# WiMAX As A Competitor To Fixed Line Broadband Technology

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*Abstract*

*This paper examines the economic and technical capabilities of 802.16e WiMAX technology and contrasts it to fixed line technology.*

*Technical capacity assessment of burst rates, statistical load capabilities and performance under streaming and heavy Peer-to-Peer (P2P) environments are compared. It also identifies frequency re-use plans and antenna sectorization for varying subscriber densities. Performance analysis includes uplink and downlink performance and throughput based upon the available modulation, coding profiles and network configuration settings.*

*Various CPE is compared identifying the trade-off of embedded CPE and network design. The cost and performance trade-offs for mobility are also defined.*

*Economic analysis takes industry averages and builds an end-to-end per subscriber cost analysis based upon various homes passed densities, in building coverage, subscriber speeds and mobility assumptions. The costs include site acquisition, construction, base station, backhaul, CPE and installation costs.*

*The conclusion section contrasts these economic and technical characteristics to fixed line and identifies the areas of opportunity for WiMAX to be competitive.*

## WiMAX History and Design Goals

To better understand the capabilities of WiMAX let's first describe the evolution of the specification and its design goals.

WiMax was created out of an IP industry effort to replicate the success of WiFi technology but to do so in a controlled, wider area macro-environment instead of the distance limited and unlicensed/unregulated Radio Frequency (RF) environment of WiFi. The economic power of WiFi is its ability to incorporate a standardized wireless broadband capability embedded into PC, laptop and portable computing devices. The incentives and economics of this arrangement are compelling for CPE manufacturers, internet access providers and network operators, as the cost of the broadband wireless capability is borne by the user. If WiMAX could utilize the same economic vision of embedded wireless broadband CPE while offering a secure, simple to access method similar to today's wide area cellular networks it would surely come out a winner. In addition, the belief that wireless technologies were overly voice centric, narrow band, circuit switched and solely focused on high speed mobility created a window of opportunity for a technology with roots in the IP and fixed broadband data world.

There were some wrong turns during the development of the WiMAX specification. Early claims aggressively cited high user capacity, over great distances (70 miles) when travelling at very fast speeds (70 mph) were possible by many simultaneous users.

Fortunately, the developers of WiMAX remained steadfast to their vision and in a very persistent manner continued to upgrade the specification and standard through numerous revisions (802.16-2001, 802.16-2004, 802.16-2005). Equally pragmatic was the philosophy of the developers to build upon core technologies and specifications with a proven track record, such as IP, DOCSIS and wideband RF channel technology while at the same time incorporating newly developed technical advancements. Foremost among these enabling wireless technologies built into the specification were OFDMA (Orthogonal Frequency Division Multiple Access) modulation, MIMO (Multiple Input/Multiple Output) antenna technology, advanced coding techniques such as HARQ (Hybrid Automatic Request) and TDD (Time Division Duplex) duplexing methods. In retrospect, their design decisions were foretelling as experts in the cellular world are using the same technologies now in their submissions for the 4G wireless standards.

Right from the start there were some inherent constraints with the WiMAX specification that still exist today. The biggest obstacle being the spectrum ranges in which WiMAX currently operates. The original standard, 802.16-2001, was for the LMDS spectrum (24, 28, 38 GHz), which is only good for line of site microwave type applications. The current 802.16-2004 (Fixed WiMax or 802.16d) and 802.16-2005 (Mobile WiMAX or 802.16e) standards are more appropriate for Non-Line-Of-Site (NLOS) applications as they operate in 2.3, 2.5 & 3.5 GHz ranges. Unfortunately, these frequencies are disadvantaged when trying to match the propagation characteristics of cellular frequencies (.8, .9, 1.8, 1.9, 2.1 GHz).

Despite these challenges the developers of the WiMax standard set out ambitious design goals for a combination fixed broadband and mobile service prior to building the specification. To summarize, the key requirements are[1]:

- High average sector throughput to support > 1 GB /user/month
- High cell edge performance on downlink (> 1,000 kbps) and uplink (> 256 kbps)
- High performance uplink & downlink from NLOS indoor locations
- Support high number of simultaneous users (>150 per sector)
- Low latency to support user experience and real time applications (e.g. VOIP)
- QOS (Quality of Service) to support differentiated services
- Full portability and nomadicity
- High speed mobility (< 120 Km/Hr).

<u>Description of WiMAX Specification</u>

The WiMAX specification is a double-edged sword. It has many flexible settings and assumptions that allow it to be optimized for a variety of business needs. For instance, if coverage, mobility and symmetrical services are desired then it can be configured to match those needs. Conversely, the network can be optimized for high capacity and asymmetrical capacity. As engineering and product marketing personnel can imagine, the numerous design “knobs” will be a huge benefit for delivering appropriate services to customers. Unfortunately, the flexibility offered by this capability comes at a cost, namely complexity and ultimately interoperability issues.

The biggest economic trade-off for a network operator is the decision to optimize for either capacity or coverage. The flexibility of WiMAX gives a network operator the opportunity to optimize the economics of a network design for either of these key criteria. Capital constrained start-up operators, without the benefit of a customer base, may opt to initially design a coverage based network that minimally meets the capacity requirements.

As the customers come online additional capacity can be added with the appropriate incremental capital. The power of the WiMAX specification is that this incremental capital can be minimized because of the high capacity capability of the standard relative to other wireless standards.

A network operator must first make the traditional business decisions of homes passed (addressable market), anticipated penetration rates, desired product speed, and applications. At that point a critical decision for the operator of a wireless network, like WiMAX, is the choice of terminal devices offered to the customers and the cell edge uplink data speeds. Outdoor fixed antennas, indoor gateways for PC's, PCMCIA cards for laptops, laptops with embedded CPE and handheld/mobile devices offer a variety of market opportunities and different applications. For the network designer each device has a unique link budget that weighs heavily on the service speeds and network costs. The limiting item for a wireless design is typically the uplink data rate at the cell edge. The cell edge is usually indoors through many walls and far away from cell site. The linkage of the choice of CPE and uplink speeds at the cell edge is a critical starting point for determining the network design and how the network should be best configured.

In the WiMAX specification there are a number of key parameters and assumptions that can be adjusted to accommodate either the coverage or capacity needs of a carrier's business plan[8]:

- CPE selection and cell edge uplink budget
- Adaptive modulation assumptions
- Frequency reuse of N=1, N=2, N=3… (where N represents reuse, such as N=1 means the same frequency is used in every adjacent sector/cell)
- Sectorization (Omni, 3 sector, 4 sector… 6 sector)
- Downlink to Uplink Ratios of 1:1, 2:1, 3:1
- Sub-channelization techniques
- Channel bandwidths of 5, 10, and 20 MHz

Antenna Technology[7,14]

- o MIMO (where there are multiple transmit and receive antennas at both the CPE & Base Station)
- o Beam forming Antennas (lock in and track the CPE and null out interference).

Unfortunately, optimizing these parameters can be a "zero sum game" for the operator. Improving one parameter can have a negative effect on others. Particularly disconcerting is the affect of optimizing for coverage and/or mobility which can severely affect capacity and vice versa. As is common in such trade-off's they typically result in economic choices. For instance, spending more money per cell site for sophisticated electronics associated with advanced antenna technology that gives the operator coverage gains versus just adding additional cost and simple base stations/sites.

Since WiMAX is a 4$^{th}$ generation (4G) wireless technology it is useful to understand how WiMAX OFDMA (Orthogonal Frequency Division Multiple Access) technology differs from the previous generations of wireless technology. Figure 1 illustrates the conceptual differences in the frequency, time and power dimensions of multiple access technologies[2]. Multiple access techniques divide channels or voice conversations by either time, frequency or unique identifiers like codes.

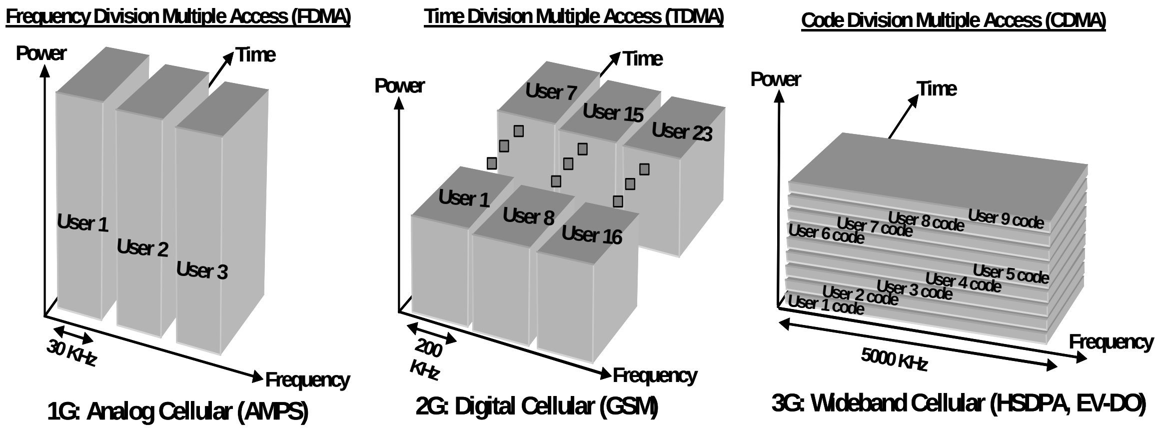



Figure 1: Conceptual Differences of Multiple Access Technologies

In Frequency Division Multiple Access (FDMA) each user receives a unique frequency as shown above in the 1st generation analog cellular example. Advancements in multiple access techniques in the late 1980s led to giving each user a unique time slot within the bandwidth allocation and digitizing the analog voice with vocoders. Time Division Multiple Access (TDMA) 2G digital cellular technologies such as GSM provided for 7 user time slots within a 200 KHz carrier. Finally, in the mid to late 90s Code Division Multiple Access technology reached maturation and was promoted as 3G wideband cellular wireless. CDMA users share time and frequency slots but employ codes that allow users to be separated by the receiver[29]. Contrasting these multiple access techniques to OFDMA is shown in Figure 2.

