

Towards a Wi-Fi ecosystem: Technology integration and emerging service models[☆]

Vinoth Gunasekaran, Fotios C. Harmantzis*

*Wesley J. Howe School of Technology Management, Telecommunications Management, Stevens Institute of Technology,
Castle Point on Hudson, Hoboken, NJ 07030, USA*

Abstract

This paper outlines emerging business models of heterogeneous wireless networks that are mainly Wi-Fi centric. Wi-Fi networks can be integrated with the Internet and cellular infrastructures to offer innovative services (data and voice) to individuals and businesses. In the metro area network or a “hot city” type of coverage, an integration of WiMAX and Wi-Fi technologies will provide the most cost-effective solution of backhaul and access, for both voice and data services. In the cellular arena, as mobile operators look for new ways to connect, Wi-Fi can easily be integrated with the existing mobile data networks (2.5 G/3 G). An integrated offering that combines the mobility of cellular and the speed of Wi-Fi is an ideal mix for mobile broadband subscribers. This article also analyzes how Wi-Fi technology is being complementary to other wireless technologies, leading to an expansion of an organized Wi-Fi ecosystem. From an integration standpoint, this article shows the importance of Wi-Fi for cellular operators and also shows how Wi-Fi is crucial for WiMAX technology to evolve, till the mobile version of WiMAX becomes a reality. Finally, the paper describes why regulators and policy makers should seek suitable strategies to promote or encourage Wi-Fi as an alternative broadband access technology.

© 2008 Elsevier Ltd. All rights reserved.

Keywords: Wi-Fi; WiMAX; Cellular; Bluetooth; VoWi-Fi; Strategy; Integration; Service models

1. Introduction and motivation

Wireless technologies are becoming increasingly integrated into other wired and wireless networks. As shown by [Lehr and Mcknight \(2003\)](#), the wireless future will be a mix of heterogeneous wireless access technologies. There are new advancements and innovative technologies conforming to industry standards. However, it is necessary to answer how one technology interoperates with others on a complementary basis. In a heterogeneous wireless network, it is assumed that interoperability exists between the network devices and the networks they are connecting to. International standard bodies and vendor groups have formed to set up standards for how one technology interoperates with another in an integrated wireless environment.

[☆]This paper is based upon contributions of the respective authors to the following conferences during 2005: 9th IFIP/IEEE international symposium on integrated network management (IM) in Nice, France; 61st IEEE semi-annual vehicular technology conference (VTC) in Sweden, Stockholm; and 6th world wireless conference (WWC) in SF Bay Area, USA.

*Corresponding author. Tel.: +1 201 216 8279; fax: +1 201 216 5385.

E-mail addresses: vgunasek@stevens.edu (V. Gunasekaran), fharmant@stevens.edu (F.C. Harmantzis).

Broadly speaking, there are only two types of Wi-Fi deployment as shown by Camponova, Heitmann, Slabeva, and Pigneur (2003): (a) in selected indoor locations or hotspots, and (b) extensive or outdoor coverage. However, lately, Wi-Fi has emerged not only as a dominant standard for wireless local area networks (LANs) but also for wireless personal area networks (PANs), wireless neighborhood area networks (NANs), and wireless metro area networks (MANs). There is clearly a widespread support for neighborhood and metro area Wi-Fi around the world. Experts believe that citywide Wi-Fi could make ubiquitous broadband a reality. Emerging wireless technologies that have become mainstream are typically more evolutionary than revolutionary.

Although market maturity in certain wireless technologies is evident, more research is needed on interoperability and integration of these wireless technologies. This paper addresses and attempts to answer the following research questions: First, how is Wi-Fi technology evolving in a heterogeneous wireless environment and how complementary is it with other wireless technologies? Second, how do new service models emerge when two or more wireless technologies integrate? A related research question is whether a wireless technology can succeed by itself or should it be complementary to other technologies. This paper also tries to determine whether cellular operators should see Wi-Fi as a complementary or a competitive technology to cellular.

The authors of this article believe this work is the first of its kind where emerging service models of Wi-Fi integrated with cellular, WiMAX, and Bluetooth have been put together to present useful insights. The other main goal of this article is to compare and contrast Wi-Fi with other wireless technologies that are likely to be or have already been integrated with Wi-Fi. From an integration perspective, the research determines Wi-Fi to be a winning technology in the wireless ecosystem.

This paper adopts a three-pronged methodology consisting of technology, architecture, and business models. The paper is organized as follows: Section 2 starts with background comparing Wi-Fi with other wireless technologies. Section 3 details the Wi-Fi ecosystem components and its architecture. Section 4 analyzes the emerging service models in the integrated wireless environment. This section also presents the cost and revenue models for these integrated wireless networks. Finally, the article ends with a SWOT analysis followed by conclusions and views on the future of the Wi-Fi ecosystem.

2. Background

The term “Wi-Fi,” another name for IEEE 802.11, was coined by the Wireless Ethernet Compatibility Alliance (WECA).¹ The 802.11² is a WLAN standard developed by the IEEE and was officially accepted in 1997. IEEE 802.11 operates in the unlicensed 2.4 GHz industrial, scientific, and medical (ISM) band with a total available bandwidth of 83.5 MHz (2.4–2.4835 GHz). The first IEEE 802.11 standard published in 1997 described only the medium access control (MAC) and physical (PHY) layer. The other 802.11 standards are either enhancements to the original MAC for quality of service (QoS) and security, or extensions to the original PHY for high-speed data transmission. IEEE 802.11g offers further high-speed extension in the 2.4 GHz band. It uses a different modulation scheme in the 802.11b frequency band (2400–2485.5 MHz) and it has a maximum data rate of 54 Mbps. 802.11g is backward compatible with 802.11b. 802.11g includes a technique for prioritizing data packets to improve quality of streaming media, such as VoIP, voice, and video-conferencing. 802.11a uses 5 GHz unlicensed U-NII spectrum and is not compatible with 802.11b. Wi-Fi throughput by three different standards is shown in Table 1a and b. Dual-band access points (AP) are used to facilitate the coexistence of 802.11a and 802.11b networks.

2.1. Cellular technologies (2G/2.5G/3G)

The evolution of mobile wireless networks began in the 1940s. These early devices and networks were based on the advanced mobile phone service (AMPS) technology. In the 1990s, mobile services based on digital

¹<http://www.wi-fi.org/>—The Wi-Fi Alliance certifies wireless devices that implement the universal IEEE 802.11 specifications (URL accessed on August 2007).

²<http://standards.ieee.org/getieee802/802.11.html> (URL accessed on August 2007).

Table 1a
Global wireless standards

Wireless standard	ETSI ^a	IEEE
WWAN	3GPP ^b , EDGE (GSM)	–
WMAN	ETSI HiperMAN	IEEE 80.16
WLAN	ETSI HiperLAN	IEEE 802.11
WPAN	ETSI HiperPAN	IEEE 802.15 (Bluetooth)

^awww.etsi.org—The European Telecommunications Standards Institute (ETSI) is an independent, non-for-profit organization of the telecommunications industry in Europe, with worldwide projection (URL accessed on August 2007).

^bwww.3gpp.org—3GPP refers to Third-Generation Partnership Project. 3GPP specifications are based on the evolved GSM standards. 3GPP Long-Term Evolution is a project within 3GPP that aims to improve 3G UMTS standards. www.3gpp2.org—3GPP2 is involved in developing global specifications for American National Standard Institute (ANSI)/Telecommunications Industry Association North America (TIA)/Electronics Industries Alliance (EIA-41) Cellular Radio Telecommunication Intersystem Operations network evolution to 3G (URL accessed on August 2007).

Table 1b
Wi-Fi throughput by IEEE standard

	IEEE standards		
	802.11a	802.11b	802.11g
Maximum data rate (Mbps)	54	11	54
Spectrum (GHz)	5.8	2.4	2.4
Standard ratified	1999	1999	2003
Non-overlapping channels	8	3	3

Table 2
Cellular technologies (2G/2.5G/3G)

2G	2.5G	3G
28–65 Kbps	56–144 Kbps	384–2000 Kbps
TDMA	GPRS	EDGE
GSM	GPRS	WCDMA
PDC	–	WCDMA
CDMA	CDMA2000	CDMA2000 1xEV

mobile technologies formed the second generation (2G) of wireless technologies. Time division multiple access (TDMA), global system for mobile communications (GSM), personal digital cellular (PDC), and code division multiple access (CDMA) are based on 2G standards as shown in Table 2. General Packet Radio Service (GPRS) represents the initial packet-based technology for advancement from 2G GSM networks to 2.5G networks. GPRS data speeds are likely to achieve data speeds of up to 171.2 Kbps. The third-generation (3G) mobile technologies are established under the ITU³ umbrella of 3G standards. Two competing technologies have emerged into 3G standards: one followed the GSM path and the other the CDMA 2000. The universal mobile telephone system (UMTS) follows the GSM path, which uses wideband code division multiple access (WCDMA) as the air interface, and the other follows code division multiple access 2000 (CDMA2000). 3G technologies such as CDMA2000 (1xEV-DO and 3x) and WCDMA theoretically offer up to 2 Mbps in a given location. But there are some significant limitations to this theoretical capacity.

