Licence-exempt: the emergence of Wi-Fi

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Received 13 September 2008
Revised 4 February 2009
Accepted 31 May 2009

This paper draws on a research project executed within the Faculty of 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: Dr A. Hills at Carnegie Mellon University, Prof. Dr M. Finger and Dr P. Rossel at Ecole Polytechnique Fédéral de Lausanne, Prof. Dr A-J. van der Veen at TUDelft, Prof. Dr W.H. Melody at TU-Denmark, Dr E. Pietrosemoli at Universidad de Los Andes, Dr K. Jakobs at University of Aachen, Dr S. Verhaegh at University-Twente, and Dr L. van den Audenhove at Vrije Universiteit Brussel; and field input from regulators: the FCC (USA), OPTA and AT (The Netherlands); various firms within the communication industry, e.g. NCR/AT&T/Lucent Technologies, and Agere Systems, Aruba Networks, Avinity, Gandalf, GreenPeak, Motorola, Philips, Qualcom, SonyEricsson; from standardization organizations: e.g. IEEE and ETSI; from operators: e.g. Casema, KPN, Swisscom, T-Mobile; and from wireless community founders: e.g. Wireless Leiden, Djürsland, AirJaldi.

Abstract

Purpose – *This paper aims to provide a description of the genesis and development of Wi-Fi, or how the industry exploited an opportunity provided by the regulators in allowing radio communications in the unlicensed bands originally allocated for industrial, medical and scientific applications.*

Design/methodology/approach – *The longitudinal case describes the genesis and development of Wi-Fi, with a focus on the interplay between regulation, innovation, standardization, and running a successful business.*

Findings – *The paper argues that the current day success of Wi-Fi is a combined result of: a change in the US communications policy in the 1980s; the industry leadership provided by NCR, its successors and collaborators, to create a global standard and to deliver compatible products under the Wi-Fi label; and 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 service, and from operators to end-users as the provider of that service.*

Research limitations/implications – *The exploration and analysis are based on contributions by experts from the field, having been involved ''first hand'' in the innovation journey of Wi-Fi.*

Practical implications – *The case describes the first globally successful large-scale application of radio communication devices operating under a licence-exempt radio frequency regime. The case is a contemporary example of innovation and product development leading to an open standard. In concluding the paper reflects on the implications of this licence-exempt case for the governance of the radio spectrum.*

Originality/value – *While many articles and books have appeared discussing the technical aspects of Wi-Fi, the case description documents the genesis and development of Wi-Fi from an entrepreneurial perspective.*

Keywords *Communication technologies, Governance, Innovation, Marketing strategy, Radio frequencies, Case studies*

Paper type *Research paper*

1. Introduction

Wi-Fi can be considered the first successful large-scale communication application under a license-exempt use of the radio frequency spectrum regime. For many 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. An impressive Wi-Fi based ecosystem has emerged and is still evolving: every laptop provided with the Intel Centrino chipset has built-in Wi-Fi functionality; in the third quarter of 2007 over 43 million WLAN network interface cards were shipped from Taiwan, 37 percent more than the previous year; a market scan executed in 2007 identified 180 vendors providing 3,289 different client devices with Wi-Fi functionality, including notebooks, PDAs, mobile phones, streaming music and video players, digital cameras, printers, video beamers, gaming devices, and home audio-systems; the count of Wi-Fi hotspots world-wide is well in excess of 206,000 in 135 countries; and in the USA over 400 cities and counties are being reported with either operational municipal networks, networks under deployment, or plans being made for Wi-Fi networks (based on: De Leeuw, 2006; De Leeuw, 2007; Kamp, 2005).

In 1985, this development had been triggered by the US Federal Communications Commission (FCC)[1] when it opened the 915 MHz, the 2.4 and 5.8 GHz bands designated for industrial, scientific and medical (ISM) applications for the use by radio systems, under the condition that spread spectrum techniques would be used (FCC, 1985).