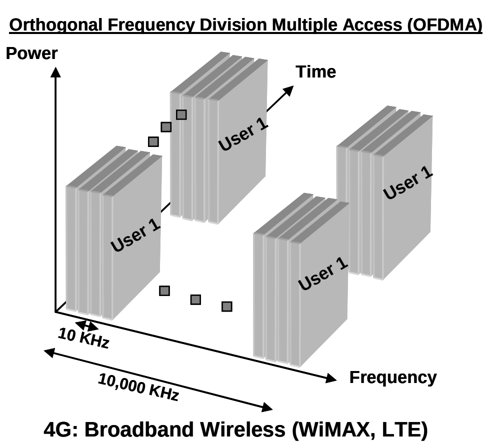



Figure 2: OFDMA

In OFDMA users share tightly spaced subcarriers and time slots. The diagram above shows over 1,000 separate 10 KHz subcarriers in a 10 MHz channel. These subcarriers are orthogonal to each other meaning they are unique and non-interfering. A stream of data from an individual user could be assigned or scheduled a variety of different narrow frequencies and time slots

The next sections will give an overview of the key aspects of the WiMAX specification by focusing in on the critical design parameters and design trade-off's.

## CPE Selection and Uplink Cell Edge Performance

Each CPE device has different output power and antenna gains. Since the uplink is typically the limiting item for the link budget there is a strong relationship between type of device and cell site range. As an illustration, a variety of different cell site ranges based upon the link budget for each of the various CPE devices[9] as shown in Table 1.

| CPE Type | Antenna Gain | Transmit Power | Cell Range |
|---|---|---|---|
| Indoor | 7 dB | 27 dB | 2.1 Km |
| PCMCIA | -2 dB | 24 dB | 1.0 Km |
| Laptop | 2 dB | 27 dB | 1.40 Km |
| Handset | -2 dB | 20 dB | .8 Km |

Table 1: CPE Devices & Cell Site Ranges

For simplicity, not all the individual elements and assumptions to the link budget are listed above. For example, in-building margins and fade margins could vary by application and CPE. Additionally, propagation models vary widely for high speed mobility and fixed applications and can have a profound effect on cell radius calculations as shown in Table 1.

As one can see in Figure 3, coverage will vary by CPE. This is mainly a result of the probability of using a higher speed modulation technique (e.g.- 64QAM) at the cell edge with higher gain CPE. Since modulation and coding modes are the key for performance, the next section will describe how modulation is uniquely used in the WiMAX specification.

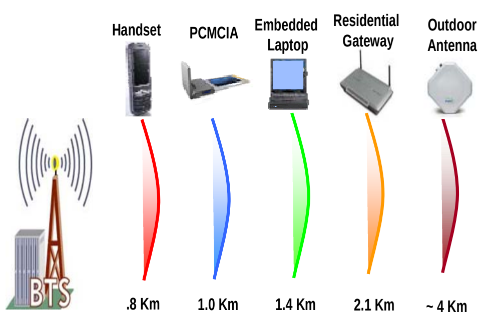



Figure 3: Coverage by CPE

## Adaptive Modulation

Adaptive Modulation is one of the critical characteristics of the WiMAX specification. Adaptive modulation techniques allow an individual subscriber to operate at different modulation rates than an adjacent customer. By having adaptive modulation, the base stations and subscriber stations are able to select at any given time the modulation rate separately for the uplink and downlink which will yield the optimum operation given the current link conditions. Chart 1 is an illustration of the coverage versus capacity tradeoff of using adaptive modulation schemes[17, 18]. At high modulation rates (64QAM) the sector capacity is very high (10 Mb/s) but the range is low (< 1 Km). Likewise at the lower modulation levels a great distance can be achieved but only at the expense of sector capacity.

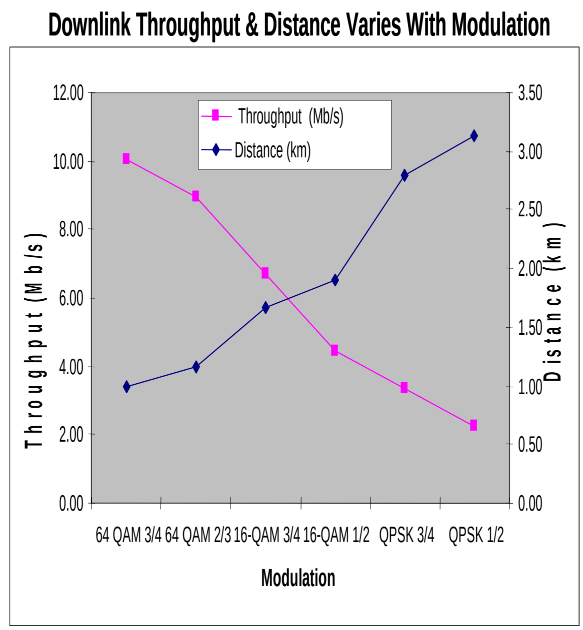



Chart 1: Speed & Distance by Modulation

Switching between modulation rates and coding is based on the Signal to Noise Ratio (SNR). Typically, high modulations are achievable for locations near the base station while cell-edge regions with low SNRs due to distance and potential interference from adjacent cells use low modulations. Fading due to distance causes subscribers at cell-edge to operate at low modulation rates which do not require high SNRs. In the presence of adjacent cell interference, the same subscribers may not be able to meet SNR requirement, and hence, results in lower modulation modes. Generally, NLOS environments suffer from low SNRs due to reflection losses, diffraction losses, multi-path fading and fading due to obstacles' scattering effect. The ability to achieve high modulation at cell edge depends highly on the ability to maintain high SNRs given the demanding link conditions of a NLOS environment. Table 2 summarizes typical downlink WiMAX modulations and SNR levels supported[4,9,10].

| Downlink Modulation and Coding | SNR Required (dB) |
|---|---|
| QPSK ½ | 1.8 |
| QPSK ¾ | 4.0 |
| 16 QAM ½ | 6.8 |
| 16 QAM ¾ | 10.4 |
| 64 QAM ½ | 12.9 |
| 64 QAM 2/3 | 14.2 |
| 64 QAM ¾ | 16.5 |
| 64 QAM 5/6 | 20.6 |

Table 2: SNR By Modulation

Without adaptive modulation, there are two likely situations which can be experienced by subscriber stations:

- Subscriber stations have high modulation rates even when link conditions yield low SNRs, resulting in high BER, and degraded performance
- Subscriber stations have low modulation rates even when link conditions yield high SNRs, hence, resulting to inefficiency.

Under both scenarios, the end result is low performance. By adaptively switching from one modulation rate to another, the system is able to ensure that[9,18,19]:

- Low modulation rates are selected when link conditions yield low SNR, resulting in low BER
- High modulation rates are selected when link conditions yield high SNR resulting in higher performance.

Figure 4 illustrates the concept of how the uplink modulation rate (QPSK ½) at the cell edge is typically the limiting design item and sets the speed of the user experience (256 Kb/s). Adaptive modulation, power and antenna gain of the CPE devices are key drivers of product speeds, cell capacity, maximum subscriber counts and coverage[3.4.16,17].

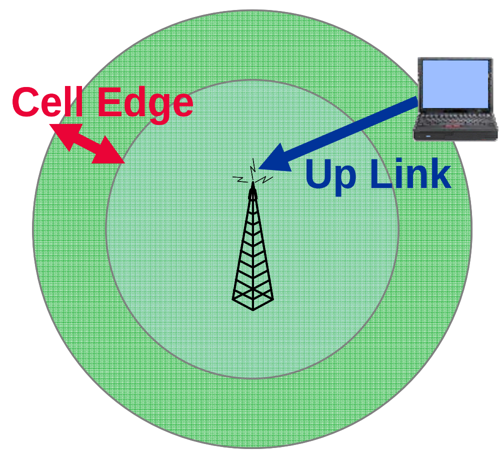



Figure 4: Uplink Cell Edge Representation

At this point it is important to briefly touch on the topic of WiMAX capacity in the adaptive modulation discussion since detailed capacity calculations will be covered in later sections. WiMAX average throughput capacity calculations are a controversial topic as there is little agreement on those numbers because there are so many varying assumptions possible. Suffice it to say, a key aspect of the uplink and downlink WiMAX capacity claims is the assumption on which modulation and coding scheme is used by the customers. For instance, peak or theoretical WiMAX capacities assume there is a single user in a sector and they are operating at the best modulation and coding rates in both the downlink (64QAM $^5/_6$) and uplink (16QAM ¾) 100% of the time. As can be imagined, high capacity claims can result across some vendors as a result of this assumption. The realism of all users always attaining the highest modulation rate is questionable, which is why we add the words theoretical and single user when using peak capacity numbers. More appropriate capacity claims are under the heading of average throughput or average channel capacity. Here again the adaptive modulation distribution assumption is absolutely critical. For example, the distribution assumption of how many subscribers (or the % of subscribers) operating in each adaptive modulation mode drives the overall average channel throughput number.

Frequency Reuse

The concept of frequency reuse is integral to any wireless and mobility technology. Without this capability the wireless industry would never have matured in a scarce spectrum environment. Basically, in a three sector cell site shown in Figure 5 each sector uses a different frequency. Cellular technologists call this an N=3 reuse pattern.

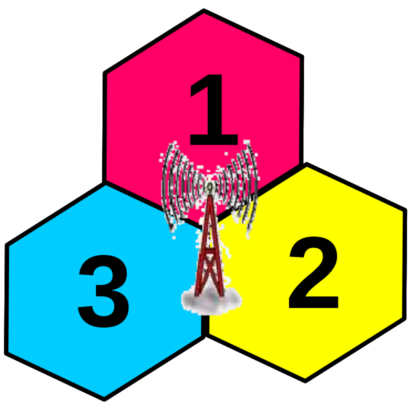
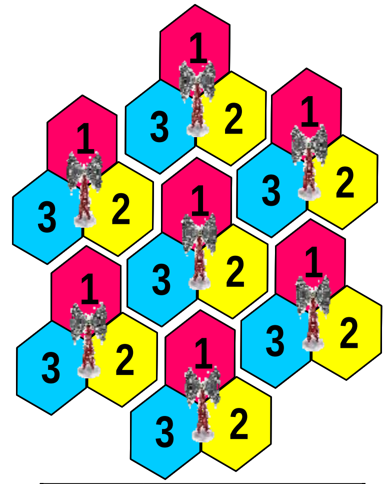



Figure 5: Frequency Reuse (N=3)

This means three different frequencies are used per site. More spectrum is used for N=3 frequency reuse (3X) than an N=1 configuration. Therefore the spectral efficiency (# of bits per bandwidth in Hz) is worse in an N=3 than a N=1 reuse pattern. Figure 6 illustrates the N=3 frequency reuse concept with more than one cell site[29,30].



| Reuse | Interference margin | |
|---|---|---|
| | DL | UL |
| N=1 | 5 dB | 4 dB |
| N=3 | 1 dB | .5 dB |

Figure 6 & Table 3: Frequency Reuse Margins

The general conclusion that can be drawn from a higher reuse pattern is there is less interference from adjacent cells occurring with an N=3 reuse over an N=1 pattern. Lower interference means a higher SNR (Signal to Noise Ratio) which translates into better modulation formats and higher throughput or coverage. Likewise, the link budget is better (lower interference margin) in a higher reuse pattern. Table 3 shows interference margins for various reuse patterns[3,4,7,8]. A 4dB difference between an N=3 and N=1 reuse for WiMAX OFDMA environments is typical.

