Understanding Wi-Fi and WiMAX as Metro-Access Solutions

This paper provides incumbent wireless Internet service providers (WISPs), new WISPs and demanding new markets (such as government and education) with a technical analysis of alternatives for implementing last-mile wireless broadband services.

Summary

This paper provides incumbent wireless Internet service providers (WISPs), new WISPs and demanding new markets (such as government and education) with a technical analysis of alternatives for implementing last-mile wireless broadband services. The paper compares current 802.11 single hop and 802.11 mesh networks with 802.16, a new technology that solves many of the difficulties in last-mile implementations.

In this paper, the term WISP encompasses Internet service providers and new market players in vertical segments (such as government and education) that want to expand public and private network access through unlicensed wireless bands.

The paper explains in detail the technical differences between revisions of 802.11 and 802.16, describes the technology positioning, and reviews the standards and technology associated with various usage models. Several wireless broadband deployment solutions, scenarios and their merits, including their challenges, are also described.

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Introduction

WISPs have been striving for wireless technologies that make wireless metro access possible. Access to areas that are too remote, too difficult or too expensive to reach with traditional wired infrastructures (such as fiber) require new technologies and a different approach.

The three key deployment types that make up wireless metro access are backhaul, last-mile and large-area coverage (referred to as hot zones). Wireless last-mile coverage typically uses the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard with high-gain antennas, while hot zones use modified IEEE 802.11 equipment in a mesh deployment.

Open standard radio technologies—including 802.11, 802.16 and future standards—offer advantages to WISPs and users. For the first time, industry-wide support and innovation are driving broadband wireless networking technologies. Network operators, service providers and users benefit from a wide array of high-performance, feature-rich and cost effective products.

Wireless Fidelity (Wi-Fi) revolutionized the market for unlicensed client-access radios in a wide variety of applications. Starting in 2005, Worldwide Interoperability for Microwave Access (WiMAX) certification of the IEEE 802.16-2004 standard for fixed-position radios will do the same for point-to-point (P2P) and point-to-multi-point (P2MP) wireless broadband equipment in both the licensed and unlicensed bands. In 2006, the IEEE 802.16e standard for portable operation is expected to be ratified, thus standardizing client radios in unlicensed and licensed bands. This certification will provide users with an alternative and allow service providers the benefit of additional tier services.

The cost and limited flexibility of wired backhaul limits wireless access growth. In the face of the technical challenges, WISPs have begun to look ahead at WiMAX-certified solutions, which will be available in early 2005.

To date, WISPs have capitalized on the cost and complexity associated with traditional high-speed wired broadband infrastructures by applying ingenuity to solve last-mile problems. WISPs modified existing wireless technologies, typically based on the IEEE 802.11 standard, to patch last-mile gaps. Limitations in these deployments surfaced, however. Because wired backhaul solutions can be too expensive for establishing widespread wireless access and because a standard means for deploying IEEE 802.11 into the last mile or within a hot zone has not emerged, each WISP implements long-distance IEEE 802.11 solutions differently.

WiMAX is a wireless metropolitan-area network technology that provides interoperable broadband wireless connectivity to fixed, portable and nomadic users. It provides up to 50-kilometers of service area, allows users to get broadband connectivity without the need of direct line-of-sight to the base station, and provides total data rates up to 75 Mbps—enough bandwidth to simultaneously support hundreds of businesses and homes with a single base station.

This white paper discusses wireless metro-access technologies: Wi-Fi with high gain antennas, Wi-Fi meshed networks and WiMAX. It explores how the technologies differ and how they can be combined to provide a total last-mile access solution now and in the future.

Challenges

Typical modified IEEE 802.11 network topologies associated with last-mile and hot-zone coverage use either directional antennas or a mesh-network topology. Wi-Fi provides the certification for IEEE 802.11 client-to-access point (AP) communications. However, implementations of AP-to-AP and AP-to-service providers (that is, backhaul applications) that are typically needed for wireless last-mile and hot-zone coverage are still proprietary, thus providing little or no interoperability.

Because the IEEE 802.11 standards were designed for unwiring the local area network (LAN), metro-access applications are facing the following challenges:

- **Non-standard wireless inter-AP communication.** Today, wireless links used to connect 802.11 APs for inter-AP communication in mesh networking are vendor-specific. The proposed IEEE 802.11s standard, estimated to be ratified in 2007, will standardize Wi-Fi mesh networking.
- **Providing quality of service (QoS).** QoS refers to the ability of the network to provide better service to selected network traffic over various technologies. The goal of QoS technologies is to provide priority (including dedicated bandwidth to control jitter and latency) that is required by some real-time and interactive traffic, while making sure that in so doing the traffic on the other paths does not fail. In general, unlicensed bands can be subject to QoS issues because deployment is open to anyone. Advances in the associated standards and related technologies, however, help mitigate problems with unlicensed bands, such as multi-path interference. The proposed IEEE 802.11e standard, which is projected to be ratified in 2006, will standardize Wi-Fi mesh-network topology.

- **Expensive backhaul costs.** Backhaul refers both to the connection from the AP back to the provider and to the connection from the provider to the core network. To extend wireless access nodes, providers still rely on wires for long-distance coverage. Some providers find wiring large areas too expensive.
- **Limited services.** Without QoS, applications such as voice over Internet protocol (VoIP) may reduce a call's quality, thus limiting the provider's ability to tier services and obtain additional revenue streams. Current Wi-Fi last-mile and large-coverage solutions offer excellent data transfers. Some vendors offer proprietary QoS.

Despite the challenges, wireless metro-access solutions are continuously sought after for the following reasons:

- Wireless metro-access solutions available today, such as mesh networking implementations, are more cost-effective and flexible than their wired counterparts.
- These solutions provide a standards-based connection from AP-to-mobile users for hot-zone coverage.
- WISPs can offer broadband services to geographically challenged areas (such as rural towns).
- Local governments can provide free access for businesses or emergency services (such as police and fire fighters).
- Educational institutions can broaden learning through online collaboration between students and faculty on and off campus.
- Enterprises and large private networks can communicate and monitor supply-chain activities in near real time.

