Building the Wireless Internet Infrastructure: From Cordless Ethernet Archipelagos to Wireless Grids

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The development of wireless internet infrastructures is progressing at a staggering pace. As the telecom sector emerges from the collapse of the internet bubble, incumbent wireless carriers, as well as a plethora of new start-ups, are investing in a range of technologies that offer near ubiquitous mobile access to the internet. Alongside these corporate efforts, there is also a bottom-up alternative driven by users who are buying inexpensive radio equipment to build wireless local area networks (WLANs) over unlicensed frequencies. The technology most commonly used is the IEEE 802.11 standard, also known as Wi-Fi. Despite (or perhaps because of) the lack of central planning, Wi-Fi is fast reaching "infrastructure" scale: almost unknown three years ago, about 26.5 million Wi-Fi capable devices were sold in 2002 alone, and have been deployed by a multitude of individuals and organizations, from large companies to community groups.

Today this nascent technology is primarily used to extend the reach of broadband internet connections for a few dozen feet within the home or office. Increasingly, it is being deployed outdoors to offer connectivity to business travellers and wireless enthusiasts in airports, hotels, cafes and parks. The result is a patchwork quilt of Wi-Fi networks that resemble cordless archipelagos within a vast ocean of wired infrastructure. However, as the density of these networks increases, it is possible to imagine a future in which wireless devices communicate with each other, largely bypassing the existing cabled infrastructure for traffic exchange. The ultimate vision is that of a wireless grid in which users will self-organize to manage their own local networks and peer with others to create a distributed system capable of performing the task we associate with broadband internet services (SAWHNEY, 2003; MCKNIGHT, ANIUS & UZUNER, 2003).

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This paper raises two related questions about such vision. The first is whether these grassroots efforts to build a wireless grid represent a significant alternative to the traditional, centrally-driven process by which most large-scale communication networks have been built. It is true that cooperative efforts have proved successful in building roads, canals and telephone exchanges in the past, particularly in rural areas. Historically, decentralized network segments based on new technologies often served initially to extend previous generation infrastructure and then eventually expanded to become the dominant infrastructure. Could the uncoordinated efforts of communities and individuals to extend the reach of their wired connections be assembled into an integrated wireless grid, eventually replacing the dominant wired infrastructure? Or will Wi-Fi continue to evolve within the established trajectory, namely, as a convenient complement to broadband access that provides mobility and reduces the cost of cabling homes and offices?

Our second question relates to the technological and policy challenges for building the wireless grid. The existing policy and commercial arrangements that govern the wired internet will be clearly inadequate to enable the scaling of dynamic, peer-to-peer Wi-Fi networks into an integrated public system. These arrangements were designed for a network of networks operated by large organizations based on reliable fixed connections and a relatively stable physical architecture. The wireless grid, by contrast, will be a dynamic, ad-hoc network environment populated by small mobile devices belonging to multiple individual and organizations and talking to each other via volatile wireless links. New arrangements will be needed for securing privacy, sharing resources, managing traffic and ensuring a certain quality of service, among other challenges. How may such arrangements emerge? In the past, these problems have been internalized within large organizations that centralized network management and the coordination of resources. Alternatively, aggregators often emerged to assemble local networks into virtual large-scale systems. Could wireless internet evolve in the direction of increasingly centralized operation and management, or would new cooperation and aggregation mechanisms enable a truly decentralized wireless grid?

In the first part of this paper we outline our theoretical perspective, which draws on three related bodies of literature: the social constructivist history of large technical systems, institutional economics, and the political economy of communication networks. We then review the key stages in the development of Wi-Fi and the configuration of the existing cordless archipelagos. Next we examine possible scenarios in the future trajectory of Wi-Fi networks and discuss the key technological and policy challenges for the building the wireless grid, drawing on the evidence of the past development of large-scale communication networks such as the railroads, telephone, and broadcast networks. While our study focuses on the US case, similar past trajectories and future challenges are to be found elsewhere. We conclude by discussing the implications of national and local policy choices for the future evolution of wireless networking infrastructure.

■ Wi-Fi in perspective: how, why and for whom large networks are built?

Our approach to Wi-Fi stems from the confluence of three bodies of research. Firstly, we draw on the social constructivist approach to technology and the development of so-called "large technical systems" (JOERGES, 1988). This line of work is dedicated to the study of the social dynamics shaping the development of diverse network technologies (the railroads, the telegraph, the telephone, etc.) and finding historical patterns of old technology displacement and new infrastructure growth. The underlying assumption is that an understanding of the evolution of more mature technologies offers valuable insights into the future of emerging ones. Given that new technologies evolve within an environment already populated by old ones, it is critical to understand the historical patterns of accommodation and displacement between them.

A classic model of infrastructure evolution is presented by HUGHES (1983). Drawing upon his study of the transformation of the American electricity system from local to regional to national grids, Hughes distinguishes three main phases in the growth of large technical systems. The first phase is that of *invention and innovation*, when maverick inventors attempt to create and perfect the technology. In this phase, adoption is limited to isolated experiments aimed at testing the possibilities offered by the new system. The second phase is that of *transfer*, whereby the system is piloted in various geographical, economic and legal environments. In this phase, users often manipulate the new technology to adapt it to local conditions, and connections begin to be made between previously isolated experiments. The third and final phase is that of *growth and consolidation*, characterized by the scaling up of the system through the interconnection of local/regional systems into an integrated national grid. In this phase, government and large corporations replace users as key players as the need for financing and coordination escalates.