2.1.1. Wi-Fi vs. cellular

2.1.1.1. *Spectrum of operation.* Cellular operates at different licensed bands as shown in Table 3. Cellular technologies built on 2G are basically for voice application; later on, 2.5G and 3G technologies added data

Table 3
Wi-Fi vs. cellular

	Wi-Fi	Cellular (2.5G, 3G)
License	Unlicensed	Licensed
Spectrum	2.4 and 5.8 GHz	800, 900, 1800, 1900, 2100 MHz
Coverage	Several km	300 ft for indoor usage, can be extended up to 1 mile
Data rate and speed	802.11b, 11 Mbps 802.11a/g, 54 Mbps	2.5G, 170 Kbps 3G, 300 Kbps

capability to it. Several service providers are short on bandwidth for both their voice and new data subscribers. Wi-Fi operates in the unlicensed frequency band and is designed for high-speed data service. Wi-Fi can be used to extend and complement 2.5G/3G data service.

2.1.1.2. Data rate and speed. 2.5G is able, theoretically, to support data rates in the range of 170 Kbps, and 3G systems are able to support 2 Mbps; Wi-Fi can support up to 54 Mbps. More practical data rates for 2.5G are currently in the range of 40–60 Kbps; for 3G, it is up to 300 Kbps. The available data rate of the cellular technology today is not enough to provide emerging multimedia applications.

2.1.1.3. Coverage. There is a clear tradeoff between coverage and capacity. Wi-Fi has enough capacity compared to cellular, but it has certain limitations in terms of coverage, as it is intended for a range of about 300 ft. However, coverage of cellular networks is much wider than that of Wi-Fi networks and has a range of several kilometers.

2.1.1.4. Standards and bodies. There are two main cellular technologies: GSM and CDMA; their respective migration path to 3G is via 3GPP and 3GPP2. On the other hand, Wi-Fi has 100% global recognition and has become the “single” networking standard for all developers, equipment manufacturers, service providers, and end users. An advantage with Wi-Fi is that a large-scale service-level roaming between different wireless Internet service providers (WISP) is possible as Wi-Fi certification has become a de facto standard for IEEE 802.11b-based products.

2.2. WPAN (Bluetooth)

This technology enabled the mass replacement of many of the short-range cables used today. It is convenient because of its easy-to-use and ad hoc networking (Bray & Struman, 2001). Bluetooth is a worldwide open standard, short-range radio specification focused to replace cables and wires. This technology standard is developed by the Bluetooth special interest group (SIG). There are currently more than 2000 member companies that support this technology. Bluetooth SIG’s goal was to build up an open specification for a low-powered, short-range, RF-based wireless communication technology. Bluetooth allows devices to talk to each other in the 2.4 GHz unlicensed ISM band. Bluetooth technology uses low power and signals over a relatively short distance, usually 10 m. Bluetooth devices usually communicate at less than 1 Mbps. Bluetooth radio is optimized for very low power utilization, short-range communication, and minimal interference through fast frequency hopping. The nominal distance for a Bluetooth device with a 1 mW RF power output is 10 m and this is extendable to 100 m by raising the power to 100 mW. The raw data rate for a Bluetooth device is 1 Mbps; however, the available data rate is 723 Kbps.

2.2.1. Wi-Fi vs. Bluetooth

2.2.1.1. Spectrum of operations. The main similarity between the two systems is that both share the same unlicensed 2.4 GHz radio spectrum, which causes Bluetooth and Wi-Fi systems to interfere with one another. The 2.4 GHz ISM radio band is the busiest radio spectrum in the world.

Table 4
Wi-Fi vs. bluetooth

	Wi-Fi	Bluetooth
Spectrum (GHz)	2.4 and 5.8	2.4
Data rate (Mbps)	Up to 54	1
Range (m)	100	10
Power	Medium	Low
Transmission type	DSSS and OFDM	FHSS
Primary devices	Laptops, printers, and other networking devices	Cellular phones, headsets, other small powered devices
Standard body	WECA	Bluetooth SIG

2.2.1.2. Range and power. As shown in Table 4, IEEE 802.11b is basically a technology intended for wireless networking, specifically WLANs. Bluetooth utilizes low power consumption and short range of approximately 10 m, making it a WPAN. IEEE 802.11b, on the other hand, has higher energy consumption but can transmit up to 100 m.

2.2.1.3. Transmission types. IEEE 802.11b and Bluetooth products use different transmission types with their own features to transmit signals. Bluetooth uses FHSS (frequency-hopping spread spectrum) while IEEE 802.11b uses DSSS (direct-sequence spread spectrum).

2.2.1.4. Data rate. Bluetooth does not have the data rate that a Wi-Fi can provide. IEEE 802.11b offers higher speeds than Bluetooth. 802.11b is a higher bandwidth standard designed for large quantities of data. Bluetooth has reasonably low transmission speeds of up to 1 Mbps suitable for transmitting data files; apart from this, it is ideal for voice transmission.

2.2.1.5. Time duration and type of network. Wi-Fi is used for a longer duration connection, whereas Bluetooth is optimized for peer-to-peer temporary connections. Infrastructure-based networks need an AP, which acts as a bridge to other wireless or wired networks and has most of the functionality built in the AP. Ad hoc networks have no permanent infrastructure, and each node is very complex. Every node has to implement medium access techniques including mechanisms to handle hidden or exposed terminal problems. IEEE 802.11 is basically an infrastructure-based network. The main advantage of Bluetooth is that it is a purely ad hoc network.

2.3. WMAN (WiMAX)

“WiMAX” stands for Worldwide Interoperability for Microwave Access. It is a standard-based technology that enables the delivery of “last mile” wireless broadband access. A group of vendors and service providers (those who founded the WiMAX forum)³ believe that it will be widely deployed in the same way as Wi-Fi was. Standardization will not only reduce equipment and components costs, allowing mass production, but it will also allow interoperability of equipment from different vendors. IEEE standard 802.16 is the foundation of WMAN for the next few decades (Eklund, Marks, Stanwood, & Wand, 2002). The most suitable frequency band for WiMAX is 3.5 GHz, followed by 5.2–5.8 GHz. It is also expected that 2.5–2.7 GHz band is a potential band for WiMAX in some countries. The economics of FBWA (fixed broadband wireless access) technology never made it suitable for the “last mile.” It was also thought that it could be deployed only in areas where there was no preexisting infrastructure. Recent developments in WiMAX have been changing the whole BWA industry dynamics, but it still has a long way to become ubiquitous. As shown in Table 5, there are several ways WiMAX can be deployed. The first and most popular

³The WiMAX forum (www.wimaxforum.org) is an industry-led non-profit organization formed to promote and certify compatibility and interoperability of broadband wireless products.

Table 5
WiMAX standard

	Pre-WiMAX fixed outdoor—IEEE 802.16a	WiMAX fixed indoor—IEEE 802.16d	WiMAX full nomadic—IEEE 802.16e
Frequency (GHz)	5.8, 2.5, 3.5	2.5, 3.5	5.8, 2.5, 3.5
WiMAX applications	Outdoor mount antenna, needs truck roll ^a	Indoor access and fixed Internet applications, self-install	Broadband access, anywhere, anytime

^aThe “truck roll” is an on-site visit by carrier employees or agents required for each wireless equipment installation in the customer premise. Most fixed WiMAX installations in the customer premise need truck roll.