Interestingly, the 1980 MITRE report that investigated the potential benefits, costs, and risks of spread spectrum communications on behalf of the FCC did not identify a strong requirement or need from the industry to assign radio frequency (RF) spectrum for spread spectrum based applications. The report concludes that spread spectrum technology is inherently more complex and thus more costly (Mitre Corp., 1980). However, the report did identify that spread spectrum techniques are inherently more resistant to interference. Moreover, the report identified the ISM bands as bands ''... in which spread spectrum techniques may be able to improve the utilization of the spectrum ... [as these bands] are relatively unsuitable for applications requiring guaranteed high levels of performance. Indeed, since users of the ISM bands are not nominally protected from interference, it can be argued that any productive use of these bands frees other spectrum resources that are needed by applications requiring protection from interference'' (Mitre Corp., 1980). 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 the early 1980s. 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 introduced.

The current success of Wi-Fi is also remarkable as most significant developments in RF technology – radio-relay systems, radio and television broadcasting – have emerged under a licensed regime, whereby a government agency assigns exclusive rights to the use of a specific part of the RF spectrum, thereby providing the application protection from harmful interference by other RF applications and users. The success of Wi-Fi, emerged under a license-exempt open-access regime, whereby it had to contend with many other applications and users in the same RF band, including microwave ovens. Similar situations of open access to a common resource have often led to a so called ''tragedy of the commons''.

Another unexpected outcome is the application of Wi-Fi in closing the digital divide in 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 broadband infrastructure to less profitable areas in a timely manner.

In this paper we provide a description of how the industry exploited an opportunity provided by the FCC in allowing radio communications in the unlicensed bands allocated for industrial, medical and scientific applications. The case describes the genesis and development of Wi-Fi, with a focus on the interplay between regulation, innovation, standardization and running a successful business. We would argue that the current day success of Wi-Fi is the combined result of:

- a change in the US communications policy in the 1980s;
- the industry leadership provided by NCR, its successors and collaborators, to create a global standard and to deliver compatible products under the Wi-Fi label; and
- 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 service, and from operators to end-users as the provider of that service.

In concluding we assess the implications of this case for government policy. The exploration and analysis is based on contributions by experts from the field, having been involved ''first hand'' in the innovation journey of Wi-Fi.

2. NCR – responding to a market need

Preceding and closely linked to the development of wireless-LAN is the development of the wired-LAN, in particular Ethernet. In 1979 DEC, Intel and Xerox formed the DIX alliance with the goal of establishing an industry-wide *de facto* wired-LAN standard. DEC needed to link its new VAX computers to create a distributed computing environment. DEC liked the Ethernet solution as it seemed possible to increase its throughput and Metcalfe had suggested to contact Xerox to license the technology. The alliance opted for an open standard as this would increase the adoption of their LAN systems and increase the overall market. Moreover, Xerox and DEC were pursuing an open strategy to attract third-party supplier of Ethernet components. In particular IC manufacturers, Intel being their first supplier. According to Von Burg the three firms complemented each other very nicely:

> Xerox had the technology; DEC provided market clout, credibility, and some Ethernet components; and Intel brought the chips, so vital in achieving steep price reductions (Von Burg, 2001).

One of the earlier network standards established under the leadership of Loughry at HP was approved in 1974 as IEEE 488, and was aimed at the remote control of programmable instruments in industrial processes. Recognizing the distance limitations of this standard Graube at Tektronix started pushing for a new standard and submitted in 1979 a project authorization request to the IEEE, which would be approved and the first meeting of IEEE 802 would be convened in 1980. Participants were computer manufacturers, vendors of office automation products, vendors of factory automation systems and LAN start-ups, e.g. 3Com – established by Metcalfe in 1979, and Ungermann-Basss – a 1979 spin-off of Zilog. However, the various participants were pursuing different objectives and could not agree on one single standard. Hence, the IEEE Standards Activities Board would ultimately approve three standards: in 1985 the IEEE 802.3 for Ethernet, primarily supported by the DIX alliance, HP, Data General, 3Com and Ungermann-Bass; also in 1985 the IEEE 802.4 for Token Bus, supported by the vendors of factory automation systems; and in 1986 the IEEE 802.5 for Token Ring, with IBM as its main proponent. In 1987 HP initiated an extension effort to standardize a 10 Mbit/s version of Ethernet, which would use telephone wire rather than coax. In 1990 this so-called 10Base-T standard would be approved by the IEEE Standards Board (Von Burg, 2001)[2].

