Evolving Wireless Access Technologies for Municipal Broadband

Marvin Sirbu
(Carnegie Mellon)

William Lehr
(MIT)

Sharon Gillett
(MIT)

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Abstract

In recent years, the landscape for wireless technology has changed substantially, with profound implications for the evolution of last-mile access infrastructure. This paper provides a high-level introduction to emerging trends in wireless technology, with a special focus on how these are impacting municipal broadband deployments. This paper discusses some of the key architectural and design choices for wireless networking systems and their implications for cost and system performance. In addition, we provide examples of how the new wireless technologies are being deployed by municipalities in a variety of contexts, with reference to wireless technologies currently available from vendors. The policy implications of these trends are discussed further in a companion paper in this issue.

I. Introduction

Broadband infrastructure has been evolving rapidly in recent years. Over the past decade, broadband Internet access has emerged as a mass market and now accounts for the majority of Internet homes (over 58% as of April 2005[1]). Most of the broadband deployed to mass market consumers to date has been wired broadband, in the form of cable or DSL modems provided by the incumbent local cable TV or telephone service provider.

Contemporaneously with the growth of the Internet and the emergence of broadband, the world of wireless services is being transformed with important implications for the entire communications services value chain. Mobile service

[1] According to Nielson/Net Ratings data, 58.46% of Internet households had broadband access as of April 2005, up from less than 10% in 2000 (See: http://www.websiteoptimization.com/bw/0505/, visited May 23, 2005).

providers are deploying broadband wireless data services via so-called "3G" networks.[2] At the same time, the proliferation of wireless LAN (WLAN) technologies like WiFi are supporting wireless data services in homes and businesses, and are providing new types of "hot spot" public infrastructure.[3]

Advances in wireless technology (including ultrawideband, smart antennas, multiuser detection theory, and ad hoc routing) have dramatically expanded the range of potential architectures, technologies, and RF frequencies which are available for developing wireless broadband access infrastructure.[4] Convergence of wireless and wired data networks and the trend towards ubiquitous computing are making wireless services an increasingly important component in,[5] complement to,[6] and potential substitute for more traditional telecommunications access infrastructure.[7]

Although broadband penetration has grown rapidly, there are still many areas that remain under-served (rural or otherwise high-cost-to-serve). For these communities, wireless offers a host of new options and opportunities. Additionally, wireless changes the cost and policy calculus for deploying last-mile infrastructure.

This paper provides an introduction to the important trends in wireless technology and networking architectures that are shaping the landscape for municipal broadband deployments. We explain key architectural features and their implications for the cost and operation of municipally-deployed wireless infrastructure. This provides a basis for understanding how emerging trends in wireless change the decision-making calculus for municipal entry.

In the following section (Section II), we provide a brief tutorial on some of the key design features for wireless networking systems that define the space of alternatives within which local governments are formulating broadband policies. In Section III we discuss examples of how these technologies are being deployed by municipalities. In a

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[2] So-called "2.5G" services that support sub-100kbps data services began to be offered in 2002 (see "Verizon launches first U.S. '3G' Network," 2002). Only recently, however, have true-3G services offering data rates of several hundred Kbps become available in selected markets in the United States (see "Verizon Wireless Makes Strides With Planned BroadbandAccess 3G Network Expansion," 2004); and 4G services offering data rates of several Mbps are beginning to be test marketed (see "Nextel debuts wireless broadband in North Carolina," 2004). At these higher data rates and with coverage that is expected to extend over wide-portions of the mobile carriers serving areas, mobile broadband services will increasingly appear as viable substitutes to fixed line DSL or cable modem offerings.

[3] See Lehr and McKnight (2003) or Werbach (2003).

[4] The diversity in wireless architectures and the implications of such diversity for business models and policy is discussed further below.

[5] For example, WLANs can extend the physical reach of wired infrastructure.

[6] For example, wireless data services expand the range of services that can be offered by 2G voice-telephony mobile service providers.

[7] For example, 3G mobile services may compete with fixed line telephone and broadband data services; or alternatively, broadband wireless fixed access (BFWA) technologies can provide an alternative to the wire-based local access facilities typically deployed by incumbent telephone and cable television operators.

companion paper in this issue, we analyze how the evolution of wireless technologies impacts the policy and economics for municipal broadband.[8]

II. Changing Landscape for Wireless Technology

In recent years, wireless technologies have made substantial advances that have made it feasible to deploy wireless communications offering improved capabilities, including supporting higher data rates, offering more flexibility with respect to RF spectrum used, and increased reliability in adverse environments (*i.e.,* improved operation in non-line-of-sight environments, ability to support reliable communication in low signal-to-noise circumstances, reduced power operations). These technologies are being incorporated into a diverse array of wireless services and products, including 3G mobile networks, WLANs, BFWA MAN networks, and satellite nets.[9] End-users and service providers are deploying myriad types of wireless networks (PANs, MANs, and WANs) to complement and substitute for wired infrastructure.[10] All of this wireless technology is changing the landscape for broadband access. To better understand some of the economics of alternative wireless technologies, it is necessary to understand a bit more about the wireless broadband landscape.