CDMA technologies can use a N=1 frequency reuse because channels are separated by codes not frequencies. OFDMA systems, such as WiMAX, have that luxury only at a capacity and coverage cost. OFDMA can approach N=1 frequency reuse but still must combat adjacent cell or sector interference.

Fortunately, sub-channelization techniques in WiMAX OFDMA systems can combat N=1 frequency reuse interference. In reality, all WiMAX vendors recommend the use of frequency reuse patterns greater N=1 as this provides the optimum trade-off of spectral efficiency, capacity & coverage. Again, a word of caution is needed here when looking at WiMAX spectral efficiency (bits/Hz) claims as N=1 frequency reuse assumptions are always used. Although N=1 is technically feasible the only way to get that reuse pattern and still attain claimed capacities (average sector throughputs) is to reduce the cell site radius to a very small distance. The frequency reuse, spectral efficiency, coverage tradeoff just described is a perfect illustration of the "zero sum" nature of wireless technology when it comes to capacity versus cell range versus spectrum utilization.

Sub-Channelization Techniques

One of the most enabling core technologies in the WiMAX specification is the concept of sub-channelization. Dividing the overall channel (e.g.- a 10 MHz channel bandwidth) into sub-channels used only by certain subscribers on the uplink improves overall cell range and uplink capacities tremendously. OFDMA sub-carriers (shown as arrows in Figure 7) are grouped to form Sub-Channels.

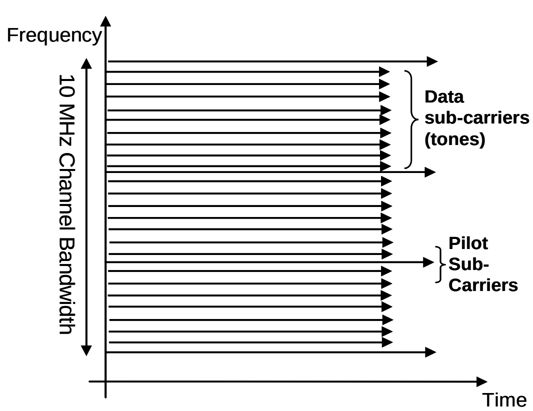



Figure 7: WiMax OFDMA Sub-Channelization

High data rates are attained in OFDMA systems because the information rate is transmitted in parallel over a large number of sub-carriers (1,024 in a 10 MHz channel)[1,8,11]. For instance, the CPE's data stream is divided into several parallel streams of reduced data rates and each sub-stream is modulated and transmitted on separate orthogonal (unique) subcarriers. The high level diagram in Figure 8 illustrates this concept for the transmit portion of a CPE device.

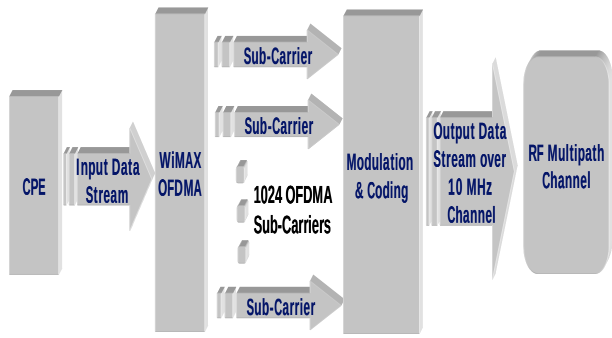
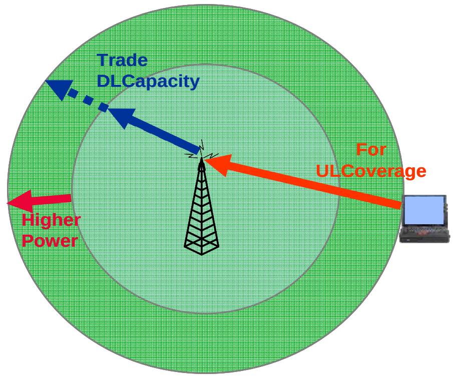



Figure 8: OFDMA Subcarriers

A key enabler in the WIMAX OFDMA system is the MAP (Media Access Protocol) scheduler that allocates bits across various time slots and sub carriers (frequencies). In effect, this function is a very smart control channel that obtains feedback on the channel quality for each user and then tightly schedules and packs user traffic in the optimum time and frequency[2,3].

Channel Bandwidth and TDD (Time Division Duplex)

TDD (Time Division Duplex) technologies utilize the same slice of spectrum for both uplink and downlink communication. A core advantage of TDD is the ability to allocate more of the available capacity to the downlink than the uplink which is particularly useful for asymmetrical data traffic. An overall high channel capacity can be obtained if a very high DL/UL ratio is assumed. In fact, most WiMAX peak or theoretical capacity claims assume the highest 3:1 ratio as this optimizes for capacity. Unfortunately, there is a coverage penalty for choosing such a asymmetrical ratio. Figure 9 illustrates the trade-off possibilities of TDD spectrum and WiMAX technology. An operator can choose to maximize for coverage and provide less cell sites by adjusting the DL/UL ratio[16,17].




.Figure 9: Dl/UL Trade-off's

Configuring a 1:1 DL/UL ratio gives 1.5 dB of link budget improvement for the uplink[10] over a 2:1 ratio. The higher power from the Base Station makes up the loss in DL link budget. Figure 10 illustrates this phenomenon when a coverage versus capacity calculation is performed[5]. For a new entrant operator without customers it makes sense to initially deploy the network with a coverage optimized TDD DL/UL ratio of 1:1 and incur the capacity "hit" and then change to a more capacity optimized DL/UL ratio later on. Table 4 shows the DL and UL capacities for each of the possible TDD ratios [9,10].

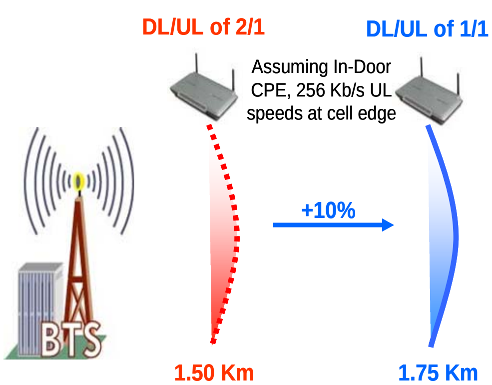



Figure 10: DL/UL Representation

**Average Sector Throughput (Mb/s)**

| TDD Ratio (DL/UL) | Downlink Capacity | Uplink Capacity |
|---|---|---|
| 1/1 | 5.57 | 4.76 |
| 2/1 | 7.28 | 3.30 |
| 3/1 | 8.25 | 1.99 |

5 MHz Channel Bandwidth, with 2x2 MIMO

Table 4: DL/UL Ratio's

The technical details on why this effect occurs goes back to the concept of sub-channelization and the subcarriers in OFDMA technology[6,8,11]. The UL coverage gain in going from a 2:1 ratio to a 1:1 TDD Ratio (DL/UL) occurs because with a 1:1 ratio, there are more uplink symbols (time slots) available for a subscriber data rate (256 Kb/s). Specifically, 21 UL symbols versus 15 UL symbols. The fewer tones (data sub-carriers) needed to be allocated in the uplink results in a reduced uplink signal bandwidth (670 KHz versus 930 KHz). The same power across a smaller bandwidth results in an improved sensitivity. This means the uplink coverage improves while maintaining the subscribers uplink data rate of 256 Kb/s. The frequency and time domain representation in Figure 11 illustrates this concept[9,12,13].

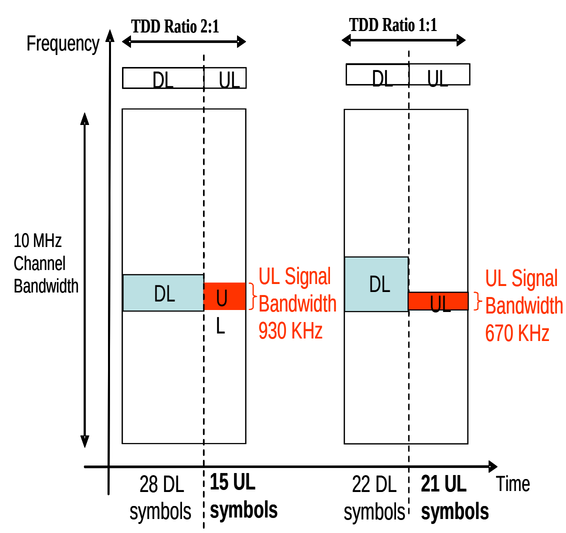



Figure 11: Details of DL/UL Trade-off's

## Channel Bandwidth Selection

WiMAX is unique from previous wireless standards in that it allows for flexible or scalable channel bandwidth choices by the operator while maintaining the same interoperable specification. The ability to have the same CPE operate in either a 5 MHz or 10 MHz channel is extremely valuable as the network can grow in capacity without adding equipment or changing out CPE. Although the RF front-end hardware of current WiMAX CPE and Base Stations are not capable of handling 20 MHz channels the specification is capable of growing to a 20 MHz channel size. Interestingly the 4G cellular specifications being created (called LTE for Long Term Evolution) envision a 20 MHz OFDMA channel [1,3].