NCR[3] as leading provider of point-of-sale terminals had recognized the opportunities and benefits provided by wired-LANs in connecting its terminals to the back-office computer systems and had initiated the development of the MIRLAN product, using Ethernet components. However, one issue the sales force had identified had remained unresolved: the lack of ''portability''. 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 early Ethernet systems being based on coax cables was cumbersome and costly. In 1985, to address this issue NCR had conducted a study into the use of infrared light technology, but according to Don Johnson at the NCR Corporate R&D organisation, they had quickly recognized that the use of radio technology would be a much better option:

> . . . if it was permitted, if we could make it work and if we could turn it into affordable products (Johnson, 2007).

2.1 Enabled by changing RF spectrum regulation

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 was the Report and Order of May 9, 1985 of the US Federal Communication Commission to ''[authorize] spread spectrum and other wideband emissions not presently provided for in the FCC Rules and Regulations'' (FCC, 1985). For NCR the FCC decision opened a new avenue to explore.

2.2 Initiating a feasibility study

In 1986, following the FCC Report and Order, NCR Corporate initiated a feasibility study into the use of a wireless technology in local area networking; The study would have to demonstrate the feasibility of spread spectrum use in WLANs, and upon a positive outcome would have to generate a product specification, a design description, as well as models for the modem and a prototype of the system (Johnson, 1987).

In comparison with copper wires, coax and (shielded) twisted pair used as medium in wired LANs, such as Ethernet, the electro-magnetic waves differ 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). Any possible further impact on the higher layers of the stack (network through application) would also have to be assessed.

2.3 Assignment of the task to the Dutch Engineering Centre

The seed money from NCR Head Quarters in Dayton Ohio kicked off a development process whereby a Dutch based NCR entity 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 US market. The choice of the Utrecht Engineering Centre for the execution of the technology investigation was based on their signal processing and hardware design expertise in local area networks and the recently acquired radio technology expertise from Philips Electronics.

The first step in the feasibility project was to determine what power levels were needed and under what rules such spread spectrum products could be certified by the FCC. One of the issues was the so called ''processing gain'' requirements, the factor to be used in a spread spectrum system to ''expand'' the bandwidth above the bandwidth you would ''normally'' need just to get your 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 an unlicensed band (Tuch, 2007)[4]. 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. A visit to the FCC Labs in Maryland 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 to established a code that had a length of 11 with the required properties that were determined from indoor propagation studies[5].

The other major research topic was related to the system costs, and revolved around the best approach to achieve the receiver function for spread spectrum. According to Tuch, one option was to use integrated circuits with digital signal processing techniques totally or to augment this with a component called a surface acoustic wave (SAW) Filter doing the spread spectrum processing (Tuch, 2007). At the time SAW filters for this type of function were military components costing $100 or more, however, this could be done by normal silicon processing techniques that NCR had available in the micro-electronics division, the issue was the appropriate design. To address this issue Professor Venema at Delft University of Technology (TUDelft) was contacted as the expert in SAW devices and a research project was started to design a ''SAW Spread Spectrum Demodulator'' at different code lengths. For this purpose NCR sponsored a PhD student, Jaap Haartsen, who would successfully defend his thesis in 1990, and later, while working at Ericcson, would become one of the originators of Bluetooth[6]. The research project resulted in a working design, which was used in the Wireless LAN Demo unit, and had a projected cost of less than US$5[7].