An interesting adaptation of this framework to the telecom sector is offered by SAWHNEY (1992). The author suggests that network technologies tend to follow a so-called Infrastructure Development Model (IDM) comprising of eight stages: (1) sprouting of infrastructure islands (e.g. the early point-to-point telephone connections); (2) development as a feeder (e.g. early telephones as local feeders to the telegraph network); (3) encouragement by the old system (e.g. Western Union and National Bell agree to carve the market into long-distance and local services); (4) system formation (e.g. isolated telephone operations are connected into a national grid); (5) competition with the old system; (6) subordination of the old system (e.g. the telegraph is relegated to a secondary role); (7) reversed feeder relationship (now it is the telegraph that complements the telephone); and (8) a new technology emerges and the cycle restarts.

This framework is useful to conceptualize how new technologies such as Wi-Fi progress from invention to large-scale adoption (or failure), how they interact with existing systems and how different market players (users, incumbent firms, would-be entrants, governments) shape its trajectory. There are several consistent findings in this literature that relate to Wi-Fi. One of them suggests that networks tend to grow in a decentralized and uncoordinated manner, rather than being guided by a grand plan. This is particularly true in the U.S. context, where the fragmentation of political authority and a normative orientation in favor of private entrepreneurship discourages centralized network planning by government authorities [1]. Another relevant finding is that new technologies are often conceived as appendices for existing systems, only to become dominant later on. Much as the telephone was once considered a feeder for the telegraph, or radio as an extension of telegraphy into the sea, Wi-Fi was originally conceived as a cordless extension of wired internet – essentially as a substitute for cable on closed LANs within homes or office buildings [2]. It was only when users and small entrepreneurs started taking Wi-Fi beyond these boundaries that alternative possibilities were revealed. The key question today is whether

[1] In Europe, by contrast, centralized network planning has historically been more acceptable and politically feasible (MAYNTZ & SCHNEIDER, 1988).

[2] As Apple CEO Steve Jobs explained when the company introduced *Airport*, the first consumer product based on the IEEE 802.11 specifications: "It's a liberating experience to surf the internet while freely moving about your home or classroom" (Remarks at the Macworld trade show in New York City, July 21st, 1999).

Wi-Fi will actually evolve beyond this appendix role into a full-fledged system.

Another consistent pattern in the history of large-scale technical systems is that they rarely evolve according to their original design, and that users play an important role during the formative years in shaping the system and discovering new applications (NYE, 1990; FISCHER, 1992). The amateur radio operator of the early 20th century is perhaps the best example. As DOUGLAS (1987) reveals, these users experimented at length with radio equipment and modified it to extend its range and performance, much as Wi-Fi users are today tinkering with homemade antennas and creating software tools to extend the reach and improve the functionality of Wi-Fi networks [3]. At the time, the mushrooming of amateur radio operators and the way these users were adapting and improving the technology, took the dominant industry players (notably RCA) completely by surprise. As discussed later, in the case of Wi-Fi many incumbent operators have also been surprised by its rapid growth and have so far struggled with a technology that is as much driven by corporate strategies as by the trial and error of users. Early adopters have, in fact, already made several important contributions to Wi-Fi such as routing protocols for mesh networks, authentication software (such as NoCat) and the real-life testing of signal propagation and interference problems. Through such learning by doing, many Wi-Fi users have accumulated greater expertise than incumbent firms.

A second relevant approach is the work of economic historians concerned with the evolution of technology and technical standards. This body of work studies the economic forces that shape the trajectory of new technologies and the dynamics of displacement. The concept of path dependency is of particular relevance to our case. The concept suggests that the long-term evolution of a technological system depends on the specific historical circumstances of its origins and emphasizes the importance of present-time small events in the future trajectory of the system as a whole. The classic example is the configuration of the typewriter keyboard (DAVID, 1985). The important insight is that the process of technological evolution – as well as many others that are based on durable arrangements such as sunk investments and complex political institutions – is what statisticians call non-ergodic: how it got there matters for where it is

3 It is amusing to note that the notorious Pringles can antenna used by many Wi-Fi enthusiasts has a precedent in radio, as amateur radio operators often used Quaker Oats containers to build radio tuners.

going in the future. To some extent, this approach questions the notion that new technologies will replace (or find accommodation with) old ones in a predictable pattern. Path dependency suggests that new technologies have multiple possible trajectories (including non-adoption, of course), though the accumulation of sunk investments steers evolution along one trajectory over time and thus forecloses others.

These concepts have interesting implications for both stability and change in the evolution of Wi-Fi. Firstly, they call attention to the significance of the choices made by policymakers, firms and early adopters in the initial stages of development. The non-ergodic character of technological change suggests that, in the present context, several trajectories are still possible for Wi-Fi, but that the range of opportunities will soon begin to close as the technology matures and investments continue to be made in equipment, R&D, training etc. Secondly, this framework is also useful to theorize the relation between Wi-Fi and competing technologies such as 3G mobile telephony. While these technologies still differ enough to be considered somewhat complementary today (Wi-Fi for short-range, high-speed access, 3G for roaming, low-speed access), it is possible to imagine a future scenario in which they compete head-to-head (Lehr and McKnight, 2003). The nature of such competition will be characterized by learning effects (ROSENBERG, 1982); network externalities (KATZ & SHAPIRO, 1985), lock-in effects (ARTHUR, 1989) and other dynamics associated with path dependency.

This approach also highlights the importance of so-called critical junctures. These are narrow windows in time, typically in the early adoption stages, when small events or choices made by key players have a disproportionate effect on the evolutionary path of the technology. Large technical systems are built sequentially by market players that continually adapt their strategies to the changing political, economic and technological environment. The process is nonetheless highly discontinuous, characterized by critical junctures in which seemingly random events channel the technology along a certain path, thus foreclosing other trajectories. Thomas Edison's personal decision in 1889 to abandon the fight against AC electrical systems (HUGHES, 1983), the Titanic tragedy in 1912, which led to considerable limitations on amateur radio operators (DOUGLAS, 1987), the unexpected opening of the NSFNET to commercial traffic in the late 1980s and other small, but significant events in the early days of these technologies represent turning points that would significantly shape their future evolution. As we shall argue in this paper, Wi-Fi is probably at a critical juncture today, much as electricity was in the 1890s and radio in the

1910s. The choices made by key players thus have the potential to send this fledging technology along starkly different evolutionary paths. We will later suggest what these choices are and what these likely paths may be.