A non-intuitive concept of OFDMA and WiMAX that is foreign to the world of CDMA is the concept of being able to increase capacity by increasing the channel bandwidth without losing coverage. Increasing from a 5 to 10 MHz channel adds considerable network capacity to a sector (cell). Either greater speeds can be provided to the same number of subscribers or more subscribers can be served at the same product speeds. Increasing from 5 to 10 MHz bandwidth causes a 3 dB downlink loss in the link budget[3] as shown in Figure 12. If the full channel is used then less BTS power is applied across the larger 10 MHz channel. There is no loss in the link budget for the up link because of sub-channelization. The bandwidth of each sub-channel is the same regardless of the total channel bandwidth therefore the same amount of power from the CPE is applied across the uplink bandwidth. Since the uplink is usually the most limiting item for coverage there is no reduction in cell range when WiMax capacity is increased (as shown in Table 5) by going from 5 to 10 MHz. In the rare situation that the design was downlink limited the network would lose coverage when going from a 5 MHz to 10 MHz channel bandwidth[11,12,30,31].

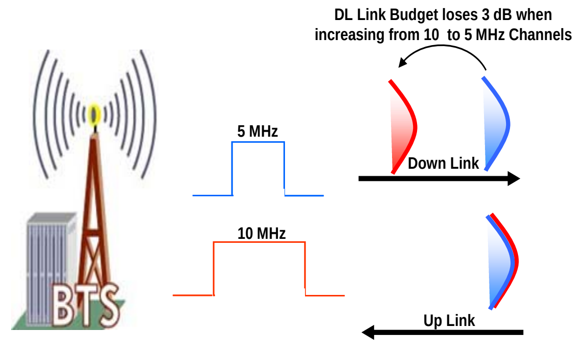



Figure 12: Channel Size Trade-off's

Throughput improves when increasing channel size from 5 to 10

Average Sector Throughput (Mb/s)

| Channel Bandwidth | Downlink Capacity | Uplink Capacity |
|---|---|---|
| 5 MHz | 7.28 | 3.30 |
| 10 MHz | 13.81 | 6.71 |

2/1 DL/UL TDD ratio with 2x2 MIMO

Table 5: Channel Size Capacity

## Advanced Antenna Technology

Because WiMAX utilizes TDD and OFDMA technologies it has some inherent advantages when it comes to smart antenna technology. In TDD operation the same RF channel is used for both transmit and receive so the RF channel link conditions at any point in time are known. This allows for fast, closed-loop type adjustments by the base station and CPE that can increase performance. Additionally, OFDMA is not as susceptible to frequency selective fading as other technologies, which plays to the strengths of advanced antenna techniques[6]. In the specification WiMAX has many smart antenna technologies incorporated into the standard as options. There are so many options and unspecified vendor implementations that it adds a level of complexity to the standard that will surely cause many interoperability issues with CPE devices. If the interworking aspects can be resolved over time some extremely beneficial capacity and coverage gains will be reaped with these technologies. There are various technologies that focus on either improving cell site range such as Adaptive Antenna Systems (AAS or Beamforming) or increasing capacity such as MIMO (Multiple Input Multiple Output) Spatial Multiplexing (SM) technology.

Increasing capacity is the main benefit of MIMO. MIMO can improve capacity by transmitting parallel data streams using multiple antennas at both transmitter & receiver. For example, if there are two transmit antennas then each will carry ½ of the total data in the same spectrum at the same time. Likewise the receive antennas demodulate and combine in the same way. Therefore twice the capacity is possible. MIMO uses multipath to its advantage and works best in urban environment where the signals transmitted by the antennas bounce off buildings and take many paths before they reach the multiple receive antennas. If the received signals are uncorrelated they can be combined in many ways (e.g.- Maximum Ratio Combining or MRC) to increase performance. If two transmit antennas are at the BTS and two receive antennas at the CPE it is called 2x2 MIMO in the downlink[7,14].

MIMO capable CPE will have two receive antennas and one transmit antenna while base stations will initially have two transmit and two receive antennas evolving to 4 transmit and receive antennas on the base station side. If the CPE and Base Station have only one transmit and one receive antenna then it is called a SIMO or SISO (Single Input Multiple Output or Single Input Single Output) configuration. It will take many years to get CPE prices low enough to accommodate two transmit antennas on the uplink from the CPE.

WiMAX will be using mainly 1x2 and 1x4 MIMO capabilities on the uplink. MIMO transmit diversity puts the extra antenna at the base station instead of the CPE in order to keep the subscriber unit costs low. Figure 13 illustrates the typical WiMAX 2x2 MIMO configuration downlink and 1x2 MIMO uplink.

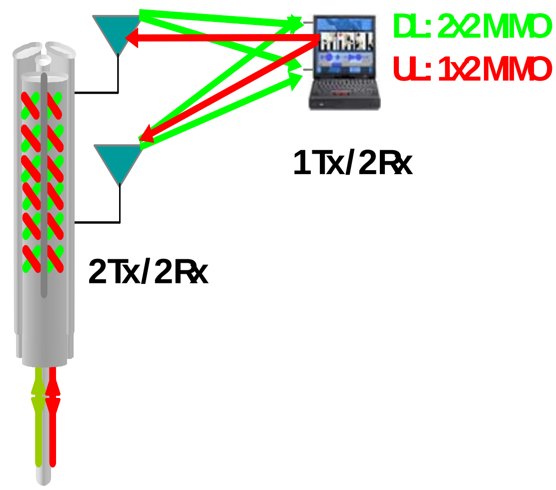



Figure 13: 2x2 MIMO

Adaptive Antenna Systems (AAS) or Beamforming improve link budget & reduce interference. Several antennas (at the base station only) form large directional arrays with a narrow beam width. The higher antenna gain improves range and the narrow beam reduces interference to and from other cells. In the same way signals are added to improve gains, unwanted signals or interference can be subtracted to create a null directed towards interferers and thereby reduce interference. Finally, Adaptive MIMO Switching or AMS is the technology that adjusts the downlink to choose the best advanced antenna option for the current RF conditions. For instance AMS can dynamically switch from a MIMO capability to an AAS mode dynamically[6]. Because of the complexity of AAS, MIMO and AMS these capabilities will be proven out in during later phases of the WiMAX industry certification and interoperability testing.

<u>WiMAX Capacity Claims</u>

The WiMAX Forum and other vocal proponents of WiMAX technology typically state peak data rate capacities. Although interesting numbers these claims are very theoretical as they represent the peak rate a single user operating in perfect conditions can obtain at the highest modulation and coding rate. In addition, MAC (Media Access Control) layer overheads for functions such as resource allocation and access controls are not taken out of the number. Overall, stating peak rates and comparing them with other wireless and fixed technologies is not very useful. Table 6[1,5,23,24,26] lists the aggressive WiMAX Forum capacities on the far right column for a 10 MHz channel, 3:1 DL/UL ratio and N=1 frequency reuse configuration. Peak, average sector throughput and spectral efficiency numbers are listed for downlink and uplink in SIMO and MIMO environments.

The middle column illustrates much more realistic assumptions that reflect the real world mobile wireless environment of today. As an example the 14.1 Mb/s MIMO downlink claim by the WiMAX forum versus the 9.0 Mb/s industry average is a 35% reduction in capacity due to changing assumptions.

| WIMAX Capacity<br>N=1 reuse, 10 MHz BW, 3:1 DL/UL ratio | | WiMAX Industry<br>More Conservative Assumptions | WiMAX Forum<br>Aggressive Assumptions |
|---|---|---|---|
| Downlink Peak Data Rate (Mbps)[1] | SIMO | 23 | 23 |
| | MIMO | 46 | 46 |
| Uplink Peak Data Rate (Mbps) | SIMO | 3.5 | 4.03 |
| | MIMO | 3.5 | 4.03 |
| Downlink Avg. Sector Throughput (Mbps) | SIMO | 7.5 | 8.8 |
| | MIMO | 9.0 | 14.1 |
| Uplink Avg. Sector Throughput (Mbps) | SIMO | 1.1 | 1.38 |
| | MIMO | 1.5 | 2.19 |
| Downlink Spectral Efficiency (b/Hz) | SIMO | 1.0 | 1.21 |
| | MIMO | 1.2 | 1.93 |
| Uplink Spectral Efficiency (b/Hz) | SIMO | .40 | .55 |
| | MIMO | .60 | .88 |

Table 6: Capacity Comparison

A large contributor to higher capacity numbers is the type of traffic model used in the simulation. For example, a simulation that sends 100% large packets (called full buffer) will have a much smaller MAC layer overhead count therefore making the average throughput capacities larger. If more realistic call & traffic models are used that represent a mix of large and small packet type traffic (such as web browsing) the overhead counts will be higher and result in lower net throughput capacities[27].

Additionally, a lower gain, less complex type CPE receiver is used instead of the more advanced non linear receiver assumed by the WiMAX Forum[1,2,3,8]. Certainly these advancements may be possible in future years but it is yet to be proven in commercial deployments.

Lower power base stations that provide 2 to 4 watts at the antenna were assumed because the cost and size of a high power amplifier may be difficult to implement. The WiMAX Forum is assuming a 20 watts at the ground assumption[1,8] which is a less practical RF implementation for tower configurations. The effect of higher power base station causes a larger distribution of subscribers obtaining the higher modulation rates which increases channel throughput capacity. It is very important to realize that average throughput capacity claims assume a mix of modulation modes.