A. Understanding the key design parameters

"Wireless broadband" encompasses an almost dizzying array of technologies with widely disparate economic and performance characteristics. Technologies vary across a number of distinct dimensions, including:

- What part of the spectrum they use;
- Antenna characteristics;
- How bits are encoded at the physical layer;
- How multiple users share the available spectrum;
- Maximum bit rate and reach;
- Approach to providing backhaul from a wireless access point; and,
- Price

[8] See, Lehr, William, Marvin Sirbu, and Sharon Gillett (2005), "Wireless is Changing the Policy Calculus for Municipal Broadband," forthcoming in *Government Information Quarterly*, 2005.

[9] 3G stands for Third Generation which refers to the evolution of today's Second Generation (2G) digital mobile telephone services into 3G broadband mobile data/voice services. WLANs are wireless local area networks (LANs). BFWA stands for Broadband Fixed Wireless Access and MAN for metropolitan area networks. PANs are personal area networks. WANs are wide-area networks. PANs, LANs, MANs, and WANs refer to successively larger network coverage areas ranging from a few feet (PANs) to a few hundred feet (LANs) to a few 10s of miles (MANs) to hundreds of miles (WANs).

[10] For example, Wireless Local-Area-Networks (WLANs) using WiFi can complement wired infrastructure by lowering the cost of supporting the last couple of hundred feet of connectivity and by offering mobility. Alternatively, WiFi connected to DSL or Cable modem fixed line services may be a substitute for wide-area 3G mobile data services and BFWA systems can substitute for fixed line local access services.

Each vendor and service provider makes different decisions with respect to these key variables that affect how their product is situated in this multidimensional feature space, resulting in systems with widely varying characteristics. Let us take a closer look at the range of variation along each of these dimensions.

1. Spectrum

Wireless broadband access systems have been deployed at frequencies ranging from 400 MHz to about 30 GHz. Different parts of the spectrum have dramatically different physical properties.

For example, at 30 GHz, signals attenuate rapidly with distance, are limited by rainfall, and are limited to Line of Sight (LOS) deployments. These frequencies have been used most often as a substitute for high-capacity point-to-point links such as are used by service providers and large enterprise customers to connect backbone nodes or buildings. Because of the relative abundance of unencumbered spectrum at higher frequencies, it is feasible for operators to secure licenses for large bandwidth channels which permits these systems to operate at high bit rates per channel. This is in contrast to the limited bandwidth allocated to each license for such lower frequency services as mobile telephone. In the 1990's, vendors such as Teligent, Winstar, and ART deployed so-called Local Multipoint Distribution Services (LMDS) using these higher frequencies to link office buildings in downtown areas with 150 Mbps or higher speed services that could compete with optical fiber. However, the equipment costs for deploying these technologies were high using earlier generation digital processing technology and the market was limited to large enterprise and service provider customers. Because of these and other difficulties, virtually all of these companies went bankrupt, and LMDS services are no longer expected to play a major economic role.

In recent years, reductions in the costs of high-speed digital processing technology and other improvements have dramatically reduced the costs and performance of wireless point-to-point transmission services that operate in the upper portion of the RF spectrum. For example, the FCC recently issued an order setting forth a liberalized licensing regime for millimeter wave systems which operate above 70GHz[11] and a number of new firms are selling low-cost Free Space Optics systems (*i.e.,* fiber-optic systems that use optical-frequency lasers to transmit through the air instead of through cables) that can be deployed to support Gbps communications using desktop systems costing a few thousand dollars to interconnect downtown buildings.

While the physics of operating at frequencies above 10GHz have not changed, the costs of deploying affordable services have declined substantially and the range of potential uses has expanded.

In contrast, at lower frequencies, below say 10GHz, the spectrum is much more encumbered by legacy incumbents and licensees are typically limited to smaller bandwidth channels. However, the spectrum is less susceptible to interference from

[11] See FCC Docket WT-146 (2003).

rainfall and can operate in Non-Line-of-Sight (NLOS) situations (*e.g.,* reach inside buildings to a desktop or mobile antenna), and requires less costly technology.[12] Several bands—at 900 MHz, 2.4 GHz and 5 GHz—are available for unlicensed use, allowing Wireless ISPs (WISPs) to deploy MAN-sized networks without first seeking a license from the FCC, which substantially reduces the entry barriers faced by such carriers. Earlier, a number of service providers sought to deploy MAN-sized wireless networks in the licensed Multipoint Multimedia Distribution Service (MMDS) band at (2.5-2.7 GHz) to support WISP-like services. Sprint and Nextel are the largest license holders for this spectrum.

The lower the frequency, the better the penetration of buildings or of foliage, and immunity to rainfall, but there is less bandwidth available: 28 MHz in the 900 MHz unlicensed band, 85 MHz in the 2.4 GHz band and 300 MHz (soon to be 500 MHz) in the 5 GHz UNII (Unlicensed National Information Infrastructure) band. Maximum power limits set by the FCC are greater in the UNII band, potentially allowing for greater reach.

Thus, different RF frequencies have traditionally been associated with different types of communication services: above 10GHz with point-to-point backhaul transmission, below 10GHz with MAN-sized access networks, narrowband mobile communication services, and shorter-distance WLAN services. With advances in technology, the services have become somewhat less frequency-dependent (*i.e.,* it is possible to support services in multiple frequency bands), but operating in the different bands still implies different costs, architectures, and performance characteristics.

2. Antenna characteristics

Another key design characteristic is the antenna. This is related to the frequency of operation since the size of the antenna is proportional to the wavelength which is inversely proportional to the frequency (*i.e.,* high frequency antennas can be smaller).

