

STARBUCKS (2004) "Starbucks builds continued success with T-Mobile HotSpot", available at Business Wire (accessed on 2007–08–30).

STARBUCKS (2007) "Highspeed wireless internet access" (accessed on 2007–08–28).

TAPIA, A., STONE, M., et al. (2005) "Public-private partnerships and the role of state and federal legislation in wireless municipal networks", Telecommunications Policy Research Conference.

TUCH, B.T. (2007) Personal communication. Personal Communication.

TUCH, B.T. and MASLEID, M.A. (1991) *Wireless information transmission system*. USA: US Patent and Trade Mark Office.

U.S. CENSUS BUREAU (2006) "Population" (accessed on 2007–09–12).

VAN AUDENHOVE, L., BALLON, P. et al. (Forthcoming) "Government policy and wireless city networks: A comparative analysis of motivations, goals, services and their relation to network structure", *The Southern African Journal of Information and Communication*.

VAN DE VEN, A.H., POLLEY, D.E. et al. (1999) *The innovation journey*. Oxford, UK: Oxford University Press.

VAN NEE, R. (2006) "Current status of Wi-Fi standardization", 9th Annual International Conference Economics of Infrastructures. Delft, the Netherlands.

VIJN, M. and MOURITS, G. (2005) "Wireless netwerk dekt Leiden", *Informatie*, Vol. Oct.

VON BURG, U. (2001) *The triumph of Ethernet*. Stanford, CA: Stanford University Press.

VON HIPPEL, E. (1988) *The sources of innovation*. Oxford, UK: Oxford University Press.

VON HIPPEL, E. (2005) *Democratizing innovation*. Cambridge, MA: MIT Press.

WALKER, J. (2000) *Unsafe at Any Key Size: An Analysis of the WEP Encapsulation*. Intel.

WEISS, M.B.H. and HUANG, K.C. (2007) "To be or not to be: A comparative study of city-wide municipal Wi-Fi in the US", Telecommunications Policy Research Conference.

WI-FI ALLIANCE (2007) "Get to know the alliance" (accessed on 2007–08–16).