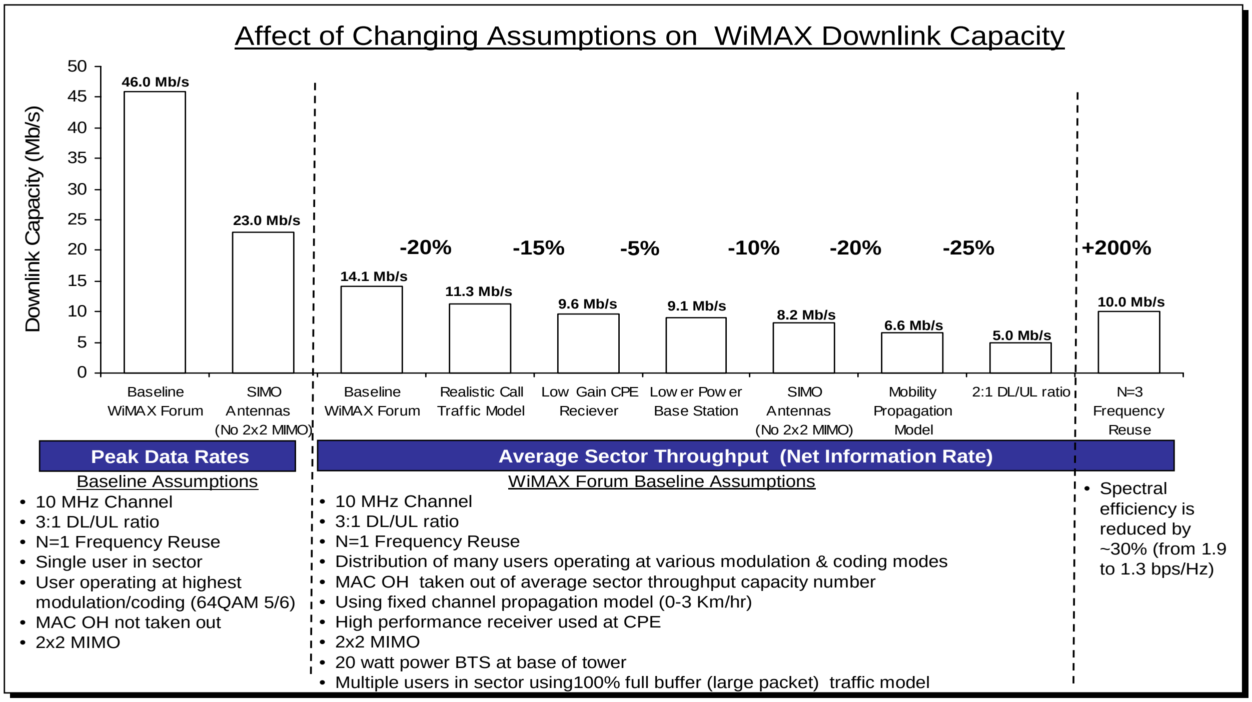



Chart 2: Impact of Assumption Changes on WiMAX Downlink Capacity

Therefore, if one simulation assumed a majority of users get 64QAM versus a second simulation which assumed a lower percentage of the users are able to obtain the highest modulation rate then a lower capacity claim will result in the second simulation.

Chart 2[3,5] gives a more detailed breakdown of how on a broad-guage percentage basis varying the key assumptions mentioned above will affect the WiMAX downlink capacity numbers. Additional assumption changes that may reduce average sector throughput from the baseline WiMax Forum numbers are; no MIMO antenna capability, using a full mobility channel propagation model and reducing the downlink to uplink ratio. WiMAX deployments with a simpler SIMO antenna scheme or perhaps rural applications where little multi-path fading exists will severely hamper the MIMO gains anticipated in computer simulations. Additionally, MIMO gains have not been fully proven when a user is operating at low modulation rates such as QPSK ½, which will be the case at cell edge operation[6]. Regarding the affect of mobility, when a 30 Km/hr channel propagation model [27,28,29] is used instead of a mix of channel models skewed towards a fixed environment, (e.g.- 0

to 3 Km/Hr used by the WiMAX Forum), the anticipated gains and ultimately sector capacities are reduced[16,17,22].

Finally, if either a more symmetrical user service or a network design optimized for coverage is required then a 2:1 DL/UL (or even 1:1) ratio will be required and impact capacity. In fact, a subscriber average uplink service level of 256 kb/s combined with a moderate VoIP mix of services and the need to optimize for range will quickly drive the operator to design to a 1:1 DL/UL ratio because of uplink requirements[25,26,27]. In these situations a large overall average sector throughput reduction for the downlink will result as shown in the chart above. This is an illustration of a classic design trade-off where uplink demands result in a downlink capacity "hit".

On the positive side, extremely large capacity gains are possible by increasing the frequency reuse to an N=3 scheme and reduce interference as shown above. There are tradeoffs to this design decision particularly, the negative effect on spectral efficiency. Although the average sector throughput capacity increase is greater than 100% with an N=3 frequency reuse, it also means three times the spectrum is used. The spectral efficiency bits per hertz ratio is upwards of 30% lower for N=3 over N=1 because of the much larger total spectrum used[9,16,30].

One could infer from Chart 2 that a wireless operator with a large amount of contiguous spectrum and a willingness to use an N=3 frequency reuse and build a very dense network (< 1.5 Km cell radius) could offer some reasonable downlink capacities. For instance, the 9.1 Mb/s sector capacity (before MIMO was removed) could feasibly double to a 15 to 17 Mb/s average sector throughput. The operator would have to be willing to forego offering mobility (change from a mobile to a fixed propagation model) and take the uplink capacity restriction associated with a 3:1 DL/UL ratio. Although a WiMAX 20 MHz channel bandwidth is quite a bit down the road in developmental time frames, downlink sector capacities under similar assumptions might some day be able to approach 25 to 30 Mb/s downlink.

To summarize, channel bandwidth, frequency reuse and downlink to uplink ratios are very big drivers of capacity. As noted in Chart 2, MIMO antennas, base station power, CPE receive sensitivity, traffic models and channel propagation model assumptions can also skew results in a variety of directions.

In conclusion, one sees many differing capacity claims regarding WiMAX. It is feasible that all these claims are the result of very accurate and sophisticated simulations, but are not necessarily comparable, (nor realistic) as the key underlying assumptions will most likely vary.

Good historical references from other new wireless technologies, such as CDMA, exist. When CDMA was first deployed the claims on capacity and coverage were based on simulations. As commercial deployments were rolled out it became apparent that many claims were either based on faulty assumptions, never achievable, or would take many years of fine tuning and enhancements to reach. Over time (10 to 12 years), CDMA technology met its original claims and well exceeded the prior wireless technologies in capacity, coverage and performance. It is the opinion of the authors that in the same way OFDMA will surpass its predecessor wireless technology.

## WiMAX Subscriber Speeds and Services

Translating WiMAX channel capacity numbers we have just gone through into a useful understanding of the number of subscribers that can be served in a WiMAX cell site and network requires standard traffic engineering dimensioning. Paramount to this analysis is an understanding of the likely product mix, and market statistics as shown illustratively in Table 7 & 8.

These design assumptions are needed to determine the cell site radius, number of sites and sectors and subscribers served per sector. Desired product speeds, market density and subscriber penetration levels are particularly important starting points as is the overbooking ratio (or concurrency) assumption. Since the small packet size and large header requirements of VoIP services are a burden on capacity, the VoIP penetration level is likewise necessary.

| Component | Assumption |
|---|---|
| Total Area | 443 km$^2$ |
| CPE | Indoor Gateway |
| Market Penetration | 10% |
| Total Homes in Area | 186,000 |

| Product Speeds (DL/UL) | Take Rate | Overbooking DL/UL | Avg. Kbps |
|---|---|---|---|
| 1024 / 256 | 10 | 40 / 15 | 25.0 / 6.4 |
| 512 / 128 | 40 | 25 / 15 | 20.5 / 5.1 |
| 256 / 64 | 50 | 20 / 15 | 12.8 / 3.2 |
| Wtd. Avg | 100 | | 17.1 / 4.3 |

Table 7&8: Product Mix and Market Statistics

As customer speed requirements increase the network goes from coverage limited to capacity constrained and the cell site radius is reduced to meet the demand. Chart 3 shows the effect of desired customer speeds and CPE devices on cell site radius[13,16]. In particular, speeds in the uplink offered to customers can severely impact the cell radius calculations. The key drivers of this graphical representation are the typical SNR's and associated adaptive modulation rates required at the cell edge for both DL and UL link budgets[1,5,17,18]. It is easy to see that the link budget is uplink limited for all but the outdoor CPE case as cell radius is flat until the uplink customer speeds are increased. The design target for WiMAX networks is optimum at 1 Mb/s DL & 256 Kb/s UL for indoor CPE.

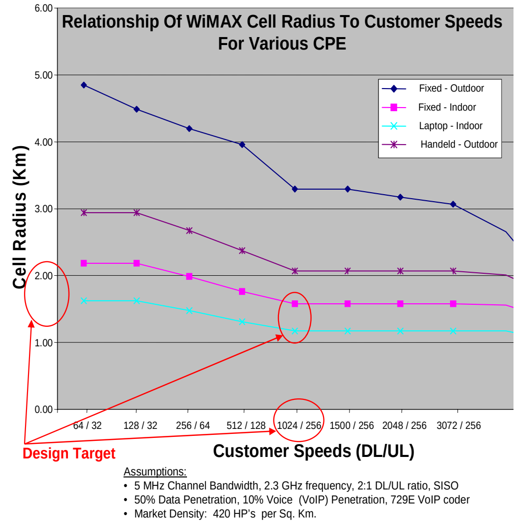



Chart 3: Cell Radius to Customer Speeds

In the same way a graphical representation of total subscriber capacity (Chart 4) in a 3 sector cell under the same varying customer speeds and CPE device scenarios[10,11,12,16,17]. Once again, SNR's and adaptive modulation rates required at the cell edge for both downlink and uplink are the critical calculators. Given the desired customer speeds at the cell edge, customer product speeds and overbooking assumptions a target number of subscribers per cell and sector can be calculated.

The conclusion of charts 3 and 4 is that a WiMAX three sector cell site has the capacity to serve approximately 125 customers per sector (382 subs / 3) at 1 Mb/s downlink and 256 Kb/s uplink when the cell radius is 1.5 Km and the CPE is a fixed indoor residential gateway. Even the subscribers at the cell edge and operating at the lowest modulation rate will be able to receive a 1 Mb/s downlink service. As wireless system design is very probabilistic and uplink limited the modeling used here focuses on the probability of serving customers at the cell edge with 256 Kb/s uplink service.