The size and shape of the antenna can also affect the range and antenna gain. This has important implications for different applications. For example, mobile phones typically use small "stub-like" omnidirectional antennas that are not very spectrally-efficient (*i.e.,* radiate in all directions instead of just towards the base station) to the large satellite dishes used for Direct Broadcast Satellite (DBS) services. These large larger antennas allow for signals to be focused and sent relatively long distances, but raise costs both for equipment and deployment. A major tradeoff for vendors is whether to rely on fixed antennas mounted on the roof, a small desktop antenna that does not require professional installation, or a simple PC Card that allows for mobile access by a laptop or PDA. Simpler antennas sacrifice signal gain (and therefore reach or bit rate) for ease of deployment or portability.

[12] The lower frequency systems require lower speed digital processors which are lower cost. Additionally, the NLOS operation makes it easier to install customer premise equipment in contrast to systems that require costly antenna positioning on the outside of a home. With NLOS operation, end-users may be able to self-install customer premise equipment which substantially lowers the costs of service adoption.

Base stations, generally being more expensive fixed installations, are more likely to make use of sophisticated antennas (than is subscriber equipment). Beam forming antennas can allow the area around a base station to be divided into sectors, allowing additional frequency reuse among sectors. The number of sectors can range from as few as four to as many as 24. Such sectorized base stations have been used for a long time in mobile service base stations.

Once again, advances in antenna design have improved the capabilities and affordability of using high-gain, focused antennas in low-cost, portable environments. Capabilities that were previously limited to high-cost service provider base-stations and back-haul applications are increasingly finding use in a wider array of wireless applications. For example, companies like Vivato,[13] Arraycom,[14] Beamreach,[15] and others have recently begun to sell new phased array antennas that allow for a narrow beam to be formed and steered electronically to an individual subscriber terminal. This greatly extends reach and frequency reuse. Additionally, systems with multiple antennas at either the base station or subscriber end (Multi-In Multi-Out or MIMO) take advantage of multipath—signals bounced off of buildings or other obstructions, to provide superior throughput and resistance to fading. Several vendors are developing chips to support MIMO in conjunction with wireless LAN technology.[16]

3. Physical layer encoding

The modulation technique used to encode the signal onto the RF spectrum is also an important design choice. Use of a more complex approach may increase data rate and enhance spectral efficiency (*i.e.,* more bits are sent per Hz of spectrum used), but require higher cost components. Vendors have adopted a number of approaches to physical layer encoding to address these trade-offs. For example, first generation BFWA systems operating in licensed spectrum typically used single carrier encoding with limited robustness in the face of multipath reflections. Alternatively, early unlicensed systems used some form of spread spectrum—either Direct Sequence (DSSS) or Frequency Hopping (FHSS)—in order to meet FCC requirements for sharing the unlicensed band without coordination. Similarly, 3G mobile systems also use direct sequence spread spectrum.

Newer modulation techniques such as Orthogonal Frequency Division Multiplexing (OFDM), support high data rates/spectral efficiency and better multipath immunity at the price of more complex signal processing at the transceiver. Fortunately, Moore's law has meant that the cost of such processing has continually dropped to where today it can be implemented in single chips. Nevertheless, some vendors, such as

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[13] http://www.vivato.net

[14] http://www.arraycomm.com/

[15] http://www.beamreachnetworks.com

[16] (Jones, et al 2003)

Motorola in their Canopy system,[17] have selected very simple modulation schemes, to minimize cost, and maximize rejection of interference from other base stations.

As with the other design features, technical advances have lowered the costs and improved the capabilities of digital encoding schemes, allowing higher data rates to be supported per Hz of frequency used, but important design tradeoffs remain. The optimal choice of modulation scheme may depend on whether the spectrum being used is to be shared on an uncoordinated (unlicensed) basis or is licensed, and also on whether the subscriber is fixed or mobile. For example, DSSS has distinct advantages over OFDM for mobile applications; whereas OFDM has advantages over DSSS for higher data rate transmission for fixed location services.

4. Sharing the spectrum and/or the channel.

There are also many ways in which spectrum may be shared among multiple users and the choice of sharing mechanism has important implications for the cost and service quality of supporting different types of traffic in different types of network architectures (*e.g.,* large or small cell sizes, symmetric or asymmetric traffic, isochronous or asynchronous traffic).

For example, in 3G mobile networks, each user's signal is separated by the use of a different spreading code, or Code Division Multiple Access. Spreading the signal reduces the number of bits per Hz and thus limits the maximum bit rate of each user in a given channel bandwidth. Separate frequency bands are used for upstream and downstream, fixing the amount of capacity available for transmissions in each direction (Frequency Division Duplexing). By contrast, wireless LAN systems use Time Division Duplexing (TDD) where the same frequency band is used for transmission in both directions. This allows dynamic adaptation to varying levels of asymmetry in upstream and downstream traffic. Which is better depends on the type of traffic that is to be supported. For example, the 3G approach might be better if your goal is to share the traffic among a large number of users with similar and predictable service use requirements (*e.g.,* to support two-way voice communications or streaming broadcast media); while the WLAN approach may be better if traffic is more heterogeneous (*e.g.,* P2P data communications among multiple PCs).