Finally, our approach to Wi-Fi also draws on the political economy of communication networks (POOL, 1983; MANSELL, 1993; BENKLER, 1998). This vast literature attempts to conceptualize the evolution of communication networks as determined by political and market players which, under a given set of constraints such as government rules and resource constraints, make strategic choices about investments, cooperation and political action. One of the key constraining factors is the regulatory regime. Regulatory regimes are the historically specific configurations of ideas and institutions that structure the interaction between market players in any given industry (VOGEL, 1996). The ideas affect players' preferences and help define the agenda for government action. Institutions, on the other hand, are the rules of the game that define how technologies are used, by whom, and for what purposes.

Typically, regulatory regimes evolve much slower than technology. Therefore, new technologies generally evolve – at least initially – within the norms and constraints devised for the existing system, until a new political coalition is formed and succeeds in bringing about regime reforms. Examples of this phenomenon abound. It took decades to adapt U.S. telecom legislation to new transmission (e.g. microwave), switching (e.g. PBXs) and terminal equipment technologies that challenged the regulated monopoly regime (BROCK, 1981; HORWITZ, 1989). In broadcasting, the introduction of digital TV is currently taking place within the framework of the existing broadcast regime, thus favoring the continued dominance of high-power local stations (GALPERIN, 2004). The important insight is that new technologies, however innovative, do not emerge in an open legal environment; rather, they evolve within an institutional context that moulds and adapts them to established social and market practices.

Wi-Fi has so far developed within the corset of an existing legal regime that severely limits its possibilities. These include equipment power restrictions, a thin slice of radio frequencies for operation and restrictive interconnection agreements by incumbent broadband providers (JOHNSTON & SNIDER, 2003). It has similarly been constrained by the initial development around the notion that its main purpose was to extend the reach of existing broadband connections for a few extra feet. While this notion is increasingly being challenged by the efforts of new commercial operators, grassroots organizations and wireless enthusiasts, the entrenched rules of the game have, not surprisingly, proved quite resistant to change. While more frequencies have been gradually made available for Wi-Fi services, the existing rules still lock the technology into a development path of limited use. Nevertheless, as discussed later, an emerging coalition of users, equipment makers and public interest advocates have begun to challenge this regime, pressing for reforms that could change the technology's trajectory.

■ Where Wi-Fi is today

Wi-Fi has experienced extraordinary growth since 1993, when engineer Brett Stewart conceived the idea of creating *Wayport*, aimed at offering public space wireless internet access. Stewart was then working at AMD, after a licensing deal with Xircom for what became the original 802.11 MAC technology [4]. Wayport was founded in 1995, two years before the IEEE finalized the 802.11 standard in 1997. It would take two more years for the IEEE to adopt the 802.11b standard in 1999. That summer saw the mass-market introduction of Wi-Fi, with Apple's launch of its new iBook laptop, which included built-in wireless networking using Lucent's WaveLAN wireless technology, based on the 802.11b standard. The iBook came with a built-in antenna and an internal slot for a USD 99 'Airport' card. The USD 299 base station could support up to 10 computers. Apple thus offered the first operating system with built-in support for Wi-Fi, which suddenly became a relatively cheap, easy-to-install, mass-market networking alternative to wired Ethernet. The next mass-market boost for Wi-Fi came two years later, with Microsoft's October 2001 release of Windows XP, a new version of its operating system with built-in Wi-Fi support.

Since then, Wi-Fi access points and expansion cards have become available from countless other vendors and most laptops sold today come with built-in Wi-Fi. One analyst estimates that the worldwide population of Wi-Fi users has reached 42 million, 47% of which are in the U.S., while the number of public hotspots hovers around 71,000 [5]. In 2003, sales of Wi-Fi equipment reached USD 2.3 billion, an increase of 40% over the previous year, while sales of Wi-Fi access points for homes reached 22.7 million

4 See Wi-Fi timeline, at http://wifinetnews.com/archives/001315.html

5 MADDOX Kate, "Report predicts surge in WiFi use", *BtoB*, December 8th, 2003: http://www.btobonline.com/cgi-bin/article.pl?id=11989

units [6]. Intel's launch of a USD 300 million advertising campaign for its Centrino chipset in March 2003, which comes with built-in Wi-Fi and is now available inside many laptop models, undoubtedly contributed to Wi-Fi's success.

Among the many factors explaining this rapid growth, three are particularly noteworthy: Wi-Fi's technical performance (high-speed and low cost), industry-wide standardization and the use of unlicensed spectrum. Firstly, Wi-Fi connections can deliver Ethernet speeds (roughly 10Mb/s to 54Mb/s, depending on the specific standard), within a range of about 150 feet. This makes them an effective replacement for wired networks within homes or office clusters. Their price competes favorably with that of wired networks, especially since they cut out the expense and trouble of running wires. The large volume of Wi-Fi equipment now sold also means that prices are continuing to fall and U.S. customers can buy both base stations and Wi-Fi adapters for less than USD 50. Secondly, there is widespread industry support for the Wi-Fi standard, coordinated through the Wi-Fi Alliance, an industry organization including over 200 equipment makers worldwide. The Wi-Fi Alliance was formed in 1999 to certify interoperability of various wireless LAN products based on the IEEE 802.11 specification. Since the beginning of its certification program in 2000, the group has certified over 1000 products. As a result, consumers can expect Wi-Fi client devices and access points made by different vendors to interconnect relatively easily. The resulting ease-of-use has also played an important role in Wi-Fi's widespread adoption. A third key to the technology's success resides in the lack of regulatory overhead. Wi-Fi networks can generally be deployed without a license, unlike most other communication technologies using the radio spectrum. This freedom enabled a wide variety of players to build wireless networks, without any of the regulatory delays and expense traditionally associated with radio licenses.