Wireless Technology Usage Segments

The reasons behind wireless deployments are as diverse as the wireless technologies being offered today. Each wireless technology is designed to serve a specific usage segment:

- Personal area networks (PANs)
- Local area networks (LANs)
- Metropolitan area networks (MANs)
- Wide area networks (WANs)

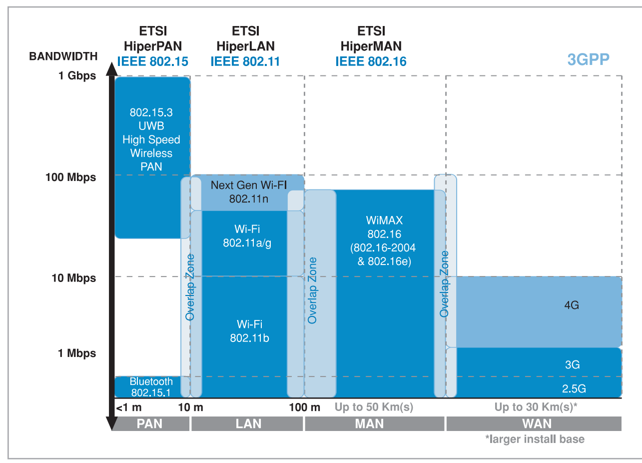
The requirements for each usage segment are based on a variety of variables, including:

- Bandwidth needs
- Distance needs
- Power
- User location
- Services offered
- Network ownership

Optimized applications exist for each usage segment. For example, in some locations it is possible to seamlessly use a third-generation handset while traveling country to country while in a wireless WAN environment.

Figure 1 shows the wireless standards organizations, the standards, and their capabilities (bandwidth and distance) mapped to the four usage segments previously mentioned.

Figure 1. Wireless technologies target segments.



The three standards organizations in Figure 1 are:

- Institute of Electrical and Electronics Engineers (IEEE)
- European Telecommunications Standards Institute (ETSI)
- Third-Generation Partnership Project (3GPP)

The IEEE and ETSI standards are interoperable and focus primarily on wireless packet-based networking. The 3GPP standard focuses on cellular and third-generation mobile systems.

Each usage segment has a corresponding wireless standard, but segment overlaps do exist. For example, ultra-wide band (UWB) supports faster file transfers and could allow a user to transport files faster than when using Wi-Fi or WiMAX. A user might employ UWB to quickly transfer a file, but distance limitations prevent this from becoming common place in the LAN or MAN. In the case of Wi-Fi and WiMAX, the lines may seem even more unclear. WISPs deploying last-mile solutions with Wi-Fi and directional antennas or using a Wi-Fi mesh topology over large areas may make it seem as though Wi-Fi is moving into the MAN. However, understanding usage segments and the associated technologies make it apparent that very little overlap exists. These technologies are extremely different, as can be shown by reviewing the three different implementation types.

1. **Wi-Fi with directional antennas**—Focus on patching last-mile gaps. Currently, WISPs offering alternatives to Digital Subscriber Line (DSL) and Data Over Cable Interface Specification (DOCSIS) use this solution. However, long-range limitations exist, specifically in dealing with multi-path interference. In addition, QoS and proprietary equipment reduce scalability. These approaches are looking ahead to WiMAX to fill in the last mile, to offer QoS and to support backhaul.

2. **Wi-Fi with a mesh-network topology**—WISPs use this technology to cover large areas and to extend the reach of the LAN for both indoor and outdoor applications. A mesh-networking topology provides a more scalable solution than a solely directional-antenna implementation. More APs (also referred to as nodes) are deployed in dense clusters to get around wire dependency and to increase client coverage. However, QoS and inter-AP communications are still proprietary—WISPs using this technology are looking ahead to WiMAX to provide inter-AP backhaul and point-of-presence (PoP) backhaul.

3. **WiMAX**—802.16-2004-based devices offer WISPs a standards-based long-range, higher performance solution. WiMAX devices for the last mile will not be available until 2005. This new technology offers a great deal of potential.

Wireless Personal Area Networks

The first usage segment is the wireless PAN, shown in the left column of Figure 1. Typical network coverage in the PAN is up to ten meters, but performance varies depending on the standard employed.

The IEEE 802.15.1 standard (also called Bluetooth) is primarily used for unwiring computing and communication peripherals, such as a computer to a printer or a handset to a headset. Bluetooth is rated up to 1 Mbps in performance data rates.

The second standard in this usage segment, the IEEE 802.15.3 standard (also called ultra-wide band), is designed for delivering multimedia services. UWB supports data rates over 400 Mbps, allowing for video of digital video disc (DVD) quality to be shared throughout the home. In this case the PAN becomes a high-speed personnel area network.

Wireless Local Area Networks

Figure 1 shows WLANs in the second column. Standards-based WLANs typically:

- Service more applications and users than do PANs
- Cover a greater distance than PANs: up to 100 meters
- Aggregate PANs

The wireless standard associated with WLANs is IEEE 802.11. Three major revisions to the physical layer have been released:

- 802.11a supports bandwidth speeds up to 54 Mbps
- 802.11b supports bandwidth speeds up to 11 Mbps
- 802.11g supports bandwidth speeds up to 54 Mbps

WISPs using directional antennas or implementing pre-standard Wi-Fi mesh topologies have been able to increase performance beyond 54 Mbps and to cover over ten kilometers (km) in range using the 802.11 standard. The increase in range has placed 802.11 into two usage segments: LAN and MAN. This overlap is shown in Figure 1. Range alone does not constitute a usage segment because the segments are based on a variety of variables, such as the distance between APs and the number of users.

Metropolitan Area and Wide Area Networks

The wireless MAN is the third usage segment shown in Figure 1. The wireless MAN aggregates LANs and typically covers areas up to 50 km. Both WiMAX and coppered wired technologies (such as DSL and DOCSIS cable) are used in this usage segment.

The fourth usage segment shown in Figure 1 is the WAN. WANs aggregate MANs across large geographic areas (over 50 km). WAN uses a variety of communication media to pass large amounts of traffic from the various MANs. However, the most common media used are fiber optic links. This set of high-speed, high-bandwidth interconnections is referred to as the core network. Performance of WAN networks is up to 10 Gbps and depends on the type of traffic the network handles: voice only or voice, video and data.

Today, the popularity, cost benefits and throughput associated with Wi-Fi networks have caused a growth in network deployments, use and adoption. This is due to the options available in achieving access to the last mile. WISPs are pushing Wi-Fi to the limits to reach and cover MANs.