Broadband Wireless Fixed Access (BFWA) systems more often are designed around Time Division Multiple Access. In these systems, a single high bit rate channel is shared among multiple subscribers by interleaving their transmissions in time. Given bursty traffic, a user can occasionally take advantage of the peak rate of the channel, but as more users share the channel, the average bit rate available to each user declines. In wireless LAN systems, this sharing is based on random access; in others, the base station allocates capacity upon request to each subscriber and can tightly control the Quality of Service given to each user.

[17] http://motorola.canopywireless.com/

Channel sharing and physical layer techniques that depend on very short propagation delays between the base station and the subscriber or limited multipath delay spread, may perform poorly as distances are increased.[18] Thus, the sharing mechanism must be optimized for the expected reach of the system.

Channel sharing overhead can be reduced if each user can transmit a large packet whenever she has a turn. However, this can lead to longer delays between successive channel accesses, which may interfere with latency sensitive applications such as Voice over IP or video conferencing. Many first generation systems opted for channel efficiency, whereas newer systems are designed to support smaller frames and provide better performance for delay sensitive applications.

5. Maximum bit rate and reach

Wireless systems also differ with respect to the maximum bit rate that can be supported. For a given average power level, sending more bits per second means less energy per bit, which in turn means more sensitivity to noise at a given distance from the base station or access point. System designers can increase reach by decreasing bit rate. Indeed, many systems, such as wireless LANs, automatically adjust the bit rate downward for far away clients as the signal strength declines with distance. Alternatively, the additional energy per bit at lower bit rates can enable the use of smaller antennas, or reception inside a building. Early broadband fixed wireless systems operated at fixed bit rates, but newer systems typically adapt the transmission rate to each user as needed. Still, vendors optimize the overall design for different assumptions about antennas, bit rate and reach.

6. Backhaul

When deploying a broadband wireless system, one must consider more than the wireless link from a base station to a user. Base stations themselves must be linked back to a city or regional node and from there tied in to the larger Internet. Some vendors provide systems only for the last wireless link. Others, provide products designed to reduce backhaul cost as well. Motorola Canopy sells point-to-point wireless radios to backhaul traffic from its multipoint base stations. Other vendors integrate DSL modems with a wireless access point to reduce the cost of using DSL for backhaul. There are WLAN access points that can bridge to Homeplug networks that deliver data over power lines, for backhaul within a home.

In so-called mesh networks, each access point, which serves end users, can also function as a wireless transit node to route traffic from other access points. Thus traffic from a subscriber may go to a first access point and then hop between several more access points before reaching one that is tied in to the wired Internet. Such systems use

[18] (Chayat, 2002)

self-configuring ad hoc routing protocols to determine the best route to a wired access point.[19]

B. Putting the Pieces Together

If we look across the range of vendors and products in the broadband wireless space, we can see that different vendors have located their products in different parts of this multi-dimensional product space. Indeed, there has been a great deal of ferment in this sector with rapid changes in cost or capabilities along each dimension, and corresponding shifts in product design. As noted by Abernathy and Utterback (1978), in the early phase of a new product market, before the emergence of a "dominant design," there is a great deal of product variety. At the turn of the 20th century automobiles came with internal combustion engines or steam engines, three four or five wheels, front steering or rear steering, and many other configurations before the dominant design of a four wheel vehicle with internal combustion, front wheel steering and rear drive wheels emerged.

At the turn of the 21st century, we are in a similar place with broadband wireless. Many vendors produce incompatible products of proprietary design. They have made very different choices in the design space, according to their respective competences, target market or limitations of the available technology at the time the design was instantiated. Standards have begun to emerge which define "dominant designs" within certain segments of the design space.

1. 3rd Generation Cellular

Third generation designs were the first cellular standards to optimize for data traffic as well as voice. The original cellular model assumed expensive, powerful, sectorized base stations, mounted on towers, and serving a radius of several kilometers. With the growth in cellular usage, base stations have proliferated to realize frequency reuse creating a demand for smaller, less expensive base stations. 3G cellular standardizes on CDMA (either WCDMA or CDMA 2000 EV-DO) for sharing the available spectrum, with a maximum bit rate of roughly 2.5 Mbps to a stationary user, and a few hundred kilobits for a mobile user. User antennas are small, appropriate to handheld devices, and the bit rate and reach are chosen to allow reception within buildings. Frequencies licensed for 3G are typically in the 1.7 –2.1 GHz range, varying by country.

Verizon introduced CDMA 2000 EV-DO in the United States in 2003 with deployments in Washington, D.C. and San Diego. They have indicated plans to roll out in major cities nationwide in 2004. The service offers 300-500 Kbps unlimited use for $80/month.[20] This is competitive with some DSL systems with respect to speed, though not on price, while uniquely providing mobility within the cellular coverage area.

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[19] Http://www.tropos.com

[20] http://news.vzw.com/lead_story/pr2004-01-08.html

2. Wireless LANs

The IEEE 802.11 committee issued the first standards for wireless local area networks (WLANs) in 1997 and products began appearing shortly thereafter. Just seven years later, vendors expect to sell 30 million units worldwide. The target market for wireless LANs—mobile computers within a building or campus—led to specific design tradeoffs and choices. The initial 802.11—which was rapidly succeeded by the almost identical, but faster, 802.11b—operates at 2.4 GHz, a band designated as unlicensed worldwide, allowing for international scale economies. Access points and mobiles use simple omnidirectional antennas. Reflecting the low power limits and simple antennas, the reach was set at about 100 meters resulting in bit rates of 11 Mbps over the channel. Physical layer encoding using DSSS provides interference protection against other users of the band (such as cordless telephones) while the channel is shared using contention access and TDD.