Table 6
Wi-Fi vs. WiMAX

Characteristic	Wi-Fi	WiMAX
Spectrum	Unlicensed 2.4 and 5.8 GHz	Both licensed and unlicensed spectrum 2–11 GHz
Coverage	(1) Designed for 300 ft range for indoor use (2) Due to recent innovations, coverage is being extended using a mesh technique or high-gain directional antennas for outdoor usage	(1) Designed for 10 km, maximum range up to 30 miles (2) Basically designed for outdoor environments (terrains, buildings, trees, etc.)
Capacity	54 Mbps in 20 MHz channel	75–100 Mbps (based on a modulation technique and it is adaptive)
Channel width	20 MHz (fixed channel size)	3–20 MHz (flexible channel size)
Quality of service	Voice over Wi-Fi is emerging and IEEE 802.11e deals with QoS issues	Standard has inbuilt QoS for voice and multimedia applications

provides backhaul for Wi-Fi APs and also serves as a backhaul between conventional cellular towers. The second type of deployment is “last mile,” which serves residential and enterprise users as an alternative to cable and DSL (Corderio, Gossain, Ashok, & Agarwal, 2003). The third is similar to metro Ethernet provided on point-to-multipoint sources that compete directly with fiber. The fourth type is the mobile version of WiMAX based on 802.16e standard. 802.16e recently ratified is not expected to be quickly adopted by operators.

2.3.1. Wi-Fi vs. WiMAX

2.3.1.1. Spectrum of operation. Wi-Fi has been deployed in two unlicensed bands: 2.4 and 5.8 GHz. The WiMAX standard operates between 2 and 11 GHz of spectrum, which allows non-line-of-sight (NLOS) environments. Globally, the WiMAX spectrum situation is more complex than the Wi-Fi, due to the fragmented radio spectrum in this operating band.

2.3.1.2. Power settings. Wi-Fi systems usually transmit at the same power level all the time as the output power is fixed. WiMAX has a separate ranging method, which calculates the right timing offset and power settings, so that the transmissions from each client device arrive at the base station at the correct time with the same power level.

2.3.1.3. Range and coverage. Table 6 clearly states the difference between Wi-Fi and WiMAX in terms of coverage. WiMAX provides a range that is broader than Wi-Fi but more limited than wide area networks. Wi-Fi is designed typically for 100 m. With high-gain directional antennas or with mesh topology, Wi-Fi coverage can be extended. On the other hand, WiMAX is designed typically for a cell size of 3–6 miles and up to 30 miles for long range. Wi-Fi is basically for indoor settings, but due to more recent technical innovations, it started to be used in outdoor environments.

2.3.1.4. Data rate or speed. WiMAX has ranges up to 30 miles and speeds up to 70 Mbps. Though the standard does not describe how much of this capacity an operator should provide to each user, a single base station can handle tens of megabytes per second of data. In a typical cell radius deployment of 3–6 miles, WiMAX systems can deliver data rates of up to 40 Mbps per channel, for both fixed and portable access applications.

3. Wi-Fi ecosystem components and architecture

The Wi-Fi ecosystem is a group of technologies that integrate with Wi-Fi, offering innovative services on a complementary basis. Wi-Fi is the only technology that seems to complement all other wireless technologies and interoperate with them. On the cellular arena, standard bodies Third-Generation Partnership Project (3GPP and 3GPP2) have been working to define specifications for cellular/Wi-Fi integration. In the same way, WiMAX also complements Wi-Fi in many aspects. Although WiMAX is emerging as a competing technology to cable or DSL, it is being positioned as a complement to Wi-Fi. WiMAX extends its reach and provides a backhaul for easy Wi-Fi access for much wider geographical coverage. Wi-Fi is being embraced by some cellular operators, municipalities, WISPs, individuals, and businesses. This is due to Wi-Fi being complementary with other wireless technologies. It is on its way to become the nucleus of the wireless ecosystem.

Although many technologies can be integrated with Wi-Fi as shown in Fig. 1, this paper focuses only on the Wi-Fi integration with cellular, Bluetooth, and WiMAX. In this section, the article will discuss the architecture of

- Wi-Fi integrated with cellular;
- Wi-Fi integrated with Bluetooth; and
- Wi-Fi integrated with WiMAX.

3.1. Wi-Fi integrated with cellular

Extensive research has already been carried out in the area of Wi-Fi integration with cellular networks (Ahmavaara, Haverinen, & Pichna, 2003; Salkintzis, Fors, & Pazhyannur, 2002, etc.). Integration of cellular (2.5G/3G) with Wi-Fi gives ubiquitous coverage and supports high data rates in strategic locations, e.g., schools, offices, airports, hotels, coffee shops, etc. If both Wi-Fi and cellular networks are integrated, then

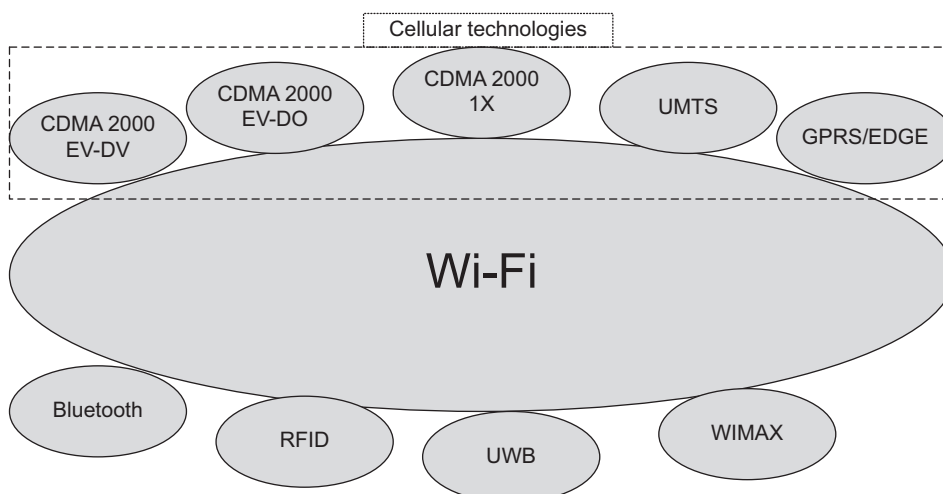


Fig. 1. Wi-Fi ecosystem.

cellular operators are able to offer 3G-like services. There has been a delay among some cellular operators in the deployment of 3G wireless networks, most anticipating high-speed mobile network architecture. This is due to 3G spectrum allocation and uncertainty around business models for 3G services. In addition, cellular cannot support the high data rates required in business and multimedia applications. If operators integrate Wi-Fi with the existing cellular network (2.5G GPRS), they could meet some requirements for 3G-like services, which allow them to provide high-quality data services in strategic locations. Even though these two technologies are quite far from completely replacing each other, some major cellular operators have realized the benefit of integrating them. With their high capacity and low implementation costs, some operators consider Wi-Fi the ideal candidate for expanding cellular data capability (Oliver & Poiraud, 2002). For example, the mobile user can schedule high-speed file transfers for downloading when she/he is near a Wi-Fi hot spot. 3GPP has mentioned six inter-networking scenarios for cellular and Wi-Fi integration. Some scenarios consider offering cellular-based services within the Wi-Fi coverage. However, seamless continuity of Wi-Fi connection from cellular network is optional. Though cellular-based services may be available in the hot spot, there may not be service continuity as the user moves from one network to the other. There are two types of integration, *tight coupling* architecture and *loose coupling* architecture.

- *Type 1: Tight coupling architecture:* As shown in Fig. 2, in this type of architecture, the Wi-Fi is connected to the cellular network as an alternative radio access network. It is connected to the operator's core network. The hotspot can re-use the cellular infrastructure, e.g., core network resources, subscriber databases, and billing systems. Mobile users can select their network preferences or choose to get connected at the best available network speed. This is all done in software and users are automatically connected to the network of their choice.
- *Type 2: Loose coupling architecture:* In this type of architecture, hotspots are coupled with the cellular network in the operator's IP network as shown in Fig. 3. The Wi-Fi data traffic goes directly to the operator's IP network, instead of going via the cellular core network. Though the Wi-Fi and cellular networks remain separate, there is a common platform for authentication, accounting, and authorization. The Wi-Fi hot spots may be owned by third-party carriers, with roaming enabled via a dedicated connection between the cellular operators and Wi-Fi providers or over an existing Internet.