These three factors combined have made it possible for Wi-Fi deployment to follow a number of different patterns, along three broad categories. We call these *Cordless Ethernet*, *Public Hotspots* and *Mesh*. Each corresponds to distinct economic and usage justifications, fitting different business models. Each creates distinct potential challenges for existing networks and opens up different avenues for the future of Wi-Fi.

[6] Figures from Synergy Research and In-Stat/MDR, cited in *Business Week*, Special Report: Wi-Fi's Growing Pains, Feb 18th, 2004:
http://www.businessweek.com/technology/tc_special/tc_04wifi.htm

While they follow different logics, these three categories have important synergies: each increases the density of Wi-Fi devices, thus making the other more appealing as a result of network externalities.

Cordless Ethernet, the deployment of private Wi-Fi networks in homes and offices, represents the initial, most obvious and most widespread use of Wi-Fi. Here, the goal is simply the removal of the Ethernet or phone cable linking a computer to the network. In this incarnation, Wi-Fi is similar to cordless phones: it lets the laptop user wander away from the desk, dispensing with tangled cords. While this obviously saves wiring expenses, it also comes with significant mobility benefits (or rather, move-ability – this isn't so much about computing while moving, but computing in different places). Furthermore, laptop users equipped with Wi-Fi at home can also connect simply when at their friends houses, or at the office, or in any public place that has Wi-Fi. In fact, having Wi-Fi in one place often prompts the need to install it in the other. Furthermore, because access points typically include routers, they readily serve as the hub of home networks that can link several computers to each other and to other devices such as printers or media servers, sound systems and televisions. As a result, Wi-Fi could serve to interconnect a variety of appliances in homes, expanding beyond simple cordless internet access for laptop computers.

There is a similar logic promoting the deployment of these cordless Ethernet networks within the home and on corporate or university campuses. The latter are obviously more complex, requiring the deployment of many access points and tighter management, particularly in terms of authentication and security. Both, however, are contained within private spaces and provide access primarily to well-known and regular users: household members in one case, employees and students in the other. These private networks account for the overwhelming bulk of Wi-Fi's sales to-date. Yet, for all Wi-Fi's success, the market is still far from saturation and the resulting patchwork of private Wi-Fi networks is still sparse [7].

Public Hotspots represent another deployment logic. These are networks established in locations frequented by the public, offering wireless connectivity as a service to passing users. In the past few years, public hotspots have appeared in cafes, hotel lobbies, airport lounges, fast-food restaurants, public parks and libraries, among others.In such cases the idea

[7] The Metagroup estimates that Wi-Fi is only available in about 10% of U.S. companies (in *Business Week*, Special Report, op. cit.).

is not to 'cut the cord', since there was seldom a cord to begin with – the provision of internet connectivity in public places usually being a new service. Three categories of players have established such hotspot networks - commercial operators, grassroots cooperatives and public agencies - each with its own motivation.

Commercial hotspot operators offer wireless connectivity for-profit, and most sell subscriptions to their service. A related and comparatively small category of commercial providers to-date offer free wireless access to encourage consumers to buy another product – a cappuccino, or a night's stay in a hotel. The first wave of such companies were start-ups that emerged in the late 1990s and early 2000s, companies like Wayport or Surf'n Sip. The central challenge they faced was to convince enough individual location owners to install one of their wireless access points in order to lure subscribers to the service. Wayport, for example, has been able to enlist several hotel chains and airports, and now offers wireless access in 700 U.S. hotels and 12 airports. It is estimated that in early 2004 there were almost 100 commercial hotspot operators in the U.S. alone and 250 worldwide [8]. Estimates of the total number of hotspots they cumulatively operate vary, but are generally in the range of 10,000 to 20,000 hotspots in the U.S. [9]. Even assuming that the higher numbers are correct, this still represents a tiny portion of the areas where customers may want to expect reliable connectivity.

Therefore the appeal of individual networks necessarily remains limited. They are primarily aimed at business travellers who stick to the same routes and hotel chains. A second wave of commercial providers has emerged to patch together disparate networks: consolidators that re-sell wireless access from several physical network operators and offer simplified access and centralized billing through a single account. Companies in this category include iPass, Boingo, GRIC, NetNearU. Each consolidator federates distinct sub-sets of the commercial Wi-Fi service provider population, offering access points ranging in the thousands (for example, iPass claims over

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[8] Definitive numbers are difficult to obtain, but a good indication of the order of magnitude is given by Wi-Fi hotspot lists such as www.hotspot-locations.com (which lists 72 commercial hotspot providers in the US, 242 worldwide as of February 25th, 2004).

[9] BW cites estimates of 20,000 to 25,000 commercial hotspots in the U.S., while the www.hotspot-locations.com directory counts 3,580, and www.wifinder.com lists 5,177 as of February 25th, 2004.

2,500, and Boingo claims 2,400 live hotspots [10]). As they each try to reach critical mass, their current competitive strategies exclude reciprocal roaming agreements. As a result, unless users establish multiple accounts, they cannot expect to obtain access to the full 10-20,000 hotspots. This may be one reason why subscription and use of such for-fee hotspot access remains relatively limited to date. According to a recent survey by Jupiter, while 70% of consumers who use the Web were aware of public Wi-Fi service at the end of 2003, only 15% of those surveyed had ever used Wi-Fi at all (that includes home networks), only 6% had ever used a public hotspot (free or paid access) and only 1% had ever paid to use a hotspot [11].