Getting its start in warehouses and university campuses, WLAN use quickly spread to residences as a means of linking multiple computers in the home, at lower cost than pulling LAN cabling. The simple design of 802.11b allowed for very low cost access points that could function as a bridge to wired Ethernets.

Two new WLAN standards have been released since 2000. Operating in the UNII band, 802.11a uses OFDM and has a peak channel rate of 54 Mbps. 802.11g also uses OFDM to realize 54 Mbps in the 2.4 GHz band. It is estimated that shipments of 802.11g will surpass 802.11b in 2004[21], with 802.11a trailing far behind. A forum of equipment vendors certifies implementations as interoperable with the trademark Wi-Fi.

The rapid and widespread adoption of 802.11b led many ISPs to attempt to use it for broader metropolitan access. By adding fixed directional antennas for both base stations and subscribers, the reach of 802.11 can be increased to several miles. However, the contention protocol for channel sharing performs poorly with longer propagation delays, and vendors have introduced products that make use of 802.11 standard chips but alter the protocol slightly for improved performance over the wider area. The original 802.11 standard specified a FHSS option that has been used by some vendors of WISP equipment. However, this option requires different silicon than is used by most WLAN equipment, and so does not benefit from the same learning curve.

3. First Generation Broadband Fixed Wireless

First generation BFWA systems varied widely in their designs. Some copied the DOCSIS design used for cable modems, merely shifting the frequencies used for transmission on cable to higher frequency wireless bands, such as MMDS. Some combined FHSS with substantial fixed antennas to realize long reach at bit rates of several megabits per second. Many operated only with direct LOS. Other physical layer technologies that have been used include single carrier (Hybrid Communications), Multi Code DSSS (Wi-Lan) or 3G WCDMA (IP-Wireless). The lack of standardization led to

[21] http://www.reed-electronics.com/electronicnews/article/CA407177

high costs, lack of interoperability, and reluctance by chip vendors to produce low cost, highly integrated components. Many of the first generation equipment vendors have been through bankruptcy or exited the market altogether.

4. Wi-Max

In 2003, the IEEE adopted the 802.16 standard known as Wi-Max to meet the need for standards based BFWA. As with the original 802 LAN standards, 802.16 actually defines a family of standards with options for specific settings. Just as the Ethernet media access control (MAC) layer can run over copper, fiber or coax, the 802.16 MAC is designed to support operation over multiple physical layers, *e.g.* frequencies above and below 11 GHz, using either FDD or TDD, different channel bandwidths, and using either single carrier or OFDM. 802.16a deals specifically with frequencies from 2-11 GHz, specifies OFDM, and is expected to be used both in unlicensed bands (e.g. UNII at 5 GHz) and licensed (MMDS at 2.5 GHz).

Vendors have announced Wi-Max products that will be designed for long reach using roof mounted subscriber antennas, and systems for shorter reach targeted at a laptop with a PC-Card. Bit rates up to 70 Mbps and reach of 30 miles have been claimed, though both numbers will not be realized simultaneously. Indeed, early implementations show a rapid drop off of realizable channel bit rate as the distance increases, dropping to 18 Mpbs at 70 miles.[22]

Variants of the standard targeting mobile users (802.16e) and providing enhanced QoS (802.16b) are already in the works. Redline Communications shipped the first 802.16a compatible equipment in March, 2004. Several chip vendors, including Intel, are working on 802.16a integrated silicon, and low cost subscriber units and access points are expected to become widely available in 2005. Already many of the surviving vendors of first generation BFWA equipment have announced they will move towards Wi-Max compatible products. Vendors touting sophisticated antenna technology, such as MIMO or phased arrays have signaled their intention to apply these to 802.16a compatible products.

The result is expected to be sharply lower costs for BFWA equipment, comparable to what has happened to the Wi-Fi market since the ratification of 802.11b. When 802.16e is adopted, supporting mobile users, Intel has said it expects to do for Wi-Max what it did for Wi-Fi with Centrino—make it a standard feature of virtually all laptops.[23]

If Wi-Max is the future, communities deploying today don't have the choice. Indeed, given the complexity of the standard, and delays by the IEEE in specifying conformance criteria, it may be later than 2005 before interoperable equipment is readily available.

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[22] http://www.dailywireless.org/modules.php?name=News&file=article&sid=1968

[23] http://www.computerworld.com/mobiletopics/mobile/story/0,10801,86093,00.html

The following figure illustrates the evolution of BFWA technology towards Wi-Max (Alvarion, 2004a).

2000 2001	2002 2003	2004 2005
Proprietary Solutions	→	Standard-based WiMAX Solutions
Data rate: 2-11 Mbps peak	Data rate: 6-54 Mbps peak	Data rates: Up to 72 Mbps peak
Chip sets: 802.11/b RF and PHY or proprietary	Chip sets: Vendors develop their own; some use 802.11a RF & PHY	Chip sets: Volume silicon supplier
Air interface: Frequency hopping and Direct Sequence	Air interface: OFDM and SCDMA approaches	Air interface: 256 FFT OFDM and OFDMA

Figure 1.