3.2. Wi-Fi integrated with Bluetooth

Wi-Fi is basically a networking technology, and Bluetooth is designed for connecting peripherals to a host system. The ISM band, apart from being used by Bluetooth and Wi-Fi, is also used by the HomeRF wireless networking system, cordless analog and digital phones, microwave ovens, and some medical equipment, as shown in Fig. 4. However, the main source of interference for Wi-Fi networks in 2.4 GHz is the Bluetooth

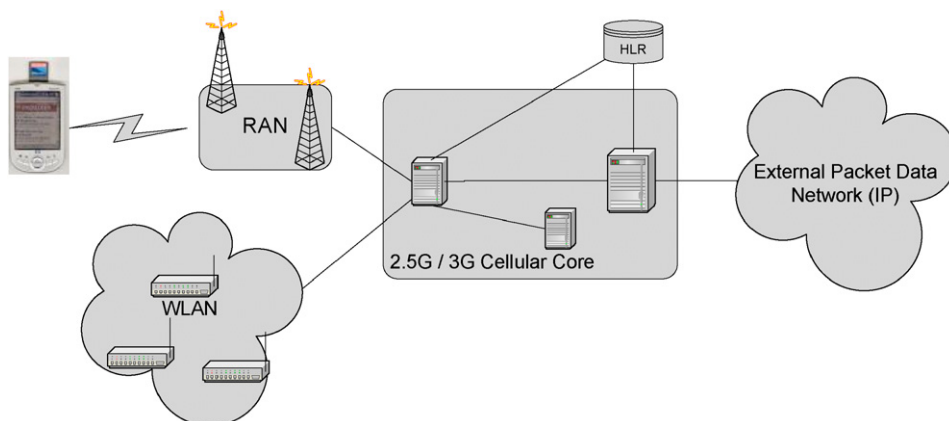


Fig. 2. Tight coupling architecture of cellular integrated with Wi-Fi.

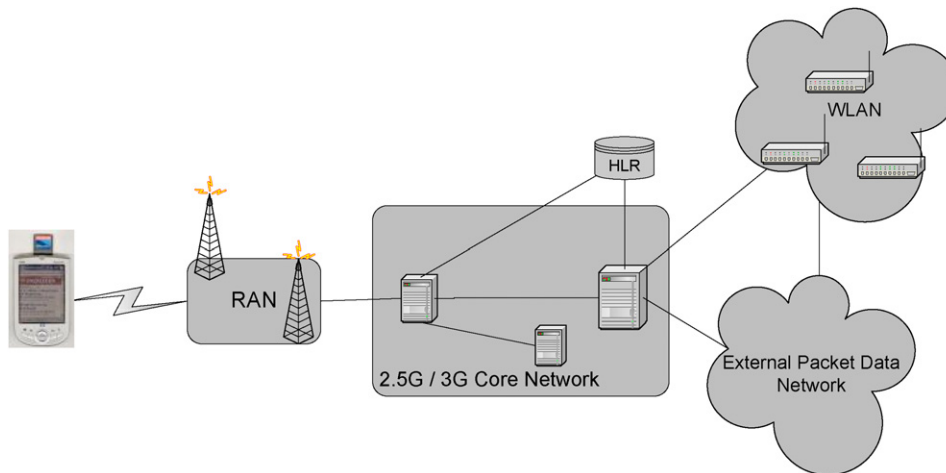


Fig. 3. Loose coupling architecture of GPRS integrated with Wi-Fi.

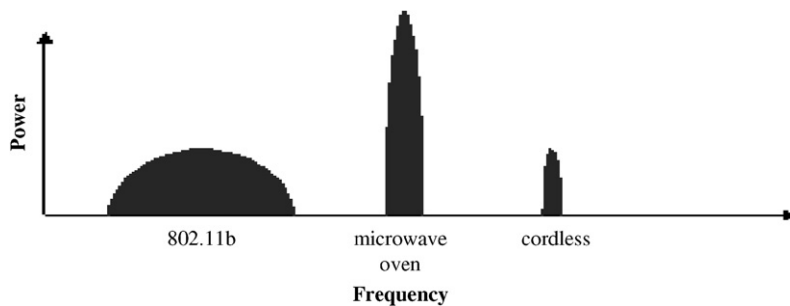


Fig. 4. The spectrum occupancy of different technologies in 2.4 GHz.

system. Users must share the radio spectrum in this unlicensed radio band, because no one owns any particular frequency in this band.

3.2.1. Bluetooth and Wi-Fi coexistence

The Bluetooth SIG and Wi-Fi Alliance work together to solve the interference problem, proposing different strategies to solve it. Many companies manufacture equipment using both systems by integrating them on a single chip, so it is in their own interest to solve the interference problem. The adaptive frequency-hopping technique in Bluetooth is a good first step. However, this solution is not a long-term one, and it does not solve the key problem to all interference problems. Any remedy to the interference issues that exist between these two technologies could enhance the adoption of both.

Frequency-hopping spread spectrum is a system that divides the spectrum into different frequencies or channels. On a particular selected channel at a particular time, the radio selects a new channel to transmit the packet. This process is repeated so that the message spreads across the spectrum. The FHSS technology is good for Bluetooth communications, but it is a severe problem for nearby Wi-Fi communications. Since DSSS systems statistically occupy a given 22 MHz channel, as shown in Fig. 5, they are stationary within the band and do not move to avoid interference. The Wi-Fi device has packet transmission durations that can be considerably longer than the Bluetooth hopping interval, which leads to interference collision in the time domain. FCC (Federal Communication Commission) in North America and ETSI (European Telecommunication Standard Institute) in Europe defined how this ISM band is to be used in North America and Europe. Their policies contain key provisions that make spectrum sharing possible. The condition is that if any of the devices uses this ISM band, it may be subject to some interference, and it should automatically adjust to reduce the interference.

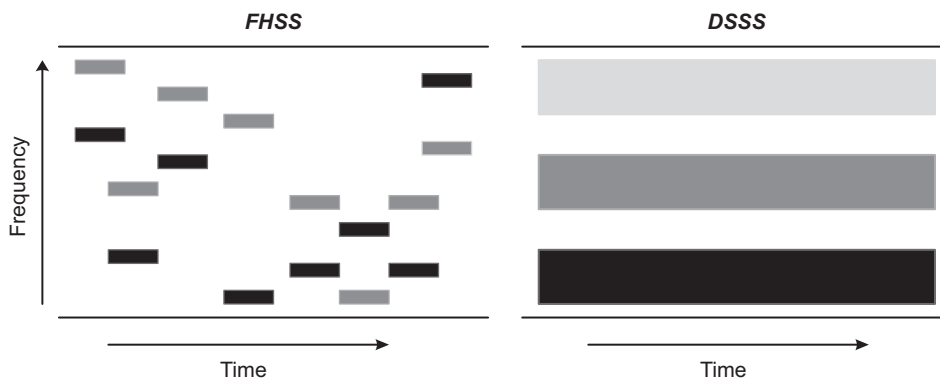


Fig. 5. FHSS (Bluetooth) and DSSS (IEEE 802.11b).

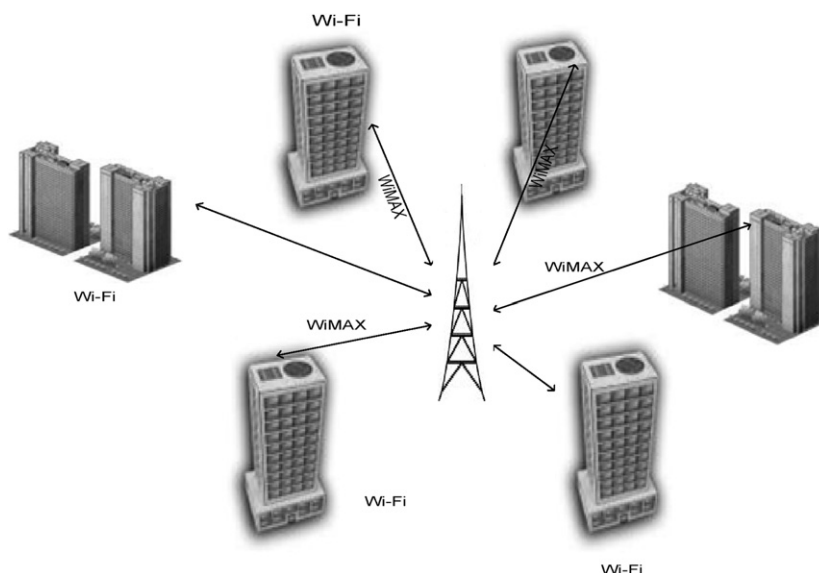


Fig. 6. Wi-Fi/WiMAX serving multi-dwelling unit.

3.3. Wi-Fi integrated with WiMAX

3.3.1. Architectural overview of Wi-Fi with WiMAX

This architecture is considered for incorporating WiMAX with Wi-Fi systems for two scenarios, where both technologies coexist to offer a cost-effective fixed broadband Internet solution. The first type is a multi-dwelling unit in a dense urban area where there are many subscribers per square mile; in the second type, the market consists of individual buildings and houses, where Wi-Fi/WiMAX serves as the last mile. Since WiMAX signals are likely to fade out like a cellular service inside of buildings, the technology is actually best when paired with interior Wi-Fi hot spots.