In 2005, WISPs have additional options with the implementation of WiMAX, which copes with some of the challenges facing Wi-Fi.

Examining the technical capabilities of the three options available for WISPs to cover the last mile provides a deeper understanding of each of these options.

Wi-Fi as a Metro-Access Deployment Option

The Wi-Fi certification addresses interoperability across IEEE 802.11 standards-based products. The IEEE 802.11 standard, with specific revisions, was designed to address wireless local area coverage.

External modifications to the standard through hardware and software allow Wi-Fi products to become a metro-access deployment option. These two major modifications address two different usage models:

- **Fixed-access or last-mile usage**—802.11 with high-gain antennas
- **Portable-access or hot-zone usage**—802.11 mesh networks

Wi-Fi products associated with the metro-access deployment option use these different radio frequencies:

- The 802.11a standard uses 5 GHz in an AP-to-AP interlink.
- The 802.11b and 802.11g standards use 2.4 GHz.

The 802.11a, 802.11b and 802.11g standards use different frequency bands; devices based on these standards do not interfere with one another. On the other hand, devices on different bands cannot communicate; for example, an 802.11a radio cannot talk to an 802.11b radio.

The most common deployments by WISPs for wireless metro access to date are the 802.11b and 802.11g standards because of interoperability and the greater range they achieve in the 2.4-GHz band.

Each standard also differs in the type of radio-modulation technology used, as follows:

- The 802.11b standard uses direct-sequence spread spectrum (DSSS) and supports bandwidth speeds up to 11 Mbps.
- The 802.11a and 802.11g standards use orthogonal frequency division multiplexing (OFDM) and support speeds up to 54 Mbps. Because OFDM is more adaptable to outdoor environments and interference, it is most commonly used for metro-access solutions.

OFDM technology uses sub-carrier optimization, which assigns small sub-carriers to users based on radio frequency conditions.

Orthogonal means that the frequencies into which the carrier is divided are chosen such that the peak of one frequency coincides with the nulls of the adjacent frequency. The data stream is converted from serial to parallel, and each parallel data stream is mapped by a modulation block. The modulated data is fed to an inverse fast Fourier transform (IFFT) block for processing. The IFFT block converts the discrete modulated frequencies into a time-domain signal, which is used to drive the radio frequency (RF) amplifier.

This enhanced spectral efficiency is a great benefit to OFDM networks, making them well suited for high-speed data connections in both fixed and mobile solutions.

The 802.11 standard provides for 64 subcarriers. These individual carriers are sent from the base station (BS) or AP to the subscriber station (SS) or client and are then reconstituted at the client side. In non-line-of-sight (NLOS) situations, these carriers will hit walls, buildings, trees and other objects, which then reflect the signal, creating multi-path interference.

By the time the carrier signals reach the client for reconstitution, the individual carrier signals are time delayed. For example, one carrier may have been reflected once and arrived 1 µs later than another, and a second carrier may have been reflected twice and arrive 2 µs later. The larger number of subcarriers over the same band results in narrower subcarriers, which is the equivalent to larger OFDM symbol periods. Consequently, the same percentage of guard time or cyclic prefix (CP) will provide larger absolute values in time for larger delays, improving resistance to multi-path interference. Because the 802.11a and 802.11g standards use OFDM, they are more resilient than the 802.11b standard in outdoor multi-path-prone environments. These factors were taken into account when developing the 802.16-2004 standard. The 802.11a and 802.11g standards have one-fourth of the OFDM symbol options for CP than in the 802.16-2004 standard.

Table 1: Wi-Fi standards at a glance.

Wi-Fi Standard	Frequency	Modulation
802.11a	5 GHz	OFDM
802.11b	2.4 GHz	DSSS
802.11g	2.4 GHz	OFDM

The 802.11g standard is often selected for a last-mile solution for three reasons.

- Speed
- The ability to handle interference
- Interoperability with 802.11b-based devices

Network-Contention Protocol

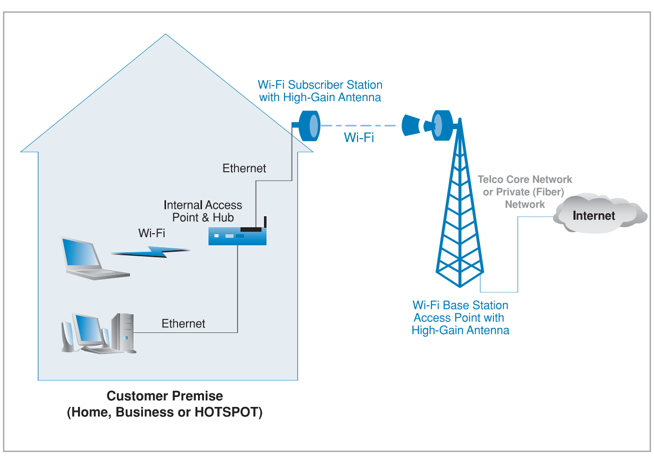
The 802.11 standard uses a carrier-sense, multiple-access/collision-avoidance (CSMA/CA) protocol, which is a network-contention protocol that listens to the network to avoid transmission collisions.

CSMA/CA contributes to network traffic by controlling the network. Before real data is transmitted across the network, CSMA/CA broadcasts a signal onto the network to listen for collision scenarios and to tell all other devices not to broadcast. Some equipment manufacturers and WISPs have been able to get around hidden-node problems by introducing APs or using intelligent APs to monitor traffic. WiMAX (IEEE 802.16-2004) uses a scheduling protocol, with all scheduling owned by the base-station AP, thus improving reliability.

As the number of users on an 802.11 network increases, however, the efficiency of the network decreases because of the overhead of managing additional subscribers. Whereas a single user may enjoy over 30 Mbps of throughput in an 802.11g network when only one user is accessing the AP, by the time 100 users are accessing the AP, the per user throughput can be less than dial-up rates.

Increasing 802.11 Range Using Directional Antennas

Figure 2: 802.11 last-mile networks.



Omni-directional antennas are often used for line-of-sight communications with mobile stations spread out in all directions. Because it is not necessary to broadcast to the clouds, omni-directional antennas propagate RF signals in all directions equally on a horizontal plane (that is, throughout a facility), but limit range on the vertical plane. Their radiation pattern resembles that of a large doughnut with the antenna at the center of the hole. Omni-directional antennas are commonly used in traditional WLAN settings and mesh networks.