5. Mesh Networks

To cover a large metropolitan region there have been three approaches:

- Use a single powerful base station with a long reach to cover the area. However, a large population in the coverage area can mean congestion among users contending for the limited bit rate of a transmitter;
- Use multiple cells, each interconnected to the wired network for backhaul as with 3G cellular
- Use wireless to link end points to each other and then back to the wired Internet.

This last approach is being used by vendors touting mesh networks. In some designs, only base stations can act as wireless routers, handling traffic for both their own clients and other base stations as well. In other designs, every subscriber unit acts as both end point and transit point, greatly increasing the redundancy, but also the complexity of the network.

Metricom with its Ricochet network was the first to use such an approach. More recently, Tropos and MeshNetworks have released mesh network products. There are also grass root efforts, using open source software to build mesh networks out of 802.11 capable end user PCs.

6. Situating Vendors in Product Space

As the discussion above makes clear, there is a great deal of product variety in the wireless broadband space. The table below gives some indication of the combinations of attributes selected by various vendors for their products.

Attribute / Vendor	Spectrum	Subscriber Antenna	Base station antenna	PHY layer	Sharing	Bps and Reach	Backhaul
IP Wireless	UMTS, MMDS	Desktop	Sectorized	WCDMA (3G)	WCDMA	16 Mbps 2.5 km	Wired
Redline	3.5 GHz	Rooftop	Sectorized	OFDM (802.16)	TDMA	≤70 Mpbs ≤70 km	Wired
Motorola Canopy	UNII	Rooftop	Sectorized	Proprietary	TDMA	10 Mbps 2 mi	Point to point wireless
Tropos	2.4 GHz	PC-Card	Omni	802.11b	CSMA/CA	11 Mbps 300 meters	Mesh
Beamreach	MMDS	Rooftop	Phased array	OFDM	TDMA	83 Mbps 35 km	Wired
Vivato	2.4 GHz	PC-Card	Phased array	802.11b	CSMA/CA	11 Mpbs 2 km	Wired

Table 1.

Larger vendors, such as Alvarion, have a portfolio of products covering different parts of the overall product space.

We can make a number of general observations about trends in this space. First, proprietary physical layer choices are giving way to a small number of standards: 3G cellular, 802.11 and 802.16. This is driven by the economics of semiconductor chips implementing these standards. Second, there is a distinct tradeoff to be made between maximizing bitrate and reach by using rooftop subscriber antennas, and reducing costs of deployment by designing for desktop or PC-card antennas that can be purchased and installed by the consumer. Serving PC-card devices well requires that the technology deal with user mobility as well. Third, long reach systems means fewer cells, and typically wired backhaul. Shorter reach systems require more cells and create a demand for distinct middle mile approaches, such as wireless backhaul or mesh networks. In the near term we are likely to see combination approaches, *e.g.*: large cell Wi-Max base stations serving fixed antennas, used as a backhaul technology for 802.11 access points serving mobile users equipped with PC-Cards or antennas built into a laptop PC or PDA. Fourth, newer generation systems, or updates to existing standards, are being designed to handle VoIP and other applications requiring QoS. Finally, systems operating in unlicensed spectrum allow rapid entry by competitive WISPs; however, congestion in the unlicensed band may lead to a preference for licensed spectrum, such as MMDS, for long reach systems. In the near term, congestion in the 2.4 GHz band from 802.11b/g is driving WISPs to the UNII band at 5 GHz.

III. Municipal Networks Use of Wireless

Not surprisingly, local governments have taken advantage of the advances in wireless technology and are using these technologies to expand the range of services they provide and the locales in which those services are provided. These efforts may be grouped into three classes of efforts: (1) municipal provision of MAN-sized access networks; (2) mobile broadband services for public safety; and (3) community "hot spots." While the first of these has already been occurring in the absence of wireless (*e.g.,* via Municipal Electric Utilities (MEU)[24] deployment of broadband services), the latter two are uniquely associated with wireless technologies and, in particular, are providing interesting test cases of the new class of WLAN/MESH-based technologies for building up community access networks.

Additionally, the municipalities that are deploying these wireless networks are utilizing the full spectrum of business models: (1) Retail service model; (2) Wholesale service model; (3) Franchisee model; (4) Real estate model; (5) Coordination model.[25] In the following we provide a brief overview of selected examples of each of these networks to provide examples of the types of activity that are underway.

These wireless networks are also expanding the range of services that can be supported. For example, in addition to supporting broadband access to residences and businesses, these wireless networks can also be used to support sensor networks and location-based services.

A. Municipal wireless MAN-sized access networks

As noted earlier, some municipalities have been providing broadband services based on wired technology (cable or DSL modems). Since such investment is associated with large sunk and fixed costs, it is not surprising that few communities have elected to invest in providing municipal infrastructure, and that the communities that have been most likely to offer telecommunication services are those that already have an MEU. In many cases, the MEU has already invested in an advanced data communication network to support its internal operations. Also, the MEU already has a relationship with residents and businesses in the community and has to maintain customer support and outside facilities maintenance services for its local electric power distribution plant. Typically,

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[24] MEUs already have the resources and experience of maintaining outside plant facilities associated with their provision of local electric power distribution services. See Lehr, Sirbu, and Gillett (2005), Gillett, Lehr, and Osorio (2003) and Osorio (2004) for further discussion of MEUs.