- *Type 1: Wi-Fi/WiMAX serving multi-dwelling unit:* As shown in Fig. 6, in this type of architecture, the majority of small office and home office (SOHOs) and households are in multi-dwelling units or apartment complexes. WiMAX is used to deliver megabits of data to apartments or office buildings; on the other hand, Wi-Fi is used to distribute services to the individual houses, offices, lobbies, conference rooms, etc. Though the WiMAX standard does not describe how much capacity an operator can feed to each Wi-Fi

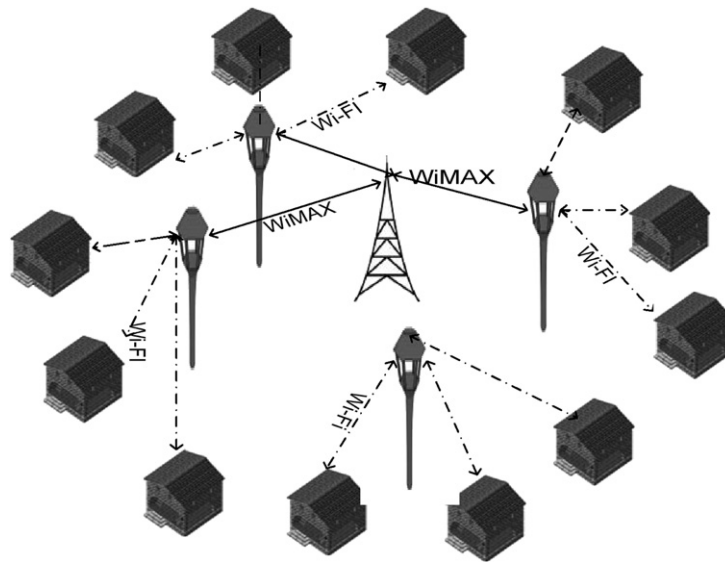


Fig. 7. Wi-Fi/WiMAX serving independent houses and SOHOs.

AP, a single WiMAX base station can handle hundreds of megabits per second of data and can feed Wi-Fi APs mounted on tall buildings.

- *Type 2: Wi-Fi/WiMAX serving independent houses:* In the second type, individual buildings and houses may be packed close to each other or may be scattered, as shown in Fig. 7. In this case, the capital expenditure is dominated by the large number of Wi-Fi APs needed to cover large geographic areas. The leasing cost would be much lower, as this type of networks can use the lamppost or the rooftop of a residential building, reducing the operating cost significantly. The coverage can be provided by the Wi-Fi APs with high-gain antennas to extend the coverage. There is a provision of using APs with higher gain antennas to extend the coverage but still limiting the maximum effective isotropic radiated power (EIRP) within the legal limit, as described by the FCC. A typical Wi-Fi AP (802.11b or 802.11g) covers only 300 ft, which is roughly 0.0102 square mile, but for outdoors, one must increase the coverage by using higher gain antennas. It is feasible to extend the coverage further by bearing additional costs for smart antennas.

4. Service and business models of integration

New products and services emerge as two or more technologies are integrated. A wide range of investment opportunities are available within these emerging wireless technologies. A device could integrate Wi-Fi with Bluetooth, ultra-wideband radio (UWB), 2.5G, 3G, and WiMAX or a subset of these technologies. These devices can communicate over the best air interface and can switch between different networks without any manual switching mode. The signal received from one network could be processed and retransmitted over another seamlessly, depending on the application chosen by the end user service model.

In the following section, the paper will analyze the emerging service models, which include the cost and revenue models of Wi-Fi integrated with cellular and WiMAX. Regarding the Bluetooth integration, the paper presents the integration role that Bluetooth plays, by being an authentication mechanism in the cellular and Wi-Fi integration.

4.1. Service model of Wi-Fi integrated with cellular

Wi-Fi integrated with cellular networks provides a significant advantage to the cellular operators. 3G systems, including CDMA 1xEVDO, cannot sufficiently handle the bandwidth necessary for future

broadband applications at an affordable price. Wi-Fi offers fast connectivity and relatively cheap services compared to all 2.5G/3G data networks. The integration not only increases the revenue but also improves the performance of the cellular system, since it reduces the traffic load in the cellular system (Doufexi, Tameh, Nix, Armour, & Molina, 2003). The operators have two choices: (a) integrate their own Wi-Fi network to the core network, or (b) collaborate with a third-party Wi-Fi network by integrating to their IP network instead of the core network. Thus, loose coupling architecture is not only beneficial to the cellular operator but also to third-party hot spots, as it increases revenue by increasing traffic load at their hot spot networks. Thus, integration provides profitable business opportunities for both the cellular operators and the new Wi-Fi startup companies. Cellular networks integrated with Wi-Fi have some advantages over the individual Wi-Fi networks controlled by micro-carriers and aggregators. This is a result of cellular operators already having an established customer base to which they can integrate Wi-Fi and offer 3G-like services with their existing 2.5G network, avoiding the cost of deploying the expensive 3G systems. Cellular operators also have the advantage of using the existing operational support system (OSS) and business support system (BSS) for the deployment of new Wi-Fi systems. With integrated billing, the operator is breaking down the barriers for people to access the service and experience the benefits of Wi-Fi connectivity.

4.1.1. Integration of VoWi-Fi with cellular

By integrating voice over Wi-Fi (VoWi-Fi) with a cellular network, Wi-Fi-based mobile phones are able to connect to a Wi-Fi AP or with the cellular base station, without using any other hardware. This can also support the seamless transfer of calls from a Wi-Fi network to a cellular network and vice versa. Hybrid VoWi-Fi/cellular phones are designed to access public or private Wi-Fi APs, and then switch to a cellular network automatically, when the caller has left the Wi-Fi coverage area. With the adoption of QoS and guaranteed call quality in VoWi-Fi, cellular operators have a choice to offer services in broadband serviced locations with high quality at lower costs compared to mobile access networks.

4.1.2. Cost model of Wi-Fi integrated with cellular

Wi-Fi APs can be deployed in locations where groups of people need high-speed wireless access, e.g., coffeehouses, subways, university campuses, airports, convention centers, and other strategic locations. Each AP in a WLAN system forms a basic service set (BSS); two or more APs form an extended service set (ESS). The APs in the ESS are connected by distribution systems. Therefore, there can be one ESS serving each cellular site. As shown in Table 7, the following additional costs are involved, apart from the existing cellular infrastructure: (additional, i.e., due to integration) capital expenditure and (additional) operating expenditure on the cost side. For the capital expenditure, one can consider the investment cost of the Wi-Fi system: cost of deployment of APs and the integration cost to cellular cells. The additional cost for integration may be due to tight coupling or loose coupling integration. This depends on whether cellular operators want to deploy their own Wi-Fi APs or whether they want to integrate with third-party hotspots. Backhaul maintenance and equipment depreciation costs should also be included in the operating cost.

Table 7
Cost model of Wi-Fi integration with cellular systems

Capital expenditure
● Wi-Fi APs cost
● Integration cost to cellular systems
Operating expenditure
● Backhaul for Wi-Fi APs
● Maintenance
● Depreciation cost
Revenue due to Wi-Fi deployment
● Revenue from cellular data subscribers
● Revenue from Wi-Fi-only service

4.1.3. Revenue model for Wi-Fi integrated with cellular

The operator has two sources of revenue coming from each Wi-Fi hotspot: (a) users of the integrated service, and (b) users of the Wi-Fi service only. In the integrated service, only the additional revenue from the mobile data users should be considered, justifying the return on Wi-Fi integration. To achieve a better return on investment (ROI) for the WLAN deployment, cellular operators can add extra customers for Wi-Fi-only service to their already existing subscriber base. Wi-Fi bundled with cellular price may well attract subscribers from other operators and help to reduce churn. Traditionally, cellular data networks (2.5G) offer simple usage-based pricing of approximately \$5 per megabyte. On the other hand, Wi-Fi service has a different revenue model. There are several payment options, such as a subscription fee on a monthly basis, a one-time charge per connection, or a usage-based pricing system. However, most Wi-Fi charges are based on flat pricing with a connection fee, which usually varies between \$4 and \$10 per day, for a single user at a given location. The price differential between the two services is not only due to the infrastructure cost but also due to their capacity characteristics.

If a cellular operator invests in Wi-Fi, the average revenue per hotspot (ARPH) increases due to two sources of revenue: one from integrated service and another from the Wi-Fi-only service. The cellular data usage (like 2.5G) has been limited to a certain size of megabytes; the users have to pay extra above this limit. Therefore, with unlimited Wi-Fi usage, users can connect at any hotspot any time to gain the most value for the money they pay. If they are outside the Wi-Fi coverage, they have to pay extra for every megabyte they exceed above the Mb limit in the 2.5G coverage.