The situation is poised to change as major telecom industry players enter the fray. Indeed, a third wave of commercial offering is now emerging, reflecting the entry of incumbent telecom providers on the Wi-Fi scene. The first was T-Mobile, the mobile communications subsidiary of Deutsche Telekom, which, as part of its 2001 purchase of cellular carrier Voicestream, acquired a Wi-Fi network serving 1,200 Starbucks locations that had initially been established by MobileStar. It has since expanded to 2,200 locations and is bringing Wi-Fi to 410 Borders bookstores, airport lounges and selected Kinko's copy stores, for a total of 4,226 hotspot locations in the U.S. [12]. T-Mobile had the only carrier-owned and operated Wi-Fi network as of 2003 and continues to lead the pack, with Wayport currently trailing a long way behind in second place. In a move to expand access for its customers, T-Mobile signed a roaming agreement with iPass [13]. Other telecom carriers are now joining the fray, although with various degrees of enthusiasm. SBC recently announced plans to deploy 20,000 hotspots in 6,000 venues over the next three years [14]. Sprint PCS's has adopted a different approach by announcing plans to roll out Wi-Fi service initially through roaming agreements with Wayport and Airpath locations, which it plans to complement later by building 1,300 hot spots of its own [15]. Verizon, on the

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[10] See company sites, at: http://www.ipass.com/services/services_wifi.html and: http://boingo.com, visited Feb 29th, 2004

[11] Wired, "Wi-Fi Grows, but Profits Don't", Dec. 16th, 2003: http://www.wired.com/news/wireless/0,1382,61618,00.html?tw=wn_tophead_2

[12] T-Mobile web site, at: http://locations.hotspot.t-mobile.com/, visited Feb. 29th, 2004.

[13] Eric GRIFFITH, "Roaming Comes to Starbucks", *Wi-Fi Planet*, December 16th, 2003: http://www.wi-fiplanet.com/news/article.php/3289701

[14] August 6th, 2003 company press release: http://www.sbc.com/gen/pressroom?pid=4800&cdvn=news&newsarticleid=20609

[15] Glenn FLEISHMAN, "Technology Briefing Telecommunications: Sprint PCS To Offer Wi-Fi Service", *New York Times*, July 22nd, 2003, Section C , Page 2.

other hand, started with a limited deployment of about 150 hotspots in Manhattan, offering free access to its DSL subscribers, but the company has now postponed plans to expand its own network [16]. Instead, it currently resells the Wayport service [17]. Overall, the varying degrees of support for Wi-Fi from telecom carriers reflects the still-uncertain business models for public Wi-Fi, as well as tension between their Wi-Fi and 3G strategies.

In addition to these commercial networks, a number of Wi-Fi networks have been deployed by non-commercial entities. The first, and currently the largest category, comprises of wireless community networks. These grassroots clusters of linked, neighborhood or citywide networks aim to provide wireless access to members of the cooperative groups who build them, to their friends and to the general public. Community wireless networks are mostly made up of their members' access points, intentionally left open and made available to anyone within range. Some of them, such as the Bay Area Wireless User Group (BAWUG), also operate long-range connections (2 miles and more) linking clusters of access points. Wireless cooperatives pursue a wide variety of goals: some simply provide a forum for their members to exchange information about wireless technologies, while others are actively engaged in building wireless networks to experiment with the possibilities of Wi-Fi technologies. There are a few dozen community networks in the U.S., each typically ranging from a few to a few dozen nodes [18]. There are also many individuals (or organizations) who volunteer to open their own access points to the public, without necessarily belonging to an organized cooperative, and advertise this fact on directories such as nodeDB.com [19].

Despite much publicity, the assemblage of these community networks remains relatively insignificant in terms of the network infrastructure it provides. Furthermore, it is unclear how many people are effectively taking advantage of this free Wi-Fi access. In cases where the community organizations track usage of these open networks, there seem to be relatively few takers [20]. Anecdotal evidence indicates that the main users of

16 Kevin FITCHARD, "Verizon's Wi-Fi Experiment Yields Results", *Telephony*, Jan 12th, 2004: http://telephonyonline.com/ar/telecom_verizons_wifi_experiment/index.htm

17 Eric GRIFFITH, "Verizon Wireless Roams with Wayport", *Wi-Fi Planet*, August 5th, 2003: http://www.wi-fiplanet.com/news/article.php/2244641

18 There are 29 such networks listed in www.hotspot-locations.com.

19 As of February 25th, 2004, nodeDB.com lists 1,128 such nodes in the U.S.

20 See for example the usage statistics of Seattle-wireless at: http://stats.seattlewireless.net.

these community networks are the community members themselves (SANDVIG, 2003). Nevertheless, these networks play an important role in the emerging ecology of Wi-Fi. If nothing else, they represent a clear disincentive for investments in commercial hotspot operations. Verizon cites the availability of free wireless access in several areas of Manhattan as the reason why it decided to offer free Wi-Fi access to its existing DSL customers. One can also expect these not-for-profit networks to develop trajectories differing from those of commercial networks. The experimental work undertaken by BAWUG (long-range Wi-Fi connections) or by the Champaign-Urbana Community Wireless Network (mesh routing) are examples of these possibilities.