[25] See Lehr, Sirbu, and Gillett (2005) for further discussion of these alternative business models.

the MEU owns or has access to outside structures (poles or conduit) which can be used to deploy the last-mile communications infrastructure. Finally, a number of power companies have been experimenting with using the existing power lines to transmit communication signals, called "Broadband over Power Lines" (BPL).[26] At least one vendor in this space uses BPL for distribution to the neighborhood, and 802.11 for the drop from the power pole.[27]

Wireless technologies expand the set of technical options, and depending on the local circumstances, may offer a substantially lower deployment cost. MEUs may elect to deploy communication services via wireless technology, instead of wireline. For example, Owensboro Municipal Utilities in Kentucky and Wheatland Electric in Kansas, are both deploying BFWA systems using Alvarion's technology to provide broadband access in their rural communities.[28] The Alvarion technology is based on relatively large cell sites (up to 30 miles at 20 Mbps; up to 70Mbps at shorter distances) which are typical of the traditional architecture employed by an earlier generation of BFWA technologies that were deployed in MMDS (2.1-2.7GHz) spectrum, but which were not successful in the market.[29] The new generation of MAN-sized wireless technologies based on IEEE 802.16 standards ("WiMAX') offer improved line-of-sight performance and should be able to be deployed inexpensively to provide a robust back-haul capability to interconnect WiFi hot spots or to provide direct end-user connection.[30] Furthermore, with the emergence of public standards for this technology, the industry will benefit from industry-sized scale and scope economies and learning effects that will lower costs and barriers to adoption (*e.g.,* end-user uncertainty, fear of stranding). For example, the costs customer premise equipment should fall much closer to the commodity-level pricing that characterizes WiFi equipment today.

The new wireless technologies are also being deployed to support MAN-sized networks in non-MEU communities and by new types of players. For example, Cumberland, the county seat of Alleghany County in Maryland, formed a non-profit broadband wireless ISP, or WISP, to provide high-speed access services to its rural communities after becoming frustrated with the incumbent wired-carrier, Verizon.[31]

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[26] Although BPL services have been anticipated for a number of years, they are only now starting to roll-out (see, for example, "Broadband-over-power-line vendor rolls out service," 2004). There are concerns about the scalability of such services to higher bandwidths and about potential interference with other RF systems (see "Broadband over power lines gets a boost," 2004).

[27] See http://www.amperion.com/

[28] See Alvarion (2004a).

[29] As discussed earlier, the market was limited given the high price of the equipment and state of data communication markets using technology available at the time, and the earlier MMDS systems offered poor NLOS performance.

[30] While Alvarion is the market leader in offering BFWA equipment, the current generation of systems were deployed before the WiMAX standard was finalized. Wi-Max compatible equipment is not expected until late 2004.

[31] The Cumberland-based non-profit broadband ISP is called AllCoNet (http://www.allconet.org/execsummary.htm) (see Fitchard, 2002).

WISPs have emerged in a number of rural communities in the United States and abroad.[32] A number of these are investor-owned service providers that serve as franchisees for municipalities wishing to construct a broadband wireless network.[33]

While most of the WISPs are providing retail services directly to end-users, there are some that have adopted an open access/wholesale model. For example, the Franklin Public Power District, an MEU in Pasco, Washington, is providing a wireless broadband open access platform for resale by third-party ISPs because state-law prohibits the MEU from offering retail services.[34]

Finally, a number of municipalities are facilitating entry by investor-owned wireless service providers by providing access to government buildings and schools for antenna siting, and in some cases, by allowing antennas to be placed on street lights and other municipally-owned property for wireless technologies based on small cell sites (short-range wireless technologies, like WiFi). For example, Cerritos California has deployed a WiFi-based MESH network using technology from Tropos Networks.[35]

For communities that do decide to deploy MAN-sized access infrastructure, the wireless technologies are important because they expand the range of players and technical options for leveraging existing investments, thereby helping to lower the costs of a municipal deployment. For example, wireless can be used to economically extend public access to municipal fiber or to local government intranet backbone services.

B. Mobile broadband services for public safety

Public safety services have an obvious need for high-speed mobile data services to allow police, fire, and emergency personnel to access on-line data (*e.g.,* to link to criminal databases and automobile registry data) and communication critical data in real-time (*e.g.,* relay medical information from the ambulance to the hospital). Traditionally, these services have been based on proprietary technologies specially developed to meet the needs of the target service.

With the advances in communications technology, and more recently, with the explosion of interest and services based on WLAN technologies operating in unlicensed spectrum such as WiFi, there is growing interest in implementing public safety systems using such technologies. For example, San Mateo, California, has installed a Tropos WiFi MESH network to support high-bandwidth mobile data access for public safety officers.[36] Although these networks have not been installed to support public access,

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[32] See Johnston and Snider (2003) for some examples of WISPs.

[33] For example, NetStar is a Tennessee-based WISP (see Blackwell, 2002).

[34] See Franklin PUD (2004).

[35] See "Nation's first wireless community broadband service deployed in Cerritos, CA," (2004) and Tropos Networks (2004).

[36] See "California Police Department uses Tropos' mesh network," (2003).

these could be shared, and by so doing, the costs of deploying broadband local access services in the community could be lower.