Cellular operators have done only price bundling⁴ so far; if they provide technology bundling, they could use their Wi-Fi networks to gain additional revenue due to integration with existing data users and also offload cellular traffic to the Wi-Fi networks. Although users would pay separately to use the Wi-Fi services, operators hope that bundled discount promotions will create more demand for their regular service. However, other kinds of revenue streams can also be added using integrated networks. The integrated users can be given an incentive even on the connection fee, so that a “heavy” user may tend to browse in a hotspot instead of a cellular coverage area.

VoWi-Fi also creates new revenue opportunity by replacing fixed line phone service inside buildings. Wi-Fi phones are not only advantageous in terms of cheaper prices for phone calls but they also have unlimited access to text messages without any additional charges. The cost of making a call over cellular networks is very high compared to broadband networks. This notable price difference between the two networks can influence the way users use these networks under different circumstances. Some users may be willing to use a VoWi-Fi network, especially for their phone calls, if they need to talk a long time or to perform a business call on the move. So, users have the choice of either using the cellular network with a higher price label (but with wider coverage) or taking advantage of VoWi-Fi services with lower prices in a limited coverage area.

4.2. Service model of Wi-Fi with Bluetooth

Wi-Fi is a networking technology, while Bluetooth is designed for connecting peripherals to a host system. Bluetooth-enabled mobile devices can also connect to private and public networks through Bluetooth APs, which can support video, data, and voice service. However, Bluetooth’s success in recent times has been diminished by the evolving ubiquity of Wi-Fi. There is a notion that Wi-Fi popularity might make Bluetooth less successful. Nevertheless, there is still considerable potential for Bluetooth technology to complement Wi-Fi due to the fact that it is already available in more end user devices. There are many devices available currently in the market which have both technologies integrated in a single chip.

4.2.1. SIM-based authentication for public hotspot via Bluetooth

If Wi-Fi networks are increasingly integrated with cellular networks, then users will expect to have simplified authentication.⁵ With the help of Bluetooth technology, seamless authentication is possible between

⁴T-mobile customers add a monthly \$20 for unlimited Wi-Fi service to their monthly cellular bill. This is a 50% discount over the company’s regular hotspot rate plans. We believe this price is low, since the subscriber has subscription to both their Wi-Fi and cellular services. But on the other hand, the subscribers, who have subscribed only to Wi-Fi, have to pay the same amount of \$40; therefore, they have an incentive to prefer the integrated service which has both GPRS and Wi-Fi, for the same amount of money.

⁵www.intel.com/business/bss/solutions/blueprints/pdf/axalto.pdf (URL accessed on November 2005).

public Wi-Fi hotspots and cellular networks. Wi-Fi users in a public hotspot can do authentication via a subscriber index module (SIM) card in to their laptop or PDA, wirelessly through Bluetooth. The client software on the device can also be used to automate the Wi-Fi network's login process, for users with Bluetooth-enabled cellular phones. If the mobile technology initiates an authentication, the client software can do the handshake process by using the Bluetooth capabilities in a laptop or PDA. The client software will access the SIM card whether it is getting attached to a laptop or PDA via Bluetooth in the mobile phone. The whole process will be seamless, if there is coordination between Wi-Fi and Bluetooth. The integrated wireless capabilities adaptively assign the frequencies for both Wi-Fi and Bluetooth to work harmoniously together. Therefore, Bluetooth has the potential to offer the most innovative solution for low to medium-speed applications in the integrated environment.

4.3. Service model of Wi-Fi with WiMAX

While backbone networks are matured, reliable, with more bandwidth, the “last mile” to the end user is weak (Fijnvandraat & Bouwman, 2006). Another major problem is that rental of the wired backhaul networks accounts for a major cash outflow in any wireless network (Bjorkdahl, Bohlin, & Lindmark, 2004). Therefore, operators could take advantage of the most matured technology, e.g., Wi-Fi, to reach the end user as the “last mile” access. At the same time, the operator could take advantage of WiMAX to minimize backhaul cost and efficiently reduce the time for service provisioning. Therefore, to reduce backhaul cost, one can use WiMAX; to have more efficient use of the wired backhaul, the operator could also consider implementing WiMAX infrastructure mesh for backhaul traffic. Aggregating backhaul lines into higher capacity lines is not only cheaper but also reduces the physical space compared to smaller speed circuits. The disadvantage of using WiMAX as the access is the total estimated cost of all WiMAX equipment sales: over half of them will be for customer premise equipment. If properly planned and deployed, Wi-Fi with WiMAX can turn the whole region within the geographic boundaries into a “hot zone.”

Broadband wireless access technologies are being embraced by everyone because of their ease of installation, low cost, and high bandwidth (Corderio et al., 2003). Wi-Fi integrated with WiMAX has not only enough potential to compete on a cost-per-megabyte with both cable and DSL but it can also make ubiquitous broadband a reality. If engineering and economics are correctly applied, a Wi-Fi network can be built around an entire city with WiMAX as a backhaul, instead of providing limited coverage at the hotspots. Cable is offered primarily to the residential market in urban and suburban regions, while DSL is limited to about 12,000 ft from the central office. In many parts of the world, the wire line infrastructure does not exist, making Wi-Fi with WiMAX an attractive technology to deliver broadband service. The citywide Wi-Fi access networks can be deployed by three main interest groups: First, by WISPs aiming to deliver high-speed fixed and mobile voice and data services. Second, by fixed line ISPs who want to expand their service offering by offering complementary wireless service. Third, by municipalities and cities that want to provide emergency services to the first responders, for example, police, fire, ambulance, etc. Apart from this, they can also provide differentiated high-speed Internet services to local residents and businesses. The city could also provide Internet access to its low-income and small businesses at affordable price, thereby bridging digital divide.

4.3.1. Cost model of Wi-Fi with WiMAX

The Wi-Fi APs' cost is very low, as they can be easily mounted on a lamppost or stop lights at a significant discount, instead of leasing tall towers to mount base station (BS) and antennas. Even with high density of Wi-Fi APs, it is more economical compared to alternative infrastructure costs. This is due to the fact that the APs capital costs are much lower and that an additional investment on the APs would not impact the net profit. The main economic advantage of WiMAX backhaul architecture is due to traffic aggregation. Unlike cable or DSL operators, a Wi-Fi/WiMAX business model has a wide range of pricing, roaming, payment, and collection options that will give operators the positive cash flow to offer the most innovative broadband services at affordable prices by lowering ongoing operating expenses. WiMAX will lower backhaul costs due to traffic aggregation and efficient use of wired backhaul, thereby reduce operating cost. Therefore, with lower backhaul costs and with zero dollars on CPE subsidies and truck rolls, the combination of Wi-Fi with WiMAX looks like an attractive alternative for broadband access. The integration of WiMAX and Wi-Fi

Table 8
Data and voice revenue model for citywide Wi-Fi

I. Individual houses/buildings
● Residential data users in individual buildings
● SOHOs data in individual buildings
● Residential VoWi-Fi in individual buildings
● SOHO VoWi-Fi in individual buildings
II. Multi-dwelling units
● Residential data users in multi-dwelling units
● SOHOs in multi-dwelling units
● Residential VoWi-Fi in multi-dwelling units
● SOHO VoWi-Fi in multi-dwelling units
III. On-demand data and voice service
● Number of data connections
● Number of VoWi-Fi connections

combines the strengths of both these technologies to create cost-effective wireless networks. This kind of integrated architecture leads to much lower equipment cost, lower installation cost, lower operating expenditure (OpEx), and a better return on investment (ROI).⁶ The Wi-Fi APs should have dual-band capabilities, providing connectivity for 802.11a/b/g devices while at the same time provide wireless self-backhaul to WiMAX base station controllers. These outdoor Wi-Fi APs will cost more than the normal APs. Operators can purchase them at a wholesale basis for approximately \$1000–\$2000 per outdoor AP. Operating expenditures include tower leasing, backhaul cost, and maintenance costs. For the cost model, the wired backhaul cost will also be there, although the wired backhaul is needed only in the WiMAX main BS. WiMAX cells are made of pico-cells. Therefore, the BS antennas can be less than 50 ft. This is an advantage, as operators can use the rooftops or the lampposts on the streets. This cost model is based on the implicit assumption that the city is providing its urban furniture at low cost for mounting Wi-Fi APs, antennas, or other equipment boxes.