2.4 The start of product development

After the feasibility study had ended with a positive results, a product specification and working models, the development team in Utrecht convinced the Retail Systems Division that product development was also best carried out by the same team. In the fall of 1988 the team set out to create a Wireless network interface card (Wireless-NIC) to build a Wireless-LAN with an over-the-air data rate of 1-2 Mbit/s. The NIC would have to operate in the 902-928 MHz band, the lower ISM band to provide the maximum possible range and to reduce the cost of the electronics.

The creation of a new medium access control (MAC) protocol became the focus of the product development effort. 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.

2.5 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 derivations of this protocol morphed into Ethernet and later in the IEEE 802.3 Ethernet 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 entity 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''[8].

3. NCR – taking the lead in IEEE 802.11

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 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 (Tuch, 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 (Tuch and Masleid, 1991) was presented to the IEEE 802.3 Ethernet standards group, to solicit interest to start a new wireless working group. 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 Tuch of NCR, the companies interested in establishing a wireless local area network standard quickly generated the necessary paper work 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 Activity Board the new ''802.11'' Working Group was born and Hayes of NCR was appointed as the interim chairperson.

November of 1990, in the first meeting of the 802.11 Working Group Hayes would be elected as the Chair for an initial period four years[9]. At the November 1991 meeting the MAC subgroup and the PHY subgroup were established.

3.1 Centralized versus decentralized architecture

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. 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.

3.2 Resolving the technology options introduced by the FCC

The second area of contention was related to the PHY. In its 1985 Report and 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 percent 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 in silicon. 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. Hence, the decision was left to the market to decide.

3.3 Different perceptions on user needs

The applications of WLAN that NCR had in mind were data-only, as was the case with many other participating vendors involved in mobile data capturing applications. However, a group of participants considered the support of isochronous services, i.e. voice, to be important to capture the market of home users. Based on an initiative by Proxim an industry consortium was established, the so-called HomeRF Working Group (Negus *et al.*, 2000)[10]. The consortium chose the frequency hopping method as the basis for their standard[11], combined with elements of the TDMA-based voice support from the DECT standard[12]. The FH method adopted by the group supported a data rate of 1.6 Mbit/s. HomeRF was positioned as a low cost solution having a relaxed PHY specification.

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 *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), to, change the frequency hopping rules in a Report and Order of August 31, 2000 (FCC, 2000).

The HomeRF battle against the 802.11 Working Group was fierce. Despite the support of major payers in the industry the HomeRF initiative failed. According to Lansford the reasons for the failure were twofold (Lansford, 2007)[13]:

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 working group felt this made the standard a proprietary system.
2. The adoption of 802.11b in 1999 and its support by several silicon vendors (Harris, Lucent Technologies[14], etc.) drove down prices relatively quickly compared with 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.

3.4 Approval of the IEEE 802.11 standard

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 percent 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 data rate of 1 Mbit/s and Direct Sequence at 2 Mbit/s.

3.5 Input from the market – the need for increased data rates

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 specification it was becoming clear to everybody in the ''802.11'' community that also higher data rate 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 least contentious was the 802.11a variant in the 5 GHz band. There were two main proposals, one from Breezecom and NEC on a single carrier modulation method and one from Lucent Technologies and NTT, based on OFDM[15]. 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 an example how different positions in technological advancements are equalized in a standards making process. The main contenders were Harris and Lucent Technologies, and a proposal from an outsider Micrilor. There was a degree of truth in a 3Com statement that most of the Lucent Technologies supporters had decided to side with Micrilor 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. As the voting stalled, representatives of Lucent Technologies and Harris sat together and acknowledged a compromise was needed. Subsequently they worked out a new radio transmission scheme, different from anything that had been proposed before, called complementary code keying (CCK). Because this proposal gave no advantage to any party the joint proposal was accepted in the next meeting of the Working Group six weeks later, resulting in the IEEE 802.11b standard.

3.6 Approval of the first extensions IEEE 802.11a and 11b

Project IEEE 802.11a and Project 802.11b were balloted at Working Group level in November 1998 and re-circulated twice to start the Sponsor ballot in April 1999. After two recirculation ballots, both were submitted to the SAB in August 1999. IEEE 802.11a was officially published on December 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 an 11 Mbit/s data rate in the 2.4 GHz band.