Additionally, mobile wireless technologies that are put in place for use within a government office, may provide the incentive and platform for extending connectivity outside the office. For example, consider the traffic officer who uses a PDA to collect data on illegally parked cars and then uses a wireless connection at the station house to download the information to automate issuing tickets and reduce data entry errors. If this system is expanded to support broadband mobile data while the traffic officer is on patrol, an automatic cross-check can be made of licenses to see if there are any outstanding warrants or other problems that require special action (*e.g.,* booting/towing the car).

C. Community "hot spots"

Another interesting trend has been the deployment of WiFi-based "hot spots" of broadband connectivity in public spaces. Sometimes such investments are justified as opportunistic ways to extend free access to under-used local government intranets, or to enhance the usability of public access terminals in schools and libraries to adjacent areas within the building or in close proximity to the building (in a nearby park). Other times such investments are justified in order to promote economic development. For example, when the mall outside town installs free wireless service in its food court to attract customers, the town may respond by installing WiFi hot spots in the depressed downtown business district to help support economic development there. For example, the cities of Long Beach (CA), San Francisco, Seattle, Jacksonville (FL), and New York have all deployed municipal public hot-spots offering "free" WiFi internet access.[37] More recently, a number of cities have announced plans to use WiFi to provide coverage over wide areas. The most heavily publicized of these deployments is Philadelphia[38]

The key attraction of WiFi hot spots is that they can be deployed with very little cost. Most private data networks are under-utilized and can support at least some additional shared use without the primary users seeing any noticeable deterioration in their service quality. WiFi equipment is quite cheap, is easily installed, and is robust. If the goal is to provide free access services in a localized area, WiFi can be quite effective.

Once deployed, WiFi hotspots can be interconnected to provide wider area coverage and agreements to allow hotspot-roaming can allow users to take advantage of WiFi access from multiple hot spot providers. While it is possible to use WiFi to construct a mesh network (*e.g.,* Tropos Networks), this was not anticipated in the original design. Most WiFi hotspots are deployed using backhaul services such as a T1 leased line, cable modem, or DSL fixed line broadband service that would need to be replaced to

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[37] See Markoff (2003).

[38] See Walsh, Trudy, "Philadelphia Free-for-all," *Government Computer News*, May 23, 2005 (available at: http://appserv.gcn.com/24_6/mobile-wireless/35315-1.html, visited on May 23, 2005). The article notes that dozens of cities are engaged in or actively contemplating similar deployments.

convert the disparate WiFi hotspots into a wireless mesh.[39] In addition to reworking/replacing the backhaul architecture, it would be necessary to modify the “hot spot” model in a number of other ways if it is to grow up or evolve into a competitor for BFWA networks. Transitioning from a “free” service that offers only “best efforts” service to a carrier-grade platform for wide-area connectivity will require a change in the underlying business model, new technology, and new investment.

IV. Conclusions

Wireless will play an important role in the broadband future. It will serve as both a complement to and substitute for wired access. The wireless future will be complex because there is no single wireless solution that is likely to predominate. Rather, there are a diverse array of technologies and options that are appropriate in different contexts. In many cases the boundaries between alternative architectures are not sharp, and solutions that may appear more appropriate in one venue may be viewed as viable substitutes in another (*e.g.,* 3G mobile services competing against WLAN WiFi technologies).

This paper provides a brief introduction to the emerging landscape for wireless broadband access technologies. It first explains some of the key dimensions along which alternative technologies differ. These include the choice of spectrum used, the antenna design, the encoding strategy, the mechanism used to share spectrum among multiple users, the bandwidth offered, and the back-haul requirements. These design choices influence the range/coverage of wireless nodes and the data rates and services which can be supported, and hence, the economics for building wireless networks. We specifically address five types of broadband wireless networks that are currently being deployed: 3G mobile, WLANs, BFWA, WiMAX, and Mesh networks. Each represents a different choice of key design parameters which directly impacts the environments and methods by which these networks are being deployed. For example, 3G refers to the broadband wireless services being deployed by national mobile service providers, whereas BFWA and WiMAX are being deployed by fixed-node service providers.

Finally, we map the various technologies to three typical contexts in which municipalities are deploying wireless technology: (1) as basic infrastructure; (2) for mobile public safety systems; and (3) for "hot spot" access. These contexts highlight three important motivations for municipalities to provide wireless access, but even in these cases, the boundaries are blurring. For example, Philadelphia is planning to provide wide area coverage (as basic infrastructure) using WiFi (tradionally a "hot spot" technology).

The picture that emerges from this analysis is complex. Communities that are evaluating wireless technologies must perforce engage in a multidisciplinary analysis with technical, business strategy/economic, and public policy dimensions that are

[39] For example, the Philadelphia network is anticipating using leased lines and pre-WiMAX wireless technologies for backhaul. (see Wireless Philadelphia Business Plan, February 9, 2005, available at: http://www.phila.gov/wireless/, visited May 23, 2005).

inextricably linked. There is no single wireless technology that is best for all circumstances and applications. The choice of technology depends critically on the municipalities goals, capabilities, and time horizon. The extent to which systems put in for one purpose (*e.g.,* public safety) may be extended to serve another purpose (*e.g.,* provide broadband access services to the general public) is being hotly debated. Similarly, there are technical debates regarding the substitutability of large-cell technologies like WiMAX for smaller-cell mesh technologies; or of the scalability of WLAN WiFi technologies used for "hot spot" access to provide wide-area coverage, as is currently being explored in Phildadelphia. For further discussion of the policy implications of wireless technologies for municipal networking, see the companion paper also in this issue.

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