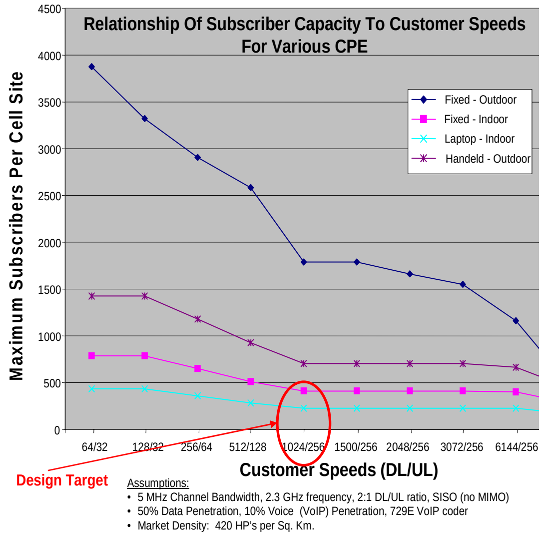



Chart 4: Cell Capacity to Customer Speeds

It is certainly possible to serve either more customers at lower speeds or fewer customers at higher downlink speeds. Using the same assumptions a 10 MHz channel would serve between 200 and 300 customers per sector with the similar service levels.

Another interesting effect that can be concluded from these charts is if a dense network is initially built then downlink speeds from 1 to 5 Mb/s can be provided to customers. The uplink on the other hand is extremely sensitive to increasing customer service levels and uplink sensitive VoIP type services. Optimizing for uplink is possible but only with a coverage or downlink capacity negative impact.

As the penetration levels increase capacity will need to be added by either growing to a 10 MHz channel bandwidth, adding more sectors and using more frequency, upgrading to MIMO CPE (mainly in urban areas), going to a higher DL/UL ratio (at the expense of adding new sites to cover the shrinking cell radius) or cell splitting (adding new cell sites). If the above scenario wasn't already at an N=3 frequency reuse increasing the frequency reuse would also help with both range and capacity increases.

Although the average service level offered to an individual customer is sized to 1 Mb/s downlink speeds certainly an individual user could burst to the entire sector average throughput number. It is unrealistic that a single CPE will have access to a fully unoccupied channel. Most of the current version CPE hardware is rate limited to 3 to 5 Mb/s downlink speeds and it is reasonable to assume most network operators will tightly control via software the downlink and uplink speeds of wireless users.

It is appropriate to reiterate in this section that average sector throughput numbers, such as the 7 Mb/s number, is truly an average. If an individual user is in perfect channel conditions and operating in a 64QAM adaptive modulation mode then that user could in theory attain a 10 Mb/s speed even though the average throughput is 7 Mb/s. Conversely, cell edge customers may not be able to burst above their stated 1 Mb/s threshold service level.

Coverage Considerations

The old cellular adage “coverage is king” certainly applies to WiMAX as well. It is a particularly appropriate mantra in the initial launch stages when the network has not added any customers and the operator is uncertain where and when they will appear.

There are many variables that affect coverage. Certainly the frequency and power limits set by the spectrum being used are foundational variables. Network and WiMAX specification settings we have mentioned are critical. Base station antenna height, TDD DL/UL ratios, frequency reuse, CPE type and smart antenna have the most impactful engineering design decisions. Customer propositions agreed to in the business case can vary cell site range quite extensively as well. For instance, uplink speeds available to subscribers at the cell edge, mobility versus fixed services, probability of attaining coverage at the cell edge and in-building versus outdoor coverage are key factors. All ten of the variables mentioned above are baked into the link budget along with the chosen vendors receive sensitivities and transmit power gains of their equipment to arrive at a maximum allowable path loss for both the downlink and uplink separately. Typically the uplink will be the most limiting so that path loss will be used to calculate the cell radius for a typical terrain (suburban, urban). Chart 5 provides an indication of the degree each of the technical variables affect cell radius[9,10,11,16,21,22].

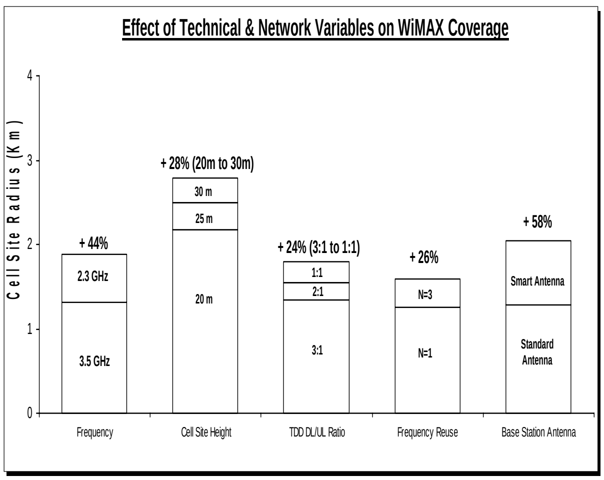



Chart 5: WiMAX Coverage Impact - Technical

Going from a 3.5 GHz to a 2.3 GHz spectrum operation can increase cell radius approximately 44%, while a 10 meter antenna height increase can easily provide a 28% improvement. As mentioned in previous sections reducing the DL/UL ratio from 3:1 to 1:1 can grow cell site range from 1.4 Km to 1.74 Km. Frequency reuse and the associated gains in link budget, by reducing interference, will increase range 26% for a 5 MHz channel at 2.5 GHz. Finally, the cell radius gains from various advanced antenna technology varies tremendously. A typical industry average can provide a 58% improvement in coverage.

Most new entrants opted for range when making decisions on the variables in Chart 5. A choice of using either 3.5 GHz or 2.3 GHz spectrum is an easy decision, as the lower frequency has better propagation. Additionally, a higher 25 meter cell site height, 1:1 UL/DL ratio and N=3 frequency reuse choices will optimize for coverage over capacity and spectral efficiency.

Chart 6 provides a similar representation of the impact on coverage for various customer impacting variables[9,10,11,16,22].

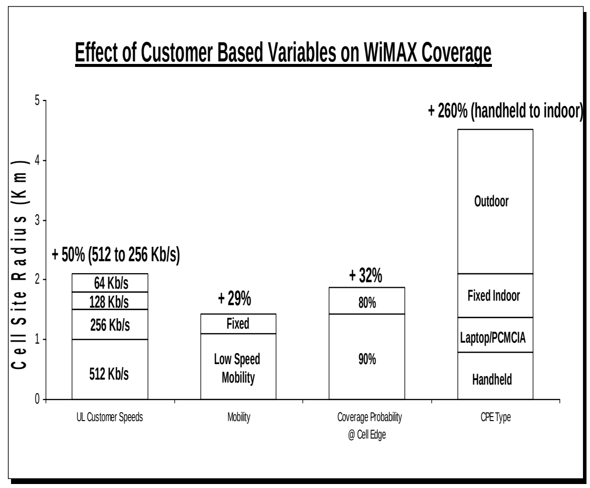



Chart 6: WiMAX Coverage Impact - Customer

Uplink speeds offered to the customer at the cell edge can cause widely fluctuating cell radius. Offering a service tier to customers at 256 Kb/s instead of 512 Kb/s can increase cell size by 50%. Cellular networks are typically designed for 64 Kb/s indoor coverage, which creates cell sizes twice the size of a 512 Kb/s designed WiMAX network.

Choosing a mobility based path loss channel propagation model introduces fading margins in the link budget that can easily add almost 30% cell reductions. Building in for overlapping cell coverage for handover also adds additional cells.

Another subtle tool used by RF engineers to increase range is to set the threshold of reliability at the cell edge to a level lower than the industry standard 90%. 80% coverage probability means 20% of all users at the cell edge will not get the minimum level of uplink service required by their service tier (e.g.-256 kb/s).

As mentioned in the very beginning of the paper the choice of CPE devices drive a wide variance in cell radius. In a 2.5 GHz design, the cell radius can grow from 1.76 Km in a suburban area for indoor CPE to 4.65 Km if the CPE is mounted outdoors. Rural terrain has an even larger effect, as a 2.32 Km indoor configuration grows to 6.55 Km with an outdoor installation.

Wireless broadband cell coverage engineering certainly contains a large amount of trial and error and has many elements of art as well as science. The end result is a somewhat variable end product offered to customers. Some subscribers will have an over- engineered service while others in difficult terrain or well inside a building made of difficult materials are unknowingly given a poor level of service.

Performance Considerations

WiMax will have many performance issues as the technology becomes developed and deployed. The most challenging aspects will be uplink related performance.

Maintaining uplink speeds and capacity at the cell edge with small packet size applications such as VoIP will be challenging. OFDMA technology performs much better than CDMA or TDMA schemes because of sub-channelization. By splitting the entire 10 MHz channel bandwidth across many subscribers each customer uses only a small subset of subcarriers with a far lower power than if it had to transmit over the entire bandwidth[3,4,5]. Even with that advantage the uplink capacity is an extremely limited resource and inefficient small packet applications such as VoIP and web browsing will take its toll on capacity. Both industry simulations and testing confirmed some major uplink capacity reductions associated with small size packet call traffic over full buffer type traffic[1,2,3,27].

Packet loss, bit error rate (BER) and packet error rates (PER) as the system is loaded and stressed will be important performance issues to watch as the technology develops and commercial networks are deployed. To the extent the complicated MAP scheduler function operates and achieves the optimal performance of the WiMAX specification will determine the BER stability.

Latency could become an issue with WiMAX as the inherent nature of TDD systems causes a longer round trip delay associated with the transmit and receive paths sharing the same swath of spectrum. Industry testing to see if actual performance matches the anticipated 50 ms specification[8,25,27] will be a closely monitored performance data point.

As mentioned in the previous section, the variability of product speeds (both downlink and uplink) seen by customers in the real world will be a marketing and technical challenge for operators. Predictive tools will help to proactively solve these issues but there will be no substitute for having ancillary CPE such as window mounted antennas and higher power devices to assist the operator in a variance of customer service levels.

Mobility will have its own share of performance issues and will be left for the later stages of WiMAX development. The specification focused on the MAC and PHY layer so handover and other key mobility functions will require greater definition in the core network to reduce interoperability issues.

MIMO technology has yet to be proven in the field. In particular, much is riding on the capacity gains associated with this feature. Very visible industry tests will be made to measure the gains associated with suburban and rural terrains, where minimal multipath exists, and to understand the gains with operation in lower modulation and coding modes.