A directional antenna transmits and receives RF energy more in one direction than others. This radiation pattern is similar to the light that a flashlight or spotlight produces. Higher-gain antennas have a narrower beam width, which limits coverage on the sides of the antennas. Directional antennas typically have gains much higher than omni-directional antennas.

High-gain antennas work best for covering a large distance in narrow areas or for supporting point-to-point links between buildings. In some cases, a directional antenna can reduce the number of APs needed within a facility. For example, a long loading dock of a distribution center many require three APs having omni-directional antennas. But the use of a high-gain directional antenna in the same situation would only require a single AP. Using 802.11 with high-gain antenna can bridge last-mile gaps, but they require more power.

Mesh Networking

Mesh-network topology extends the range of traditional LANs and WLANs. In a mesh-network topology, each node is connected and communication protocols are shared across the nodes. A Wi-Fi mesh infrastructure is formed when a collection of 802.11a, b, or g-based nodes are interconnected by wireless 802.11 links. The 802.11a standard is most commonly used in AP-to-AP links because of its performance and non-channel overlap with 802.11b or 802.11g transmissions. Mesh networks automatically learn and maintain dynamic path configurations. Wireless devices in a mesh-network topology create a seamless path for data to one another over a license-exempt spectrum at 2.4 or 5 GHz, with speeds up to 54 Mbps.

Current backend implementations of Wi-Fi mesh infrastructures are based on proprietary solutions. These proprietary-based solutions may support VoIP and QoS. They can also increase the coverage range of standard Wi-Fi's 100-meter limit to over 10 km. In addition, performance can be increased from the Wi-Fi's 54-Mbps limit to over 100 Mbps. These implementations, however, are not interoperable, have limited scalability and in certain deployments are limited by wired backhaul. The ratification of 802.11s will standardize the Wi-Fi mesh-network topology. The 802.11s standard is estimated to be ratified in 2007. Wi-Fi mesh-network topologies can be used as a last-mile solution but are better suited to blanket large areas with 802.11 access.

Mesh networking is sometimes referred to as “multi-hop” networking. Mesh topologies provide a flexible architecture that can move data between nodes efficiently.

Within the mesh network, small nodes act as simple routers. The nodes are installed throughout a large area (such as a neighborhood or a school campus). Each node then transmits a low power signal capable of reaching neighboring nodes, each of which in turn transmits the signal to the next node, with the process being repeated until the data arrives at its destination. An advantage of this topology is the ability for the deployment to navigate around a large obstacle, such as a mountain which can otherwise block a subscriber from reaching a base station. In a mesh network, blocked subscribers can get to the base station indirectly by going through other nodes. Even a small amount of meshing can greatly improve a base station's coverage if sufficient small nodes are in place.

Mesh networks provide advantages over direct line-of-sight implementations because they can adapt to changes in network topology. Nodes can be readily added and removed, and their location changed. As people become more mobile and wireless capabilities are included in new classes of devices, future business and home networks need to adapt or self-configure to these changes.

Benefits of the mesh-network topology include lower initial costs, balanced traffic, mobility and availability.

Lower Initial Costs

Mesh networks provide lower costs to the operator because users already have a client (such as a laptop with embedded Wi-Fi technology).

Balanced Traffic

Mesh networks provide greater redundancy and can be used for traffic balancing. In dense networks, such as crowded offices or apartments, each device can have many neighbors creating multiple paths between two communicating devices. In the presence of localized interference, a multi-hop network can route data along an alternate path.

If only one node requires a large amount of bandwidth, then the network can dynamically route traffic to other network nodes, avoiding the congested node. Current single-hop networks do not have the ability to dynamically adapt to interference or overburdened network nodes.

Mesh networks have some advantages over the single-hop and directional last-mile alternatives, such as:

- Robustness
- Resiliency
- Spatial reuse

Robustness and Resiliency

Mesh-network topologies are more robust than single-hop networks because they are not dependent on the performance of a single node for operation. In a single-hop network, if the node goes down, so does the network. In mesh-network architecture, if the nearest node goes down or if localized interference occurs, the network continues to operate; data is simply routed along an alternate path.

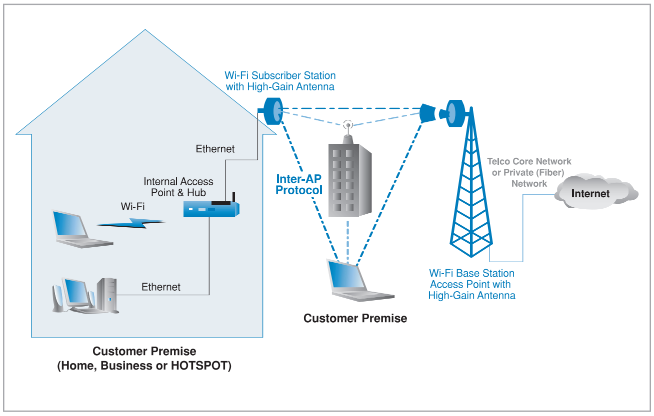
A good example of an application needing both robustness and resiliency is email, which is divided into data packets that are sent across the Internet via multiple routes then reassembled into a coherent message that arrives in the recipient's mailbox. Using multiple routes to deliver data increases the effective bandwidth of the network.

Spatial Reuse

Mesh networks use available bandwidth efficiently. In a single-hop network, devices must share a node. If several devices attempt to access the network at once, a traffic jam occurs and the system slows. By contrast, in a mesh network, many devices can connect to the network at the same time through different nodes, without necessarily degrading system performance. The shorter transmission ranges in a mesh network limit interference, allowing simultaneous, spatially separated data flows.

To deploy a mesh network cost effectively, however, service providers need a large initial subscriber base. Mesh networks are built from close proximity to the point-to-point connection, then expanding out. Service providers typically do not build a mesh network until they have established a subscriber base.

Figure 3: 802.11 mesh networking.



Mesh networks can create noticeable latency. Even when individual hops introduce small delays, latency increases with every hop. Application services that require low latency, such as VoIP and live video conferences over the Internet, can be adversely affected. As more nodes are added in the mesh-network topology, bottlenecks begin to appear as the nodes closest to the PoP function mostly as aggregators and routers for the traffic to the edges. This impacts the bandwidth availability for the subscribers for these nodes. The latency problem gets progressively worse as new subscribers are added near the edge.