4. Competing activities in the European standards arena

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 licence-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 and the measurement method to be used for approvals (ETSI, 1993)[16]. This paved the way towards a global allocation of spectrum for Wireless-LANs. This represented great news for the equipment vendors as it would allow for expansion of scale in manufacturing.

The *ad hoc* group subsequently allocated the 5150-5300 MHz and an optional extension to 5350 MHz for RLANs, using the standard tagged high performance local area networks (HIPERLAN), yet to be developed (CEPT, 1992). HIPERLAN was aimed at providing high data rate communications (24 Mbit/s typical), compatible with wired-LANs based on Ethernet and Token ring standards, aimed to cover a range of 50 m, and to support asynchronous and synchronous applications. 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 data rates up to 54 Mbit/s, for communication in the 5 GHz band between portable computing devices and broadband ATM and IP networks.

Neither the HIPERLAN/1 nor the HIPERLAN/2 standard completed in 2004 have become a success. Also HIPERLAN 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. But let's not get ahead of the game and have a look at how the market for WLANs developed.

5. 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. However, while 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 (re-)wiring was cumbersome and expensive, estimated at US$200-1,500 per ‘‘drop’’. 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 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. Prospective customers appeared to be fascinated by the technology, but the benefits were perceived as marginal and the price at US$1,390 per card as too high. However, giving the difference in implementation only a Total Cost of Ownership would provide a fair comparison with wired-LANs. Although this improved the business case significantly, within short NCR would lower the price of the PC plug-in to US$995 (Links, 2007)[17].

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 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, and became comparable to the efforts involved in the development of the NIC, when the system had to be ‘‘scaled-up’’.

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, 1999; Hills and Johnson, 1996). The acquisition of CMU as a client would provide a perfect test-bed for a large-scale deployment of WLANs.

While the early product development period 1987-1991 had been cumbersome, the second period 1991-1994, involving the general availability of the WaveLAN product and a major marketing and sales effort, had not been much better. NCR had essentially ‘‘doubled its bets’’ with adding a 2.4 GHz product, but there were no real profits in sight. It was clear what was needed were standards, higher speeds, and lower costs (Links, 2007).

Moreover, 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[18].

5.1 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). 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. The meeting in the Apple Boardroom was an interesting one, with Steve Jobs concluding the meeting with: ''We need the radio card for $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).

For Steve Jobs the job was done, for Lucent Technologies the work was starting. 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. 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 US$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. Product Line Manager 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 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 company was entering the ''tornado zone''. Within a year all other PC vendors had followed the example set by Apple. Agere Systems, had almost a clean sweep of the wireless-LAN market for PCs[19]. This success is replacing the business user as the main target of WLAN applications by the home user.

5.2 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 and 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 organization driving the adoption of a single DSSS-based world-wide standard for high-speed wireless local area networking. 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 organization had certified the interoperability of over 3,500 products (Wi-Fi Alliance, 2007).

5.2.1 The ultimate success. By early 2001 Agere had reached the summit as supplier of Wi-Fi products with an approximately 50 percent 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 from the plug-ins toward the chipsets. As a consequence the ORiNOCO brand (as successor to WaveLAN) and the related infrastructure products, access points, residential gateways and outdoor routers, were separated organizationally from the chip activities. In 2002 Agere sold the ORiNOCO business unit to Proxim in a friendly take-over valued at US$65 million. 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 million 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.

6. Shaped in the market

While the functionality of WLANs had been determined primarily by the equipment suppliers, the users are deciding on the adoption and use. This includes ''hotspot'' operators that started to use Wi-Fi to offer (semi-)public access to the internet.

6.1 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. By 2003 Wayport was serving some of the major hotel brands: Embassy, Four Seasons, Sheraton, Summerfield, Westin and Wyndham.

6.2 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 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. By the end of the year MobileStar had equipped some 500 Starbucks locations, but also had ran into financial difficulties. 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.