A second and more recent category of non-commercial networks are municipal Wi-Fi networks, deployed by city governments largely as an economic development strategy. By providing free downtown Wi-Fi access, some cities hope to help attract businesses to these areas, or to boost customer traffic. They also seek to lure conference organizers to their convention centers by making it easy for conference-goers to stay connected. This was, for example, the explicit goal behind the launch of free Wi-Fi access in its downtown, airport and convention center [21] by the city of Long Beach in California. However, not all municipalities intend to provide free Wi-Fi access. In Cerritos, California, the plan is to deploy city-wide wireless access in partnership with wireless ISP Aiirmesh, primarily to provide wireless access for municipal government buildings, mobile city workers, security and emergency services. Aiirmesh will then sell Wi-Fi access to Cerritos residents, most of whom cannot get DSL or cable modem access [22]. When it completes its deployment later this year, Aiirmesh's Cerritos network will cover 8.6 contiguous square miles, making this the world's largest Wi-Fi zone. Similar projects are now turning up in a number of U.S. cities, including Lafayette, LA, Grand Haven, MI, Charleston, NC and others [23]. In pursuing these deployments, municipal governments have a considerable advantage over commercial entities or community groups: they control prime antenna locations in the form of light posts and traffic signs, all of which have built-in electrical supply that can serve to power access

21 Interviews with Chris Dalton, City of Long Beach Economic Development Office, February 6th, 2004. See also John MARKOFF, "More Cities Set Up Wireless Networks", *New York Times*, January 6th, 2003.

22 Broadband-deprived Cerritos turns to WiFi, San Jose Mercury News, Dec. 11th, 2003.

23 For descriptions of these municipal wireless projects in the U.S. and elsewhere see: http://www.muniwireless.com.

points. They also have a direct need to provide mobile connectivity for their many city employees. Thus, municipal Wi-Fi deployments start with a significant economic advantage: they have at least one large, reliable, paying city government customer, which can often justify building the network in the first place, before adding on residential or business customers.

A number of these municipal networks use an architecture known as *Mesh* networks: rather than connecting each Wi-Fi base station to the wired network, as in the case of residential access points or commercial hotspots, devices relay traffic to one-another, with only a few of them hard-wired to the internet. They are programmed to detect nearby devices and spontaneously adjust routing when new devices are added, or to find ways around devices that fail. When Wi-Fi devices are located on light posts for example, this architecture is much more cost-effective than bringing a broadband connection to each light post. This is the solution adopted in cities like Cerritos [24] and San Mateo, where a city-wide Wi-Fi mesh network serves the Police Department [25].

In the future, mesh networks could spontaneously emerge when enough Wi-Fi devices are present within an area. Indeed, there is no fundamental difference between Wi-Fi access points and clients, so all Wi-Fi devices can be programmed to detect other devices within range and create ad-hoc connections. Traffic could then be routed through a series of short hops, bouncing from one device to the next until it reaches a backhaul link. Of course, this would only work if there are enough Wi-Fi devices in an area, but this is becoming increasingly viable as Wi-Fi prices fall and as Wi-Fi gets built into many devices other than laptops such as cell-phones and PDAs. Consider the prediction that by 2008, 28 million cars will come equipped with local networking devices [26]. These would not only serve to connect various systems within the vehicle, but to support communications with outside systems, for applications ranging from telephony to safety and cashless payment systems. Ultimately, since cars are typically always within less than

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24 Dan O'SHEA, "The Future of Wi-Fi is One Big Mesh", *Wireless Review*, Jan 1st, 2004: http://wirelessreview.com/ar/wireless_future_wifi_one/index.htm

25 "Wi-Fi Lets Computers, Cops Roam Free", *San Mateo County Times*, September 18th, 2003.

26 ABI Research, 2003, *Automotive Wireless Networks Opportunities for Wi-Fi, Bluetooth, RFID, Satellite and Other Emerging Wireless Technologies* : http://www.abiresearch.com/reports/AWN.html

a hundred feet from one another (and have a built-in power supply), they may provide a future basis for mobile mesh networks. Of course, many technical issues still need to be addressed before such networks become practical, including the development of adaptive routing software that can keep up with intermittent mobile nodes (AGARWAL, NORMAN, AND GUPTA, 2004). However, the rapidly growing number of Wi-Fi devices present in the environment creates the potential for such wireless grids to emerge, bridging the gaps between the distant islands of today's cordless archipelagos.

■ Will a thousand Wi-Fi flowers ever blossom? Scale-up challenges for Wi-Fi

For many scholars and industry analysts, Wi-Fi represents a significant challenge to existing internet market conditions, particularly in the last-mile segment (e.g. WERBACH, 2002; JOHNSTON & SNIDER, 2003; SAWHNEY, 2003). The idea of a network built from the bottom-up, " by the people, for the people" is a persuasive vision that resonates with what BAR, RICHARDS & SANDVIG (2002) have called the *Jeffersonian syndrome* that has permeated social thinking about the internet from its origins. Yet the transition from existing cordless Ethernet archipelagos to an integrated wireless grid that rivals existing wired alternatives will not be easy to accomplish. It will require transforming what today is a patchwork quilt of mostly private – though often inadvertently unsecured – networks extending only a few feet beyond their wireline "stems" into a public system that would allow seamless relay across large areas. This would demand substantial investments to ensure proper coverage (as noted, the installed base of access points is clearly inadequate). More importantly, it would also require a complex system for the management of traffic, the sharing of resources and the use of standardized protocols, among other challenges. Historical evidence points to major challenges in three major areas: standards, interconnection arrangements and regulation.