Mesh networks are also noisy. By necessity (until smart directional antennas are used at the client end, which is unlikely for a long time), every node in the mesh-network topology is an omni-directional broadcaster. This produces noise, which the nodes detect as errors. Each error forces retransmissions along the entire chain, with the throughput degrading progressively as the transmissions aggregate to the PoP. This reduces the bandwidth for those closest to the node as well as those farther away.

Both 802.16-2004 and 802.11 at a given power level and a given channel bandwidth (by default, 20 MHz for 802.11) have similar ranges. Range is the easiest problem to solve when attempting to use 802.11 for outdoor applications. 802.16 was built from the ground up to address last-mile limitations, however, and feedback from WISPs deploying 802.11 for the last mile was addressed when developing the 802.16 standard.

Network Contention

The network-contention protocol on which 802.11 is based can be the root of problems in mesh-network topologies as well. CSMA/CA can cause a hidden-node problem when clients are out of reach of one another.

Much as a broadcast storm on a wired LAN segment can bring traffic to a standstill, hidden transmitter nodes interfering with one another have a detrimental effect on the performance of every wireless node in the mesh network. This interference can cause overall performance of the entire wireless network to drop dramatically.

The revisions to the 802.11 standard address the hidden-transmitter problem using special packets called request to send (RTS), clear to send (CTS) and acknowledge (ACK). The 802.11a, b and g standards use these special packets to alert every node on the network that a transmission node has data to send, that a transmission is about to take place, and that the transmission has ended by broadcasting these packets across the entire network. This is a time- and bandwidth-consuming process required for each and every transmission by each and every wireless node in the network. In addition, proper AP placement and network design can help control hidden node issues.

Benefits

The benefits of using Wi-Fi for last-mile solutions now are:

- Off-the-shelf 802.11 standard products are currently available
- Initial investment is cost effective for small deployments
- Flexibility over wired installations can be achieved

Challenges

The limitations to mesh networks are:

- A large subscriber base is needed to cover larger areas
- Shared bandwidth
- Latency
- Proprietary implementation
- Standardized Wi-Fi mesh-network topology won't be available until the implementation of the 802.11s standard
- Standardized Wi-Fi QoS won't be available until the implementation of the 802.11e standard

Summary of Wi-Fi Mesh Usage

The majority of WISPs and service providers are using Wi-Fi mesh-network topology for:

- Wireless coverage of LANs
- Blanketing large areas with hot-zone coverage

WiMAX as a Metro-Access Deployment Option

WiMAX is a worldwide certification addressing interoperability across IEEE 802.16 standards-based products. The IEEE 802.16 standard with specific revisions addresses two usage models:

- Fixed
- Portable

Fixed

The IEEE 802.16-2004 standard (which revises and replaces IEEE 802.16a and 802.16REVd versions) is designed for fixed-access usage models. This standard may be referred to as "fixed wireless" because it uses a mounted antenna at the subscriber's site. The antenna is mounted to a roof or mast, similar to a satellite television dish. IEEE 802.16-2004 also addresses indoor installations, in which case it may not be as robust as in outdoor installations.

The 802.16-2004 standard is a wireless solution for fixed broadband Internet access that provides an interoperable, carrier-class solution for the last mile. The Intel WiMAX solution for fixed access operates in the licensed 2.5-GHz, 3.5-GHz and license-exempt 5.8-GHz bands. This technology provides a wireless alternative to the cable modem, digital subscriber lines of any type (xDSL), transmit/exchange (Tx/Ex) circuits and optical carrier level (OC-x) circuits.

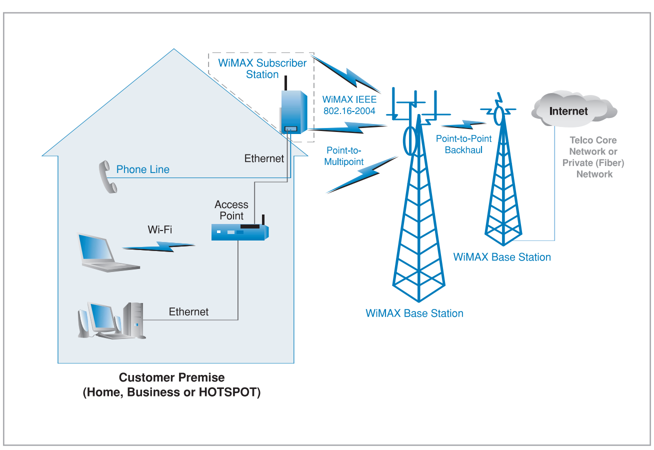


Figure 4: WiMAX network topology.

Portable

The IEEE 802.16e standard is an amendment to the 802.16-2004 base specification and targets the mobile market by adding portability and the ability for mobile clients with IEEE 802.16e adapters to connect directly to the WiMAX network to the standard. The 802.16e standard is expected to be ratified in early 2005.

The 802.16e standard uses Orthogonal Frequency Division Multiple Access (OFDMA), which is similar to OFDM in that it divides the carriers into multiple subcarriers. OFDMA, however, goes a step further by then grouping multiple subcarriers into sub-channels. A single client or subscriber station might transmit using all of the sub-channels within the carrier space, or multiple clients might transmit with each using a portion of the total number of sub-channels simultaneously.

The IEEE 802.16-2004 standard improves last-mile delivery in several key aspects:

- Multi-path interference
- Delay spread
- Robustness

Multi-path interference and delay spread improve performance in situations where there is not a direct line-of-sight path between the base station and the subscriber station.

The emerging 802.16-2004 media-access control (MAC) is optimized for long-distance links because it is designed to tolerate longer delays and delay variations. The 802.16 specification accommodates MAC management messages that allow the base station to query the subscriber station, but there is a certain amount of time delay.

WiMAX equipment operating in license-exempt frequency bands will use time-division duplexing (TDD); equipment operating in licensed frequency bands will use either TDD or frequency-division duplexing (FDD). Intel WiMAX products will support TDD and half-duplex FDD operation.

The IEEE 802.16-2004 standard uses OFDM for optimization of wireless data services. Systems based on the emerging IEEE 802.16-2004 standards are the only standardized OFDM-based, wireless metropolitan area networks (WMAN) platforms.