Interoperability will be the key performance issue. The WiMAX specification has many options, settings and specification vagueness subject to vendor interpretation and implementation. Overall the complexity and choices comprised in the standard will invariably lead to substantial interoperability challenges. Particularly challenging is CPE to base station inter-working. Initial WiMAX chipset vendors are small companies and their coordination with many large base station vendors could unfortunately lead to design errors in the world of a specification with many choices.

Finally, it will be important to manage peer to peer traffic, especially in the uplink, as is common in the fixed broadband networks. Chart 7 depicts the capacity gains possible by closely managing a WiMAX network uplink resource. The chart indicates moderate to aggressive peer to peer management can raise overall subscriber capacity by 30%.

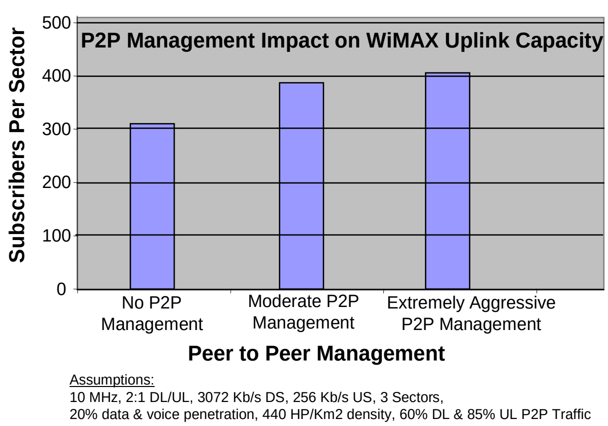



Chart 7: Peer to Peer Management

In conclusion, maintaining a high level of performance in a wireless broadband network will be challenging. Mobility and broadband have been historically two mutually exclusive design parameters. Wireless engineers are good at either optimizing a network for either mobility or separately optimizing for broadband capacity. It will be a new and challenging task to optimize for both objectives. From a cost perspective it may become an uneconomical design as there will be a requirement to design for the lowest common denominator. Mobility propagation models, cell overlap (for handover) and high speed fixed uplink services inside the home will all trigger a very dense network design.

Secondly, the fact that a wireless network has a very tight linkage between the uplink and downlink means you can not treat the engineering and design of these two segments separately. Optimizing for the downlink will surely have an effect on the uplink and vice versa. Typically, broadband networks that can separate these two dimensions are easier and more economical to manage performance levels.

Building on this second point, performance in wireless networks is all about tradeoffs. The classic analogy for wireless is that performance management is a fixed triangle, where coverage is at the apex, capacity is at one base and quality (or service levels) is at the third corner. Optimizing for one of the three corners always puts pressure and reduces the capability on one or both of the other corners. Non-negotiable trade-offs result in such an environment where there is always a losing metric with regards to performance.

## WiMAX Economics

The relationship of capacity, coverage and performance to economics is also a very important trade-off. One of the main drivers of WiMAX economics is the penetration rates and market density of the customers served. As Table 9 indicates, wireless networks with small cell radii, such as WiMAX, the linkage of market density and penetration levels to the subscribers served is critical[2,10].

WiMax Subscribers Per Site For Various Market Densities & Subscriber Penetration Levels

| Market | E. Europe Country | US Metro Area | Asia Suburbs | W. Europe City |
|---|---|---|---|---|
| Area in $Km^2$ | 20,273 | 12,949 | 443 | 830 |
| Homes Passed (HP) | 509,096 | 983,000 | 186,000 | 425,000 |
| Market Density ($HP/Km^2$) | **25** | **76** | **420** | **512** |
| **Penetration Rates** | | | | |
| 1.0% | 1 | 3 | 15 | 18 |
| 3.0% | 3 | 8 | 45 | 54 |
| 10.0% | 9 | 27 | 223 | 272 |
| 15.0% | 14 | 40 | 335 | 408 |
| 16.6% | 15 | 45 | 370 | 452 |
| 20.0% | 18 | 54 | 446 | 544 |
| 25.0% | 23 | 67 | 558 | 680 |

Table 9: Subs Per Site for Various Market Densities

Typically cities with market density greater than 400 $HP/Km^2$ such as the Western European and Asian suburbs shown in Table 9 have the best per site subscriber levels. Because WiMAX has the potential to offer very reasonable channel and subscriber capacities (compared to other wireless technologies) at short ranges, high density/high penetration conditions are very conducive to economic success.

This point is best proved by first looking at the WiMAX network cost structure. As Chart 8 illustrates the main costs associated with the upfront network build are construction related[2,19,21,23,32,33]. Typically, site acquisition, legal, civil works, tower costs, power & electrical costs are almost 50% of the total costs. This is true of most wireless networks but is amplified in a WiMAX network because the actual base station costs are reasonable. The second largest expenditure is for all the costs associated with the base station electronics. When the microwave, installation, rigging (cabling on a tower or rooftop) test & turn-up, battery back-up, environmental (A.C. or heat exchanger), cabinets and ancillary equipment are added together they account for 30% of the total costs.

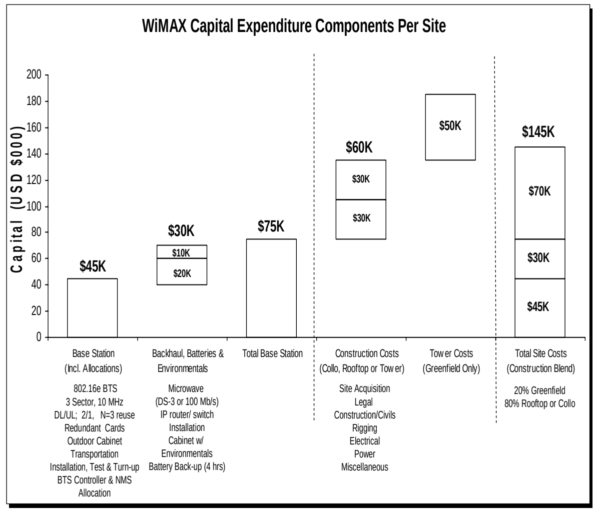



Chart 8: WiMAX Capital Cost Management

It is important to realize that the costs shown in Chart 8 can vary widely based upon the vendor's equipment and design. Certainly the type of antenna, the allocation for the base station controller function (called ASN or Access Services Network in the standard), redundant cards, spares and software feature/functionality will drive a wide range of costs.

Similarly, the construction assumptions can cause a large cost variance. Foremost in the construction economics is the degree an operator can forego the cost of building towers by obtaining collocation agreements with existing tower owners and landlords of rooftops. For the purposes of Chart 8, a 80% / 20% split of collocations to "Greenfield" new builds of towers is assumed.

One important learning we obtained in the understanding of the cost components and how to minimize expenditures was the need to minimize construction costs by obtaining a low-power, small footprint base station and its ancillary equipment. If large base station and microwave backhaul electronics are required then large shelters, air conditioning, additional power and larger battery back-up gear is needed. All these things drive higher construction costs as now cranes are needed, additional electrical work from the power company and larger concrete footings will be triggered. In the harsh environmental conditions of some rural networks the payoff of having "hardened" microwave and base station electronics is substantial in order to avoid these add-on costs.

Applying the up front Capital costs to the market density and penetration numbers discussed previously will lead to a cost per subscriber metric shown in Chart 9 [2,19,21,23,32,33]. Key to these calculations is the capacity, traffic engineering, coverage and customer performance metrics illustrated in prior sections. The resultant cost per sub is \$550 where over 40% of the costs is for CPE. Constructions costs contribute 28% and the base station, microwave and ancillary equipment split the remaining 30%. The cost structure assumes a dense 1.3 Km cell radius, moderate market density (440 HP/Km$^2$) and penetration level (20%). Finally, the network was designed for 90% coverage at the cell edge with 1 Mb/s downlink and 256 Kb/s uplink service levels.

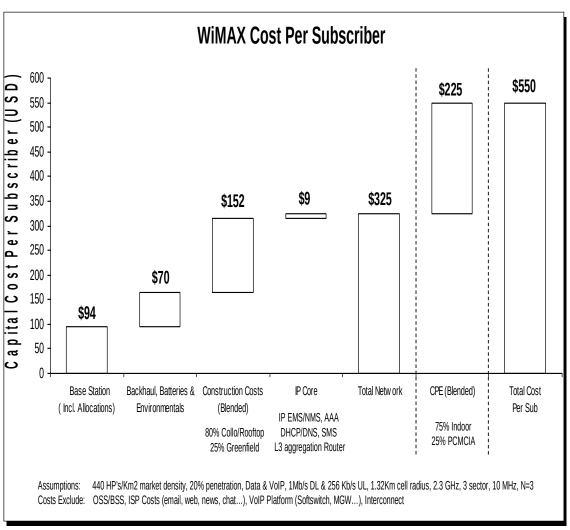



Chart 9: WiMAX Cost Per Subscriber

An interesting sensitivity to the cost per subscriber number mentioned is the effect market densities and penetration rates have on this number. Table 10 provides a variety of cost per sub numbers for the illustrative markets already discussed [2,10].

**WiMAX Costs Per Subscriber For Various Market Densities & Subscriber Penetration Levels**

| | Market | E Europe Country | US Metro | Asia Suburbs | W Europe City |
|---|---|---|---|---|---|
| | Area (KM$^2$) | 20,273 | 12,949 | 443 | 830 |
| | Homes Passed | 509,096 | 983,000 | 186,000 | 425,000 |
| | HP/KM$^2$ | 25 | 76 | 420 | 512 |
| Penetration Rates | 1.0% | \$145,225 | \$48,558 | \$9,892 | \$8,281 |
| | 3.0% | \$48,558 | \$18,350 | \$3,447 | \$2,910 |
| | 10.0% | \$16,336 | \$5,595 | \$529 | \$475 |
| | 15.0% | \$10,582 | \$3,850 | \$428 | \$391 |
| | 20.0% | \$8,281 | \$2,910 | \$377 | \$350 |
| | 25.0% | \$6,529 | \$2,389 | \$347 | \$325 |

Assumptions: 1.90 Km cell radius, 3 sector, 10 MHz channel, N=3, 2:1 DL/UL ratio, 1 Mb/s DL & 256 Kb/s UL, Fixed Indoor CPE

Table 10: Cost per Sub for Various Market Densities

Not surprisingly the cost per subscriber numbers begin to look quite beneficial for highly dense markets where operators believe they can secure many customers. For example, a Western Europe city with over 500 homes passed per square kilometer can reduce the cost per subscriber metric by 20%. .