4.3.2. Revenue model of Wi-Fi with WiMAX

The citywide Wi-Fi deployment with WiMAX backhaul has several revenue models that are different for each category mentioned earlier. As seen in Table 8, operators can have three sources of data revenue from each type of scenarios (individual buildings and multi-dwelling): the first one from residential users, the second one from SOHOs, and the third source of revenue from the “on-demand service” (on a per connection basis). There could be a monthly subscription fee for data subscribers, which may even be 50% less than the monthly subscription fee of cable or DSL service. At the same time, the service can be affordable at a lower rate for SOHO business users. The third type of data revenue is usage-based. With an average Wi-Fi connection fee of \$4–\$10 (good for a day), users can transmit unlimited volume. By paying a Wi-Fi connection fee, users can connect to the network anywhere in the city on a given day to get the most value. The fourth type of revenue would be from VoWi-Fi service with the onset of citywide Wi-Fi deployment. The voice subscribers will be able to make effective VoIP calls using Wi-Fi phones via any AP located within the city. The use of VoIP over Wi-Fi at home and office could also have significant cost savings to the customers.

A profitable business strategy for a WISP would be to serve a wide variety of customers with the same infrastructure. Another main advantage of this model is that residential and business users can access an on-demand service (on a daily or hourly basis), along with their option of traditional monthly subscription. This results in an one-time capital expenditure that can be leveraged across different customer bases, making this an optimal solution for broadband deployment. As a long-term strategy, WISPs can build broadband wireless

⁶<http://www.bbwexchange.com/pubs/2007/02/07/page1423-446763.asp> by Robert Hoskins (URL accessed on August 2007).

networks that can support both voice and data for all residential and small business customers in their service area (Wanichkorn & Sirbu, 2002).

4.3.3. Policy issues

There are a lot of public policy issues centered on municipal Wi-Fi, as it has provoked a political and legal fight with regard to the local government's right to build communication networks (Bar & Park, 2006). In many states, the big telecom companies are against the local governments initiatives in deploying Wi-Fi networks. The opponents of citywide Wi-Fi are raising many policy issues and the key arguments are centered on cost, competition, and failure to achieve the expected social fairness from the municipal Wi-Fi deployment (Tapia & Stone, 2005). On the other hand, Wi-Fi proponents quote several benefits for municipalities entering into the broadband market. First, the municipalities could improve inter- and intra governmental communications (Gillett, Lehr, & Osorio, 2004). Secondly, local governments see the provision of broadband wireless access as a way to promote local economic development. Third, Wi-Fi access technology is used as a low-cost solution to provide broadband access to low-income households and small businesses, thus bridging the digital divide (Bar & Park, 2006).

What is broadband digital divide? A gap between those who can afford broadband and those who cannot persists, despite the growth of broadband connections (Lai & Brewer, 2006). Affordability of broadband is the biggest barrier. Regardless of wired or wireless broadband, the service should be affordable to all classes of the society. As shown by Gunasekaran and Harmantzis (2007), there are three main issues in bridging the broadband digital divide: affordability, availability, and accessibility of services. Wi-Fi is a technology that can address affordability (low cost), availability (ubiquitous), and accessibility (easy access). If cities and municipalities build a Wi-Fi infrastructure, this should be affordable and available all the time, everywhere, to small businesses and low-income households. As studied by Gunasekaran and Harmantzis (2006), low-cost broadband services can be offered using Wi-Fi, while remain economically advantageous for service providers at the same time.

The form of free or low-cost Wi-Fi Internet access is becoming more prevalent in many parts of the world by the use of co-operative networks (Sandvig, 2004). Co-op networks are typically made up of their members' AP, purposely left open and made available to everyone within the coverage area. Although the main users of these co-op networks are their own community members, this kind of network plays a vital role in the emerging Wi-Fi ecosystem. To meet the societal goals and make the wireless broadband access available to everyone, it is necessary to align the talent of the co-op members who really want to help others (Sandvig, 2004). The cooperative efforts have proved successful in the past in building infrastructures like roads, canals, and telephone exchanges, particularly in the rural areas (Bar & Galperin, 2004). The policy makers can encourage underserved or rural areas to build their own broadband infrastructure through co-ops, instead of waiting for telecommunications carriers to provide the traditional DSL or cable services. Wi-Fi provides a great opportunity for underserved areas to provide advance broadband service using unlicensed spectrum. Lehr, Osorio, Gillett, and Sirbu (2005) had done empirical estimates to show that broadband access positively affects economic activity in ways that are consistent with the earlier theoretical studies.

As explained in Bar and Park (2006), there are nine possible options in deploying a citywide Wi-Fi network, as no model fits all cities. Each option leads to a unique set of business models and policy issues. In many countries, there is also no support for alternative broadband technologies and the prices for traditional broadband access remain high. In some situations, for every extra megabyte downloaded, customers are charged extra to their existing monthly bill. Since ubiquitous broadband is a daily necessity for every citizen and business, it is essential for policy makers to explore options and encourage publicly owned or public-private partnerships to build wireless infrastructure throughout the country, thereby promoting competition in the broadband market. A study by Gillett et al. (2004) presents empirical results for a sample of communities that are in the forefront to deploy publicly owned communications infrastructure. The role of state and federal legislation in wireless municipal networks for the public-private partnership has been shown by Tapia and Stone (2005). Although policy makers in many countries are aiming for liberalization in the telecom sector, they should seek suitable strategies to promote economically vital broadband technologies like Wi-Fi and WiMAX.

5. SWOT analysis of the Wi-Fi ecosystem

Wi-Fi has become the most common use of unlicensed bandwidth for so-called “hot spot” (“hot zone,” “hot city,” “hot village”) type of coverage. This is due to the widespread availability of Wi-Fi radios that comply with IEEE 802.11b and the upcoming 802.11a/g standards. Wi-Fi has 100% global recognition and has become the single networking standard for all developers, equipment manufacturers, service providers, and end users. This section analyzes the main strengths and weaknesses of going towards a Wi-Fi ecosystem (see Table 9).

5.1. Strengths

The most important strength is the high capacity the technology can offer and its low cost of deployment. Wi-Fi has various technology options compared to other wireless technologies. Wi-Fi chip makers have already announced a tri-mode chip having IEEE 802.11b/g and 802.11a for their product portfolio for the near future. Therefore, operators planning to deploy a Wi-Fi network can strategically place their APs to support as many technologies and standards as possible. This allows the client software to “sniff” and select the best technology available at any given spot. Another advantage of Wi-Fi is that large-scale service-level roaming between different WISPs is possible, as Wi-Fi certification has become a de facto standard for IEEE 802.11b-based products (Henry & Luo, 2002). Another main advantage of the Wi-Fi service is the different options the customers have in terms of bandwidth upgrade. There are also many options for data and voice services at a lower cost. With any portable devices that have Wi-Fi clients, people can connect to the network while roaming in different metro zones throughout the city. Anyone who has a Wi-Fi client device in the city can access the network from any location by logging on to the network. Traditionally, cable and DSL networks offer a simple service model with flat pricing: a monthly subscription fee. However, Wi-Fi service providers can provide more innovative service options offering “on-demand” service plans for both data and voice users. There are several payment options, such as a subscription fee on a monthly basis, a one-time charge, per connection fee, or usage-based pricing, etc.

5.2. Weakness

The main weakness is the interference due to Wi-Fi’s operation in the unlicensed band. There is also a great concern that there are a lot of devices operating in the ISM band, e.g., microwave, cordless, etc. Another

Table 9
Wi-Fi service model (SWOT analysis)

Strength	Weakness
● Excess capacity ● IEEE 802.11a, b or g (technology options) ● Global roaming (standardized) ● Wi-Fi, one of the fastest growing technology in wireless sector ● Easy to deploy ● Low cost of deployment and much cheaper compared to cellular service	● Lack of mobility (poor handoff) ● Poor coverage (difficult to cover a wider area) ● No fast roaming (IEEE 802.11r is working on this issue) ● Power consumption ● Lot of interference due to unlicensed band ● Lot of device operating in the ISM band (e.g., microwave, cordless, etc.)
Opportunity	Threat
● Internet telephony over hotspot (VoWi-Fi) ● Wi-Fi hard phones can replace old analog home phones ● Wi-Fi soft phones are very cheap and can be downloaded into any computing devices ● Coverage can be improved by having roaming agreements	● Emerging mobile WiMAX technology ● Aggressive 3G marketing ● Threats from other wired broadband players (DSL, cable, fiber, etc.) ● In some countries, policy issues are not favorable for citywide Wi-Fi deployment ● More competition due to less entry barriers

major weakness is in terms of its coverage. Although Wi-Fi technology has been improving in terms of coverage, there still needs to be a lot of research in terms of wide area Wi-Fi coverage, using mesh technology or long-distance Wi-Fi. Although many would argue that Wi-Fi may not be the best solution to the “last mile” due to its technical limitations, it is the most cost-effective wireless technology (Escudero, 2003).