In the case of 802.16-2004, the OFDM signal is divided into 256 carriers instead of 64 as with the 802.11 standard. As previously stated, the larger number of subcarriers over the same band results in narrower subcarriers, which is equivalent to larger symbol periods. The same percentage of guard time or cyclic prefix (CP) provides larger absolute values in time for larger delay spread and multi-path immunity.

The 802.11 standard provides one-fourth of the OFDM options for CP than does the 802.16-2004 standard, which provides $1/32$, $1/16$, $1/8$ and $1/4$, where each can be optimally set. For a 20-MHz bandwidth, the difference between a $1/4$ CP in .11 and 16 would be a factor of four because of the ratio $256/64$. In OFDMA with 2048 FFT size, the ratio is 32.

The physical layers (PHYs) for both 802.11 and 802.16-2004 are designed to tolerate delay spread. Because the 802.11 standard was designed for 100 meters, it can tolerate only about 900 nanoseconds of delay spread. The 802.16-2004 standard tolerates up to 10 microseconds of delay spread—more than 1000 times than in the 802.11 standard.

Range and Scalability

The 802.16-2004 standard relies upon a grant-request access protocol that, in contrast to the contention-based access used under 802.11, doesn't allow data collisions and, therefore, uses the available bandwidth more efficiently. No collisions means no loss of bandwidth due to data retransmission. All communication is coordinated by the base station. Other characteristics of the 802.16-2004 standard include:

- **Improved user connectivity**—The 802.16-2004 standard keeps more users connected by virtue of its flexible channel widths and adaptive modulation. Because it uses channels narrower than the fixed 20-MHz channels used in 802.11, the 802.16-2004 standard can serve lower-data-rate subscribers without wasting bandwidth. When subscribers encounter noisy conditions or low signal strength, the adaptive modulation scheme keeps them connected when they might otherwise be dropped.
- **Higher quality of service**—This standard also enables WISPs to ensure QoS for customers that require it and to tailor service levels to meet different customer requirements. For example, the 802.16-2004 standard can guarantee high bandwidth to business customers or low latency for voice and video applications, while providing only best-effort and lower-cost service to residential Internet surfers.
- **Full support for WMAN service**—From its inception, the 802.16-2004 standard was designed to provide WMAN service. Hence, it is able to support more users and deliver faster data rates at longer distances than last-mile implementations based on the 802.11g standard.
- **Robust carrier-class operation**—The standard was designed for carrier-class operation. As more users join, they must share the aggregate bandwidth and their individual throughput decreases linearly. The decrease, however, is much less dramatic than what is experienced under 802.11. This capability is termed "efficient multiple access."

Flexible Channel Bandwidth

As the distance between a subscriber and the base station (or AP) increases, or as the subscriber starts to move by walking or driving in a car, it becomes more of a challenge for that subscriber to transmit successfully back to the base station at a given power level. For power-sensitive platforms such as laptop computers or handheld devices, it's often not possible for them to transmit to the base station over long distances if the channel bandwidth is wide. The 802.11 channel bandwidth is fixed at 20 MHz. In contrast, applications modeled on third-generation principles limit channel bandwidth to about 1.5 MHz to provide longer range.

The IEEE 802.16-2004 and IEEE 802.16e standards have flexible channel bandwidths between 1.5 and 20 MHz to facilitate transmission over longer ranges and to different types of subscriber platforms. In addition, this flexibility of channel bandwidth is also crucial for cell planning, especially in the licensed spectrum. For scalability, an operator with 14 MHz of available spectrum, for example, may divide that spectrum into four sectors of 3.5 MHz to have multiple sectors (transmit/receive pairs) on the same base station.

With a dedicated antenna, each sector has the potential to reach users with more throughput over longer ranges than can an omni-directional antenna. Net-to-net, flexible channel bandwidth is imperative for cell planning.

The 802.16-2004 standard has strong commercial backing to go along with its technical capabilities. The WiMAX Forum*, a nonprofit group that promotes 802.16-2004 technology, has as its goal the certification of interoperable 802.16-2004 standard products, regardless of vendor. In that regard, the forum is following the lead of the Wi-Fi Alliance*, which helped popularize and commercialize 802.11 standard technology. Founded in 2003 by wireless service providers and equipment manufacturers, the WiMAX Forum now includes almost 70 member companies. Several of them expect to deliver WiMAX-certified* products later this year.

Smart Antenna Support

Smart antennas are being used to increase the spectral density (that is, the number of bits that can be communicated over a given channel in a given time) and to increase the signal-to-noise ratio for both Wi-Fi and WiMAX solutions. Because of performance and technology, the 802.16-2004 standard supports several adaptive smart antenna types, including:

- **Receive spatial diversity antennas**—Entails more than one antenna receiving the signal. The antennas need to be placed at least half a wavelength apart to operate effectively. Note that wavelength can be derived by taking the inverse of the frequency. For example, for a 2.5-GHz carrier the wavelength would be 0.13 meters or 5.1 inches. For a 5.8-GHz carrier the wavelength would be 0.05 meter or 1.9 inches. When considering half a wavelength for the frequencies of interest, we are talking one to two and a half inches. Maintaining this minimum distance ensures that the antennas are incoherent, that is, they will be impacted differently by the additive/subtractive effects of signals arriving by means of multiple paths.
- **Simple diversity antennas**—Detect the signal strength of the multiple (two or more) antennas attached and switch that antenna into the receiver. The more incoherent antennas to choose from, the higher the likelihood of getting a strong signal.
- **Beam-steering antennas**—Shape the antenna array pattern to produce high gains in the useful signal direction or notches that reject interference. High antenna gain increases the signal, noise and rate. The directional pattern attenuates the interference out of the main beam. Selective fading can be mitigated if multi-path components arrive with a sufficient angular separation.
- **Beam-forming antennas**—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. Base stations that intelligently manage sectors have been used for a long time in mobile-service base stations.

Benefits and Challenges

The key benefits of WiMAX are:

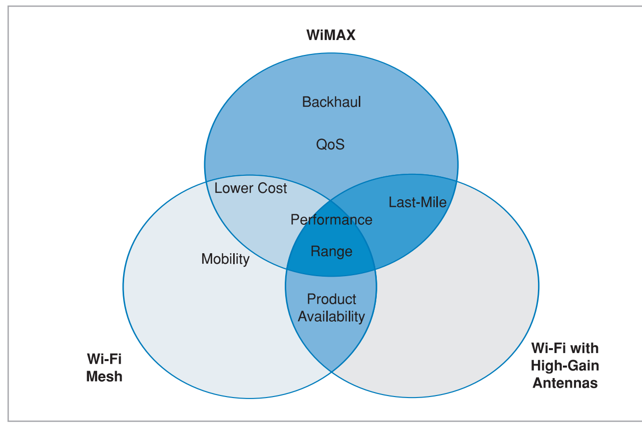
- Built-in QoS
- High performance
- Standards-based
- Smart antenna support

The most significant challenge is that WiMAX is a new technology with emerging support.