Another spin on this sensitivity is to look at the same metric while just varying the cell radius assumption [10,12,13,16] as shown in Table 11. For instance, 128 Kb/s UL speeds with 80% cell edge probability could possibly result in a 1.9 Km cell radius. Assuming all other design assumptions are the same the cost per subscriber metric improves tremendously.

**WiMAX Costs Per Subscriber For Various Market Densities & Subscriber Penetration Levels**

| | Market | E Europe Country | US Metro | Asia Suburbs | W Europe City |
|---|---|---|---|---|---|
| | Area ($KM^2$) | 20,273 | 12,949 | 443 | 830 |
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| | HP/$KM^2$ | 25 | 76 | 420 | 512 |
| Penetration Rates | 1.0% | $145,225 | $48,558 | $9,892 | $8,281 |
| | 3.0% | $48,558 | $18,350 | $3,447 | $2,910 |
| | 10.0% | $16,336 | $5,595 | $875 | $758 |
| | 15.0% | $10,582 | $3,850 | $658 | $580 |
| | 20.0% | $8,281 | $2,910 | $550 | $492 |
| | 25.0% | $6,529 | $2,389 | $485 | $438 |

Assumptions: 1.32 Km cell radius, 3 sector, 10 MHz channel, N=3, 2:1 DL/UL ratio, 1 Mb/s DL & 256 Kb/s UL, Fixed Indoor CPE

Table 11: Cost per Sub for Various Market Densities

The business case will now start to look beneficial at low penetration rates (say 10%) in the more densely populated areas. As in any sensitivity analysis there are a lot of variables to change and WiMAX certainly does not have its shortage of moving parts.

All the previous economic analysis assumed a network designed to serve an indoor high power/high gain type CPE. The costs to serve this CPE design result in $325 per subscriber of network costs and $225/sub of CPE costs. The vision of WiMAX is for customers to access a broadband network with a laptop containing an embedded WiMAX chipset and software. The economics of a laptop CPE network that obtains 1 Mb/s downlink and 256 Kb/s uplink will cause CPE costs to go down to approximately $100/sub. Unfortunately the associated network costs will rise to the $500/sub level in order to support a smaller cell radius. Therefore, in total, the costs will go up and no savings are obtained.

In conclusion, the economics of WiMAX can be compelling if the network operator has the wherewithal to spend a large sum of upfront capital to build a very dense network. This expenditure is only justifiable if there is a fairly compact addressable market and it is underserved. The definition of underserved must mean that downlink speeds of 1-3 Mb/s are not readily available from competitors and that uplink speeds of 256 Kb/s are sufficient. Additionally, underserved probably means that there is a sufficient pent up demand for mobility and portability by customers when using broadband services. And finally, these needs outweigh the inconsistent service levels a subscriber will receive because of the inherent variability of wireless technology.

Comparison of WiMAX to Fixed Broadband

Contrasting WiMAX capacities to the well known Cable High Speed Data (HSD) capabilities of DOCSIS is a very useful exercise. Table 12 compares the capacities and economics of a DOCSIS 1.x network with two different WiMAX configurations. It should be noted that although DOCSIS 1.x was chosen most operators have deployed DOCSIS 2.0 and DOCSIS 3.0 installations are expected to start in 2008. Both advancements will provide even higher capacities to the Cable side of this comparison.

A 10 MHz WiMAX channel bandwidth operating at a 3:1 DL/UL ratio with either an N=1 and N=3 frequency reuse are used. A common customer product speed offering of 1 Mb/s downstream and 256 Kb/s upstream is assumed. Although these are low speeds for a cable network, because it appears to be the "sweet spot" for WiMAX networks, we will focus first on this scenario.

**Comparison of WiMAX to Cable for 1 Mb/s Downlink and 256 Kb/s Uplink**

| Metric | | WiMAX | | Cable |
|---|---|---|---|---|
| | | 10 MHz, N=1, 3:1 DL/UL, | 10 MHz, N=3, 3:1 DL/UL, | DOCSIS 1.x |
| Average Throughput (Mbps) | DL | 8.5 | 15.0 | 38.0[1] |
| | UL | 1.1 | 2.2 | 16.4[2] |
| Max Capacity (Subs/site or node)[4,5] | | 151 | 378 | 1,024 |
| Cost/Subscriber[6] | | $ 1,185 | $ 608 | $ 31 |
| Cost/Mbps (sector/node capacity) | DL | $ 5,686[5] | $ 3,222 | $ 284 |
| | UL | $ 43,155[5] | $ 21,970 | $ 659 |

1. DOCSIS 1.x downstream: 256 QAM for a 6 MHz channel bandwidth = 42.88 Mb/s less O/H = 38 Mb/s
2. DOCSIS 1.x Upstream at 16QAM for a 3.2 MHz channel is 10.24 MB/s less O/H (20%) = 8.2 Mb/s, (2) US channels
3. Market Density is 420 HP per $Km^2$ @ 1.32 Km cell radius = 2,300 HP/site. Cable market is 4 nodes @ 575 HP/Node = 2,300 HP/DOCSIS channel
4. WiMAX site costs are $145K and $225 per indoor CPE.. Cable DOCSIS costs are loaded QAM costs of $10,800 per stream and $20 CM/EMTA.

Table 12: Comparison of WiMAX to Cable

As the numbers indicate in Table 12 the DOCSIS network has 6.5 and 2.5 times the subscriber capacities of the respective WiMAX networks. These results used a common HSD capacity traffic model that assumed a DS overbooking of 40:1 resulting in an average speed of 25 Kb/s and an US overbooking of 25:1 leading to a 10.2 Kb/s average speed. The WiMAX capacity numbers appear slightly different from previous discussions in this paper because a more realistic 30% P2P traffic assumption and equivalent circuit theory tier deduction was accounted for in the calculations.

The comparative economics illustrate a similar DOCSIS advantage of $31/sub versus $608/sub for WiMAX. In addition to the larger capacity advantage for DOCSIS, the lower cost for a QAM leads to the much lower cable cost per subscriber number. Assuming WiMAX is a new entrant, a fully loaded three sector WiMAX site is compared with an embedded Cable plant. A more detailed comparison will want to delve into the impact of adding cable upgrade costs or even a new build into the analysis.

Looking at the higher capacity customer proposition of an 8 Mb/s downstream and 1 Mb/s upstream product in Table 13 clearly indicates the capacity and cost advantage of DOCSIS over wireless broadband.

DOCSIS 1.x with two 3.2 MHz upstream channels allocated results in a 3.5 times improvement in capacity over WiMAX. In the WiMAX case the upstream is clearly the limiting item on the number of subscribers serviceable. Furthermore, the cost per subscriber advantage of DOCSIS is amplified as a $66/sub cost is associated with the Cable network while $2,456/sub is needed to build a WiMAX network. The DOCSIS capacity advantage for serving higher product speeds is very apparent in this example. If a cost per Mb/s metric is calculated and compared as shown in the first chart the WiMAX network disadvantage for both the downstream and upstream is clearly identified. The upstream economic limitations of WiMAX becomes even more pronounced when the $22,000 WiMAX metric is contrasted to the $659 cost per Mb/s DOCSIS number.

**Comparison of WiMAX to Cable for 8 Mb/s Downlink and 1 Mb/s Uplink**

| Metric | | WiMAX<br>10 MHz, N=3, 3:1 DL/UL, | Cable<br>DOCSIS 1.x |
|---|---|---|---|
| Average Throughput (Mbps) | DL | 15.0 | 38.0[1] |
| | UL | 2.2 | 16.4[2] |
| Max Capacity (Subs/site or node)[4,5] | | 65 | 233 |
| Cost/Subscriber[6] | | $ 2,456 | $ 66 |

1. DOCSIS 1.x downstream: 256 QAM for a 6 MHz channel bandwidth = 42.88 Mb/s less O/H = 38 Mb/s
2. DOCSIS 1.x Upstream at 16QAM for a 3.2 MHz channel is 10.24 MB/s less O/H (20%) = 8.2 Mb/s, (2) US channels = 16.4 Mb/s
3. Overbooking; A 1 Mb/s DL product speed uses a 40:1 overbooking which results in an average DL speed of 25 Kb/s. A 256 Kb/s UL product speed uses a 25:1 overbooking which results in an average UL speed of 10.2 Kb/s

Table 13: Comparison of WiMAX to Cable

Overall, it is clear from this analysis that a fixed broadband solution such as DOCSIS has the ability to more easily scale US and DS capacity to meet the growing capacity needs of customers. In fairness to WiMAX capabilities, the costs and capacities shown here do offer a nomadic and portable capability not possible with fixed networks.

## Conclusions

The WiMAX standard extends the state of the art for wireless technology. It lays the foundation for a true 4th generation wireless technology that offers both a broadband and mobility customer proposition. In any new technology the advantages are relative to what it is being compared to. As a comparison to existing wireless technology, WiMAX will exceed the capacity, throughput and economic capabilities of its CDMA predecessors while still offering full portability and mobility.

It is the opinion of the authors that the technical and economic viability of WiMAX versus fixed line alternatives like DOCSIS is very targeted. WiMAX seems to make sense in environments where there is a lack of viable competitor offerings of customer downlink speeds greater than 3 Mb/s and uplink speeds better than 256 Kb/s. Additionally, minimum market density environments and realistic target penetration rates must be attainable for the economics to work.

Overall, as a competitor to fixed line services, like Cable's HSD offerings, WiMAX does not have the speeds or economics to compete against an in place fixed line broadband technology. The uplink challenges, variability of service levels to customers and lack of downlink speeds for video will constrain its competitiveness against fixed line alternatives,

Once the entire WiMAX ecosystem is built out and technology, such as MIMO, advances it may offer a wireless displacement option for certain customers. If, however, speeds and consumption continue to grow, as they have historically, wireless may have a difficult time meeting the home requirements of consumers.

Finally, for fixed line operators, the use of WiMAX could serve as an extremely complementary lower speed tier that augments the high speed fixed capabilities currently available. The ability of an MSO to provide customers with a portable broadband service that also provides mobility can be a very compelling proposition.

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