6.3 Community initiatives – wireless neighborhood 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 organizations, 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 neighborhood 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). 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 neighborhood area network that includes 60 nodes and is covering most of the Leiden city and is being linked to neighboring towns to cover an area of about 500 km^2 (Vijn and Mourits, 2005). Through the organization of volunteers the ''Wireless Leiden'' network is strongly embedded in the economic and social structure of the Leiden city. Companies that 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. 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. 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 neighborhoods.

6.4 Municipal networks

Since the foundation of ''Wireless Leiden'' 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 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.

In the USA, wireless municipal broadband access has become a major item with highly visible initiatives in Philadelphia, San Francisco (involving Google), and Silicon Valley[20]. Reasons that are being stated for municipalities to pursue the opportunity to enter the market for wireless broadband service provision include:

- 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.
- To create a ''third pipe'' next to DSL and cable to improve competition.
- Making the city more competitive in attracting business.
- Improving intra- and intergovernmental communications, improving quality of work life for employees.
- 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 (Hudson, 2006; Tapia *et al.*, 2005; Weiss and Huang, 2007).

The role of local government in providing wireless broadband access is subject to intense debates whether public funds may be 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 state level to regulate if and how municipalities can enter the wireless service provider sphere (Tapia *et al.*, 2005). In a comparative study including European initiatives Van Audenhove *et al.* (2007) 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 (Van Audenhove *et al.*, 2007)[21].

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.

7. 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 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 a change in regulatory policy, developed by the industry and subsequently shaped by the users.

7.1 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 world-wide adoption of Wi-Fi demonstrates that RF spectrum can be used effectively using a licence-exempt regime. As the initial RF assignment has been based on the use of the existing industrial, scientific and medical bands the use can be considered to be highly efficient as no new spectrum had to be allocated.

The common understanding that open access regimes lead to a ''tragedy of the commons'' is shown not 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.

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 licence-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 started in the year 2000.

Notes

1. The Federal Communications Commission is a US government agency, directly responsible to Congress. The FCC was established by the Communications Act of 1934 and is charged with regulating interstate and international communications by radio, television, wire, satellite and cable. The FCC's jurisdiction covers the 50 states, the District of Columbia, and US possessions (FCC, 2007).
2. Interesting in this account of the wired-LAN developments is the role of the Aloha network; it implies that the wired-LAN was taken to the air by Abrahamson at the University of Hawaii, to return to the wire by Metcalfe at Xerox, and to be taken to the air again by Tuch of NCR.
3. 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).
4. At the time, Bruce Tuch was leading the wireless R&D efforts of the Utrecht centre.
5. 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''.
6. On July 20, 1989 Van Driest, Haartsen, Tuch, and Visee filed patent on this application of SAW.
7. Nevertheless at the code lengths of 11x coupled with the advancement in Integrated Circuit technology required, the best approach was not to use this device in the product. Here was an example of research whose negative outcome was a positive result (Tuch, 2007).
8. According to the PAR this taskgroup is denoted 802.4c which through a transcription error became 802.4l.
9. Hayes would serve as Chairperson of IEEE 802.11 Working group for 10 years, the maximum period allowed.
10. 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).
11. 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.
12. Digital Enhanced Cordless Telecommunication; originally: Digital European Cordless Telephone.
13. Lansford has been Co-Chair of the Technical Committee for the HomeRF Industry Working Group and wireless system architect with Intel Corporation.
14. With the 1996 tri-vestiture of AT&T, the WLAN activities moved to Lucent Technologies.
15. Orthogonal Frequency Division Multiplexing.
16. Note that in Europe the 900 MHz band is used for GSM.
17. At the time Cees Links was Product Line Manager of WaveLAN.
18. 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, 2003,

pp. 61-85). 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. Papers by Borisov *et al.* (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.

19. 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.
20. Tapia indicates that in 2005 over 100 cities have announced plans for municipal wireless (Tapia *et al.*, 2005).
21. The study includes the cities of Bologna, Bristol, Cardiff, Düsseldorf, Leiden, London, Paris, Stockholm, and Turku.

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