Conclusion

Wi-Fi mesh networks are driving the demand for WiMAX by increasing the proliferation of wireless access, increasing the need for cost-effective backhaul solutions and faster last-mile performance. WiMAX can be used to aggregate Wi-Fi networks (such as mesh-network topologies and hotspots) and Wi-Fi users to the backend. As Figure 5 illustrates, each wireless metro-access solution has common and unique benefits. Today, a Wi-Fi mesh-network offers mobility, while WiMAX offers a long-distance backhaul and last-mile solution. The best solution is a combination of the two.

Figure 5: 2004-2005 WiMAX and Wi-Fi metro-access solution features.



WISPs have a variety of wireless deployment options for covering large areas and last-mile gaps. The best solution varies based on usage models, time of deployment, geographic location and network application type (such as data-only, VoIP and video). Each deployment can be tailored to meet the network needs of its users.

WISPs wanting to deploy wireless solutions before the first half of 2005 for mobile users who need connections using laptop computers over large areas and who do not require QoS can use Wi-Fi mesh-network topology to extend the reach of traditional WLANs. Wi-Fi mesh infrastructures are optimized for data-only usage models, however. QoS add-ons are available for proprietary Wi-Fi mesh implementations but are not standardized and limit multi-vendor interoperability.

Intel is working within the wireless industry to drive the deployment of both Wi-Fi and WiMAX networks. Intel is one of the founders of the WiMAX Forum, the industry-led, non-profit corporation formed to promote and certify the compatibility and interoperability of broadband wireless products. In addition, Intel has help proliferate Wi-Fi adoption with the Intel® Centrino™ mobile technology brand. In 2005, WiMAX and various forms of Wi-Fi will be combined to offer optimal end-to-end performance. Wi-Fi WLANs and Mesh will coexist with WiMAX.

Recommendations for deployments:

- Use 802.16-2004 for P2P and P2MP links in rural, low-density areas.
- Deploy unlicensed Wi-Fi networks today to capture the benefits of open-standard radio and to bring low-cost wireless service to urban and suburban areas. If fully licensed operation is desired for increased RF predictability, introduce licensed WiMAX 802.16-2004 into metro-infrastructures or, when available, add WiMAX 802.16e for mobile-client devices.
- If unlicensed operation is desired for maximum flexibility at lowest cost, monitor the price-feature-performance trends of evolving WiMAX and Wi-Fi versions and introduce WiMAX if, and when, these trends move in its favor.

In 2005, WISPs wanting QoS, standards-based, scalable solutions can use WiMAX to cover last-mile deployments.

- WiMAX (802.16-2004) provides broadband connectivity to proprietary and standards-based Wi-Fi mesh networks, WLANs, hotspots, residences and businesses.
- WiMAX (802.16-2004) provides wireless broadband connectivity to areas beyond the reach of traditional broadband (such as DOCSIS cable, xDSL and T1) and enables Wi-Fi mesh-network topology growth.

With attention focused on WiMAX, it's easy to forget that Wi-Fi is also rapidly evolving. Wi-Fi radios are appearing not just in laptops and personal digital assistants (PDAs), but in equipment as diverse as mobile phones, parking meters, security cameras and home entertainment equipment. As a result of the increasing adoption rate, Wi-Fi will continue to become faster, more secure, more reliable and more full-featured. In turn, these advances will drive continued adoption.

A combined Wi-Fi mesh and WiMAX deployment, as shown in Figure 6, offers a more cost-effective solution than a sole Wi-Fi directional-antenna deployment or a Wi-Fi mesh network with wired backhaul for WISPs that want to extend the LAN or cover the last mile.

Figure 6: Phase 1 – WiMAX backhaul for a Wi-Fi mesh topology.

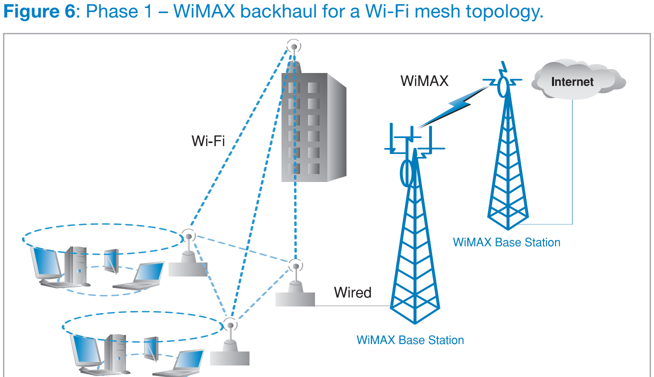
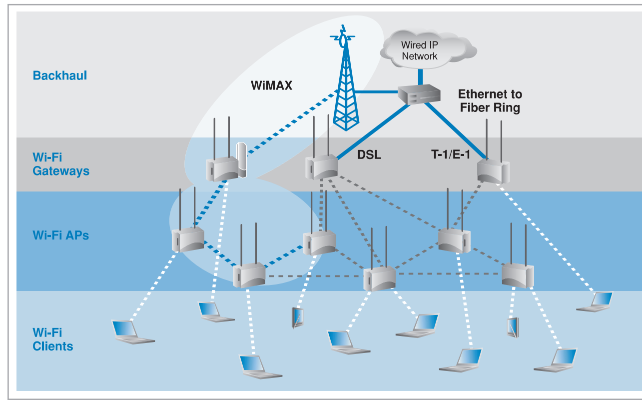
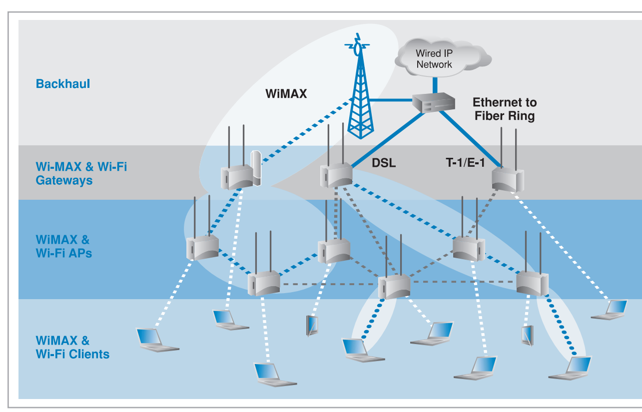


Figure 7: Phase 2 – WiMAX as an intra-mesh backhaul option.