Standards

Technical compatibility has traditionally been a major challenge for system integration and growth. From railroad gauges of different sizes to power systems of different cycles, the early history of network technologies has often been characterized by the coexistence of different standards that prevented seamless integration between local systems (HUGHES, 1983;

LIPARTITO, 1989). In our case, Wi-Fi also emerged amidst competition from alternative standards for wireless local area networks (WLANs), notably HomeRF and HiperLAN (see table 1). Interestingly, because all three standards emerged from the computer rather than the telecom industry, the standardization process was largely led by the private sector, organized around industry consortia such as the HomeRF Working Group and semi-public organizations such as the IEEE. Unlike the contentious case of standards for 3G mobile telephony, the role of governments and multilateral organizations such as the ITU has been minimal, limited only to general coordination in the allocation of unlicensed frequency bands [27].

Table 1: Standards Competition in WLANs

Standard	*Organization*	*Year Approved*	*Data Rate*	*Frequency*
Wi-Fi (802.11)	IEEE	1997 (802.11) 1999 (802.11b) 1999 (802.11a) 2003 (802.11g)	2Mbit/s 11Mbit/s 54Mbit/s 54Mbit/s	2.4GHz or IR 2.4GHz 5GHz 2.4GHz
HomeRF	HomeRF Working Group	1999	1.6Mbit/s	2.4GHz
HiperLAN	ETSI	1996 (HiperLAN1) 2000 (HiperLAN2)	24Mbit/s 54Mbit/s	5GHz 5GHz

While standardization is currently relatively unproblematic for the scaling-up of Wi-Fi, as the industry matures and creates higher requirements in terms of capacity, security, reliability and coverage, new coordination challenges will certainly arise. For example, several competing standards have emerged for extending signal coverage to wider areas, including the European HiperMAN and the IEEE 802.16 (WiMAX) [28]. The IEEE is also continuing to work on enhanced Wi-Fi standards that will allow quality of service features that are critical for advanced application such as VoIP and video streaming. In a sense, standardization problems have so far been minimal because of the very fact that the Wi-Fi networks deployed at this early stage are quite rudimentary, providing little in terms of security, reliability and quality of service. As the complexity of the technology and the range of services offered through Wi-Fi increases, so will the stakes for equipment vendors and network builders. It is possible that the standard

[27] The only possible exception is HiperLan, a standard developed by the ETSI (European Telecommunications Standards Institute) as a European alternative to Wi-Fi.

[28] The WiMAX standard was released by the IEEE in April 2002 and works on frequency bands from 2GHz (802.16a) to 66GHz, with data rates up to 75Mbit/s and a range of about 30 miles. HiperMAN operates on frequencies under 11GHz with data rates up to 25Mbit/s and a range of about 15 miles.

coordination mechanisms that drove the initial growth of Wi-Fi will not suffice to accommodate the range of interests created by future system expansion.

Interconnection and traffic arrangements

Skeptics contend that the integration of Wi-Fi networks will be frustrated by the need to establish arrangements for data relay, traffic management, billing etc. among thousands of separate local networks in a dynamic ad-hoc environment. Yet they forget that large integrated systems are often little more than arrangements between scores of separate entities – in other words, virtual systems. At the height of the railroad expansion in the 1920s there were over a thousand railroad companies in the U.S. Yet uniform operating, billing and accounting procedures meant that both people and goods could be moved around the nation on a single car, often coordinated by system aggregators – the so-called express and fast-freight companies (CHANDLER, 1977). In the case of the telephone, it was the Kingsbury agreement of 1913 that transformed the sector from an industry divided between Bell and thousands of local independents (which mostly provided only local service) into an integrated telecommunications system spanning the entire nation (BROCK, 1981). In 1914, the American Radio Relay League (ARRL) was created to coordinate the relaying of messages between thousands of radio amateurs, thus forming the first coast-to-coast communications network (DOUGLAS, 1987) [29]. While these industries would later undergo significant consolidation as a result of a variety of economic and political forces, the point is that system integration has often been achieved through the federation of fragmented networks.

Historical evidence suggests that the challenges for building a wireless grid will be organizational, rather than technological. Will it be possible to arrange cooperative mechanisms for the integration of local Wi-Fi networks? What kinds of arrangements will emerge to govern such a system? Consolidators will obviously be critical and they have already appeared under different models. For the most part however, they simply provide unified billing and network authentication services on the basis of roaming agreements. More intriguing attempts are coming from grassroots efforts to connect local networks to each other in a mesh architecture, such as Consume's Pico Peering Agreement, which outlines the rights and obligations of peering parties [30]. While simple contracts might prove useful

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[29] AT&T inaugurated its transcontinental service shortly after in 1915.

[30] Available at: www.picopeer.net.

for peering among like-minded individuals or small-scale community networks, new arrangements will be needed to integrate Wi-Fi networks of different sizes and complexity, as well as users and organizations with different needs and expertise (SANDVIG, 2003).

On the other hand, there are a number of factors that could facilitate system integration in the case of Wi-Fi networks. The first is the architecture of the internet itself. The internet is the ultimate example of a decentralized system that integrates an ever-increasing number of constituent networks managed separately and built under different technical specifications. Another advantage is that the wireless grid can grow without large capital outlays. As noted, incumbent carriers often downplay the threat of Wi-Fi on the basis that it would be uneconomical to replicate the coverage of existing broadband systems. Yet because infrastructure investments are made by users themselves (either individually or organized locally), and because wireless technology dispenses with the labour costs typically associated with building physical networks, system growth does not necessarily require centralized funding by large companies or government agencies. It is thus possible for the system to grow organically, based on small-scale investments by users in inexpensive radio equipment.