5.3. Opportunities

There are great opportunities for the public voice over Wi-Fi model, if it becomes a reality. The most widely known standard 802.11b supports a smaller number of audio streams, compared to the high-performing standards, e.g., 802.11a or 802.11g. Nevertheless, 802.11a with eight non-overlapping channels can be a technology of choice for voice applications like VoWi-Fi, making it an attractive alternative to 802.11g, which has only three non-overlapping channels. Wi-Fi service providers can consider installing APs that include both 802.11a for voice users and 802.11b for data users. However, this is a business decision that may or may not be economical, as profit will be determined by the amount of traffic at particular Wi-Fi coverage locations.

5.4. Threats

The most important threat is that some cellular operators still view Wi-Fi as a competing technology and promote their cellular data services, due to the heavy investments already made in 2.5 and 3G infrastructures. The emerging mobile WiMAX technology, which is based on IEEE 802.16e standard, may be a threat to Wi-Fi in the future. In addition, the Wi-Fi service industry is too fragmented and there is more competition due to low barriers of entry. There are also free Wi-Fi services being offered in some selected locations, which may be of big threat to the paid Wi-Fi service model. In most countries, 2.4 GHz bandwidth is license-exempt, although some may require registration of use. The main threat for a citywide Wi-Fi deployment comes from the policy side. In some countries, the politics of alternative broadband access will be of special interest, if incumbents want to protect their licensed monopolies or duopolies.

6. Conclusions and the future of Wi-Fi ecosystem

Since more products use 2.4 GHz band of the radio spectrum, various interference management techniques are needed to combat interference in this unlicensed band. Though Wi-Fi systems are well established, coexistence between Bluetooth and Wi-Fi is the key issue in the 2.4 GHz ISM band for the success of Bluetooth. Many question Bluetooth's future, due to the huge success of Wi-Fi in the last years. Wi-Fi technology will dominate all high-speed applications. However, Bluetooth should come up with more innovative applications and carve out a niche interoperating with Wi-Fi.

For a cellular service operator, an integrated offering that combines the mobility of cellular and the speed of Wi-Fi is a perfect mix for mobile users. In addition, by integrating two technologies together, operators can attract new customers with value-added services provided by Wi-Fi networks, thereby reducing the churn (hopefully). Furthermore, if Wi-Fi is integrated with existing 2.5G networks, then cellular operators can delay their 3G deployments, as the integration could offer 3G-like services with less additional investment on Wi-Fi networks, instead of investing billions of dollars in 3G infrastructure.

On the WiMAX side, the position of the WiMAX technology today follows similar footsteps to the Wi-Fi technology a few years ago. Standardization and interoperability between different vendor products lead to low Wi-Fi prices and facilitated rapid penetration from a niche to mass market. It is expected that at some point, WiMAX will also reach a price and performance level similar to Wi-Fi. At least for the next few years, Wi-Fi will proliferate rapidly as a “last mile” option and deliver wireless broadband access at a dramatically lower price than WiMAX. Until we find the mobile version of WiMAX (i.e., IEEE 802.16e), both technologies, i.e., Wi-Fi and WiMAX, should coexist on complementary basis, addressing different tasks. Wi-Fi integrated with WiMAX can offer a cost-effective broadband solution to compete on a cost-per-megabyte basis with both cable and DSL to offer a cost-effective alternate broadband solution.

This article also shows that for a technology to succeed, it must take the whole sector with it by driving other technologies and interoperate with them, being complementary to others. One such technology is Wi-Fi

as it is illustrated in this paper: Wi-Fi with 2.5G/3G, Wi-Fi with WiMAX, and Wi-Fi with Bluetooth. It is more evident that in the near future, most of the wireless devices will have embedded Wi-Fi chips and will connect automatically to APs when they are within the coverage. Wi-Fi networks will be ubiquitous than any other form of wireless network, as they can be integrated with Internet and cellular infrastructures to offer both data and voice services.

References

- Ahmavaara, K., Haverinen, H., & Pichna, R. (2003). Interworking architecture between 3GPP and WLAN systems. *IEEE Communications Magazine*, 41(11), 74–81.
- Bar, F., & Galperin, H. (2004). Building the wireless Internet infrastructure from cordless Ethernet archipelagos to wireless grids. *Communication and Strategies*, 54(2), 45–54.
- Bar, F., & Park, N. (2006). Municipal Wi-Fi networks: The goals, practices, and policy implication of the US case. *Communications and Strategies*(61), 107–125.
- Bjorkdahl, J., Bohlin, E., & Lindmark, S. (2004). Financial assessment of fourth generation mobile technologies. *Communication and Strategies*, 54, 71–94.
- Bray, J., & Struman, C. F. (2001). *Bluetooth-connect without cable*. NJ: Prentice-Hall.
- Camponova, G., Heitmann, M., Slaveva, K. S., & Pigneur, Y. (2003). Exploring the WISP industry Swiss case study. *Presented at the 16th Bled electronic commerce e-transformation conference*, 9–11 June 2003, Bled, Slovenia.
- Corderio, C., Gossain, H., Ashok, R., & Agarwal, D. (2003). The last mile: Wireless technologies for broadband and home networks. In *Proceedings of 21st Brazilian symposium on computer networks* (pp. 19–23).
- Doufexi, A., Tameh, E., Nix, A., Armour, S., & Molina, A. (2003). Hotspot wireless LANs to enhance the performance of 3G and beyond cellular networks. *IEEE Communications Magazine*, 41(7), 58–65.
- Eklund, C., Marks, R., Stanwood, K., & Wand, S. (2002). IEEE standard 802.16: A technical overview of the wireless MAN air interface for broadband wireless access. *IEEE Communications Magazine*, 40(6), 98–107.
- Escudero, A. (2003). WLAN (802.11b) and WMAN (802.16a) broadband wireless access: When opportunities drive solutions. *Presented at the wireless Internet opportunity for developing nations, W2i and UN ICT Task Force*, New York.
- Fijnvandraat, M., & Bouwman, H. (2006). Flexibility and broadband evolution. *Telecommunications Policy*, 30(8/9), 424–444.
- Gillett, S., Lehr, W., & Osorio, C. A. (2004). Local broadband initiatives. *Telecommunications Policy*, 28(7/8), 537–558.
- Gunasekaran, V., & Harmantzis, F. (2006). Financial assessment of city wide Wi-Fi deployment. *Communications and Strategies*(63).
- Gunasekaran, V., & Harmantzis, F. (2007). Emerging wireless technologies for developing countries. *Journal of Technology in Society*, 29(1).
- Henry, P. S., & Luo, H. (2002). Wi-Fi: What's next? *IEEE Communications Magazine*, 40(12), 66–72.
- Lai, B., & Brewer, A. G. (2006). New York City's broadband problem and the role of municipal government in promoting a private-sector solution. *Technology in Society*, 28, 245–259.
- Lehr, W., & Mcknight, L. (2003). Wireless Internet access: 3G vs. Wi-Fi? *Telecommunications Policy*, 27(5/6), 351–370.
- Lehr, W., Osorio, C. A., Gillett, S., & Sirbu, M. (2005). Measuring broadband's economic impact. *Presented at Telecommunications Policy Research Conference (TPRC)*, 23–25 September 2005, Arlington, VA.
- Oliver, S., & Poiraud, P. (2002). *Public WLAN for mobile operators*. White paper, Alcatel.
- Salkintzis, A. K., Fors, C., & Pazhyannur, R. (2002). WLAN-GPRS integration for next-generation mobile data networks. *IEEE Wireless Communications*, 9(5), 112–124.
- Sandvig, C. (2004). An initial assessment of cooperative action in Wi-Fi networking. *Telecommunications Policy*, 28(7/8), 579–602.
- Tapia, A., & Stone, M. (2005). Public-private partnership and the role of state and federal legislation in wireless municipal networks. *Presented at telecommunications policy research conference (TPRC)*, 23–25 September 2005, Arlington, VA.
- Wanichkorn, K., & Sirbu, M. (2002). The role of fixed wireless access networks in the deployment of broadband services and competition in local telecommunication markets. *Presented at telecommunications policy research conference (TPRC)*, 28–29 September 2002, Alexandria, VA.