For intra-mesh connectivity, Wi-Fi offers advantages today. Industry-proven Wi-Fi chipsets and radios are readily available and economical. They readily operate in unlicensed regions of the spectrum. The result is an intra-mesh technology that offers reliable high performance at the lowest cost. Essentially, the inter-mesh backhaul connections can reduce costs associated with wiring each node. When they become available, the dual Wi-Fi and WiMAX APs will provide higher performance and an even more robust solution. As shown in Figure 8, APs with dual Wi-Fi and WiMAX radios can be easily integrated into a mesh network. The solid blue links show WiMAX backhaul and inter-mesh connectivity.

Figure 8: Phase 3 – WiMAX as a client connection option.



With the emergence of WiMAX in the near future, deployments that combine the two technologies can be constructed to take advantage of the strengths of both Wi-Fi and WiMAX.

Figure 6 shows the topology that could be used by a municipality that wants to extend broadband connectivity to two new rural community centers and a park. The municipality wants to provide free Internet service to local residences and staff to promote education, cultural arts and local businesses. The deployment must be completed within three months. A combination of WiMAX and Wi-Fi mesh-network topology provides the best solution for this situation. WiMAX can be used to aggregate the community centers. WiMAX extends the reach of broadband, while the proprietary Wi-Fi mesh network available today can provide mobile client access throughout the community centers and park. As dual-mode Wi-Fi and WiMAX cells are introduced into high-capacity network centers in licensed or unlicensed bands. The WiMAX cells will interoperate seamlessly with existing Wi-Fi cells; always selecting the best path for delivering maximum user throughput end-to-end.

Deployment Examples

Deployments of last-mile wireless solutions during 2004 and 2005 require analysis of immediate service needs and technology investment goals. Here are some examples of how these needs can be balanced.

WiMAX Recommended

Last Mile

Challenge	Solution
A WISP wants to expand its service coverage to underserved markets. QoS is a significant factor for this deployment because some of the new customers are local government and small and medium businesses requiring a guaranteed level of service for certain applications. Deployment cost and vendor interoperability is key because many users within the target-market segment may end up owning their own WiMAX CPE.	WiMAX provides the best and the most cost-effective broadband solution to this challenge because the cost of deploying and providing traditional broadband services is prohibitively expensive. WiMAX is designed from the ground up to provide a fast, cost-effective and easy-to-deploy solution with built-in QoS. WiMAX is based on IEEE standards and WiMAX-certified products are vendor interoperable.

Backhaul

Challenge	Solution
A carrier is deploying two new cell towers and a Wi-Fi hotspot in a rural community within the next two months. They want to be able to connect their cell towers to their core network and the hotspot to the Internet.	WiMAX provides the best solution for this challenge because it provides a cost-effective, rapidly deployable point-to-point backhaul solution.

Wi-Fi Mesh Recommended

Vertical (Government and Education)

Challenge	Solution
A school with existing broadband access (based on T1) wants to expand connectivity to a new a classroom building and the school's main courtyard. Students and faculty members are mobile and use their notebook computers and PDAs to access the Internet and the school's network resources. The primary use of the network is to download documents and presentations, access Web-based portals (such as a blackboard), review class schedules and send instant messages to students and instructors. The solution is needed now and the school is willing to work with a single vendor.	Wi-Fi mesh-network topology provides the best solution to this challenge because it's a quick solution to expand coverage to an existing wireless infrastructure and because 802.11-based products are available today.

Key Terminology

3GPP – Third Generation Partnership Project

AP – Access point. An AP operates within a specific frequency spectrum and uses an 802.11 standard specified modulation technique. It informs the wireless clients of its availability, authenticates and associates wireless clients to the wireless network and coordinates the wireless clients' use of wired resources.

BS – Base station

CSMA/CA – Carrier sense multiple access with collision avoidance

CSMA/CD – Carrier sense multiple access with collision detection

DOCSIS – Data over Cable Service Interface Specification

DSL – Digital subscriber line

DSSS – Direct sequence spread spectrum

ETSI – European Telecommunications Standards Institute

FCC – Federal Communications Commission

IEEE – Institute of Electrical and Electronics Engineers

IP – Internet Protocol

LAN – Local area network

MAC address – Media access control address. This address is a computer's unique hardware number.

MAN – Metropolitan area network

OFDM – Orthogonal frequency division multiplexing

OFDMA – Orthogonal frequency division-multiple access

P2P – Point-to-point

P2MP – Point-to-multi-point

PAN – Personal area network

PHY – Physical layer

PoP – Point of presence

QoS – Quality of service

RF – Radio frequency

SS – Subscriber station

UWB – Ultra-wide band

VoIP – Voice over Internet Protocol

WAN – Wide area network

Wi-Fi – Wireless fidelity. Used generically when referring to any type of 802.11 network, whether 802.11b, 802.11a, dual-band, and so on.

WiMAX – Worldwide Interoperability for Microwave Access

WISP – Wireless Internet service provider

WLAN – Wireless local area network

WMAN – Wireless metropolitan area network

WWAN – Wireless wide area networks

Additional Resources

White Papers

Intel Corp., *IEEE 802.16* and WiMAX: Broadband Wireless Access for Everyone*, 2003, *www.intel.com/ebusiness/pdf/wireless/intel/80216_wimax.pdf*

WiMAX Forum, *WiMAX's Technical Advantage for Coverage in LOS and NLOS Conditions*, Aug. 2004, *www.wimaxforum.org/news/downloads/WiMAXNLOSgeneral-versionaug04.pdf*

General Resources

WiMAX Forum: *www.wimaxforum.org*

WiMAX technology overview: *www.intel.com/netcomms/technologies/wimax*

WiMAX World Conference & Exposition: *www.wimaxworld.com*

Tropos Networks: *www.tropos.com*