Regulation and policy

The existing legal framework severely restricts the future trajectory of Wi-Fi, confining the technology to the cordless Ethernet model. This partly reflects the fact that Wi-Fi networks have flourished from a modest experiment in spectrum management initiated by the FCC in 1985, when it decided to allow radio equipment to operate on the so-called Industrial, Scientific and Medical (ISM) bands on a license-exempt basis. While the current supply of unlicensed bands has facilitated the mushrooming of Wi-Fi islands, it is clearly inadequate for scaling-up the system into a wireless grid. In effect, at its current growth rate, the present regime will soon prove inadequate, even for the cordless Ethernet model. The situation today is comparable to that of FM radio in the 1930s, cable TV in the 1960s or computer data networks in the 1970s: as the new technology evolves, it begins to disrupt established industry arrangements, challenging economic privileges as well as the existing legal apparatus (HORWITZ, 1989). Yet, institutional inertia and the pressure wielded by incumbents typically delay reforms.

Several regulatory battles currently being waged have the potential to define the future of Wi-Fi for years to come. Incumbent broadband carriers, many of whom have sunk large sums into competing technologies, are clearly uneasy about the success of Wi-Fi. Interestingly, some have engaged in some of the same preemptive strategies as their historical counterparts, notably that of refusing interconnection by writing restrictive service agreements for their broadband customers that penalize bandwidth sharing. This is precisely what AT&T once attempted – ultimately unsuccessfully – by preventing customers from attaching "foreign" equipment to its network [31]. Another important battlefront is spectrum management reform. For Wi-Fi to scale-up, more unlicensed spectrum will need to be made available (preferably below 3GHz), and power levels between licensed and unlicensed devices will need to be rebalanced in favour of low-power users. These reforms, however, will not be easy to implement.

The current reform efforts are reminiscent of the formative period of broadcast radio, when an eclectic political coalition sought to maintain a balance between large radio networks and small, non-commercial local operators (McCHESNEY, 1993). At the time, the reform coalition lacked major industry allies, given the vertical ties between commercial broadcasters and equipment manufacturers. Today, some of the information technology industry heavyweights such as Intel and Cisco have thrown their weight behind the expansion of unlicensed bands. This is important because incumbents have often used their control over equipment supply to cut off supplies to fledging systems in the past (the classic example being the Bell's contract that prevented Western Electric from selling to independents). Another factor favorable to reformers is the growing consensus among academics and policy elites that the existing spectrum regime requires substantial revision. As DERTHICK & QUIRK (1985) have shown in the case of telecommunications, changes to the accepted consensus within academia and regulatory elites are often a prologue to wide-scale industry reforms.

31 See In the Matter of Use of the Carterfone Device in Message Toll Telephone Service, FCC 2d 420 (1968).

■ Conclusion

The deployment of wireless internet infrastructure stands at an important juncture. With Wi-Fi, the unlicensed spectrum experiment has to-date succeeded beyond any regulator's dreams. The immediate result and most significant aspect of this success is the spectacular diffusion of Wi-Fi devices. With tens of millions of units sold in just a few years, we have now reached a critical mass of Wi-Fi radios in the environment. All of the signs suggest that this trend will continue in the coming few years: Wi-Fi devices are becoming very cheap and embedded in a wide array of consumer devices, from cell-phones to televisions, appliances and cars. Once density reaches a certain threshold, the existing deployment model – referred to here as cordless Ethernet – will need to be revisited, for the system will reach capacity as too many devices compete for scarce resources such as frequencies and backhaul links.

So far however, the wireless grid remains in the embryonic stages of its development. In Sawhney's typology, we note the sprouting of wireless islands and feeders in homes, campus networks and some community networks (stages 1 & 2). Indeed, all of the U.S. public hotspots combined would cover an area approaching the size of a small town like Cerritos, CA. We also observe some timid encouragement from incumbent infrastructure providers (stage 3), particularly from broadband carriers who see home Wi-Fi networks as a good way to promote cable or DSL services. In this sense, Wi-Fi provides much added convenience and encourages consumers to use more of the old wired networks through their cordless Ethernet, but does not fundamentally challenge the established network, nor does it introduce a new infrastructure paradigm that could unsettle the existing industry arrangement.

The central question is whether the large and fast growing number of Wi-Fi devices present in the environment can be organized differently to create a fundamental challenge to existing networks. We believe that the market is fast approaching a point where this might happen, because of two related developments: firstly, the bottom-up dynamics associated with Wi-Fi deployment, whereby multiple network players are independently pursuing the deployment of wireless infrastructure. As households, commercial hotspots providers, grassroots community networks, corporations and universities build their own cordless Ethernet archipelagos, the incentives will increase to share resources, reach roaming or peering agreements and devise new cooperative mechanisms to manage this decentralized wireless infrastructure as a public grid. The possibility to do just that is tied to the second development, the recent emergence of working mesh protocols that can knit together neighboring Wi-Fi devices into a single network. Mesh technology to-date has been worked out for centrally deployed network devices and much technical work remains to be done for spontaneous mesh networks to become a reality. Nonetheless, as with other technologies, experimentation by users and corporate R&D will eventually result in a workable solution.

A greater challenge, however, will be to create new organizational arrangements to manage the wireless grid and reform the existing legal regime, which confines Wi-Fi to its present role as an appendix to wired networks. This is not a purely technical problem, but an evolutionary process whereby various stakeholders, from users and wireless start-ups to equipment manufacturers and incumbent carriers, will seek to shape the technology in different ways. While some battles will be market-driven, other will take place in the courtrooms, in regulatory agencies and within standards-setting organizations. DAVID (2002) aptly described the internet as the fortuitous legacy of a modest R&D program, which was later adapted and modified by various economic and political players to perform functions never intended by its original creators. Wi-Fi has similarly emerged from a rather modest experiment in spectrum management that has unexpectedly resulted in the proliferation of local wireless networks in homes, offices and public spaces. Having outgrown its original purpose, it is now at a critical juncture, for it embodies technical possibilities of a potentially disruptive character, yet it is in the decidedly social realm of economic and political interactions that its future is being cast.

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