A Comparative Analysis of Mobile WiMAX™ Deployment Alternatives in the Access Network

May 2007

Disclaimer

Performance of wireless systems is highly dependent on the operating environment, deployment choices and the end-to-end network implementation. Performance projections presented in this paper are based on simulations performed with specific multipath models, usage assumptions, and equipment parameters. In practice, actual performance may differ due to local propagation conditions, multipath, customer and applications mix, and hardware choices. The performance numbers presented should not be relied on as a substitute for equipment field trials and sound RF analysis. They are best used only as a guide to the relative performance of the different technology and deployment alternatives reviewed in this paper as opposed to absolute performance projections.

About the Author

Doug Gray is a Telecommunications Consultant and is currently under contract with the WiMAX Forum®. Gray has had extensive experience in broadband wireless access systems in engineering and management positions at Hewlett-Packard, Lucent Technologies and Ensemble Communications.

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Table of Contents

A Comparative Analysis of Mobile WiMAX™ Deployment Alternatives in the Access Network 6

1. Introduction 6

2. Metropolitan Area 6

  2.1 Demographics 8

3. Determining Coverage Requirements 8

4. Determining Capacity Requirements 9

5. Mobile WiMAX™ Base Station Deployment Alternatives 16

  5.1 Antenna Configurations 16

    5.1.1 (1x2) SIMO Base Station 17

    5.1.2 (2x2) MIMO Base Station 17

    5.1.3 Base Station with Adaptive Beamforming 19

    5.1.4 Base Station with Adaptive Beamforming and MIMO 23

  5.2 Frequency Reuse 23

  5.3 Relative Channel Capacity 25

  5.4 Frequency Band and Other Range-Related Considerations 27

  5.5 Other Deployment Factors 31

    5.5.1 Channel Bandwidth 31

    5.5.2 UL Link Budget 31

    5.5.3 Duplexing: TDD or FDD 32

6. Key Metric: Number of Base Stations 33

  6.1 Base Station Components 33

    6.1.1 Base Station Infrastructure 34

    6.1.2 WiMAX™ Base Station Equipment 35

    6.1.3 Base Station Backhaul 35

7. Comparing Mobile WiMAX™ Deployment Alternatives 36

7.1 Spectrum Comparison: 2500 MHz and 3500 MHz 36
7.2 Comparison of WiMAX™ Base Station Antenna Alternatives 37
7.3 Channel Bandwidth Comparison 39
7.4 Spectrum Allocation 41
7.5 Other Deployment Considerations 42
8. Conclusion 44
Acronyms 46
References 47

Figures

Figure 1: Typical Metropolitan Area 8
Figure 2: Commuter Traffic will Increase Daytime Busy Hour Traffic in Urban Areas . 12
Figure 3: "Available" Data Rate vs. Activity and DL Duty Cycle 15
Figure 4: SIMO/MIMO Base Station & Mobile Station Options 19
Figure 5: Beamforming Throughput Gain vs. SNIR Improvement 22
Figure 6: Frequency Reuse of 1 with 3-Sector Base Stations 24
Figure 7: Frequency Reuse of 3 with 3-Sector Base Stations 25
Figure 8: Relative Channel Capacity for Varied BS Antenna Configurations 27
Figure 9: Range Relative to Device Type and Location 29
Figure 10: Relative Range for Suburban Environment 30
Figure 11: Downlink Throughput for TDD with 10 MHz Channel BW 33
Figure 12: WiMAX Base Station in the Access Network 34
Figure 13: 2500 MHz to 3500 MHz Comparison 37
Figure 14: Base Station Count for Alternative BS Configurations 39
Figure 15: Benefit of Deploying with Wider BW Channels for Cases 1 & 2 40
Figure 16: Base Station Requirements for Varied Spectrum Allocations 42
Figure 17: Typical Market Adoption Rate 43

Figure 18: 10-Year Dense Urban Deployment for (1x2) SIMO 44

Tables

Table 1: Hypothetical Metropolitan Area for Analysis 8
Table 2: Calculating the Required Data Density 11
Table 3: Estimated Peak Busy Hour Data Rate Requirements 14
Table 4: Mid-Sized Metro Area Data Density Requirements 16
Table 5: Advanced Antenna Options 17
Table 6: Adaptive Beamforming vs. (1x2) SIMO at 2500 MHz 22
Table 7: Multipath Models for Performance Simulation 26
Table 8: Relevant Parameters for Performance Simulation. 27
Table 9: Deployment Options for Frequency Band Comparison 37
Table 10: Scenarios with Varied BS Antenna Configurations 38
Table 11: Channel Bandwidth Comparisons 40
Table 12: Scenarios for Analysis of Spectrum Availability 41

A Comparative Analysis of Mobile WiMAX™ Deployment Alternatives in the Access Network

1. Introduction

This paper is intended to provide the reader with some insights as to the tradeoffs associated with different Mobile WiMAX™ deployment alternatives in the access network. A basic overview of the performance tradeoffs for different base station antenna configurations is provided. The performance tradeoffs between frequency bands ranging from 2300 MHz to 3800 MHz are presented along with a comparison of channel bandwidths.

For all of the analyses the same hypothetical metropolitan area is used as a deployment venue. The demographics for the metropolitan area are representative of many mid-sized cities in developed countries.

An approach for estimating the data density requirements to meet specific customer performance expectations is presented. This is especially important for the delivery of broadband services in the higher population density areas which, for most deployment alternatives, will be limited by capacity requirements rather than by range.

The metric used for providing a quantified comparison of the varied deployment scenarios are the number of base stations required to meet the capacity and coverage requirements for the different demographic regions throughout the metropolitan area. Other aspects associated with a complete WiMAX™ end-to-end network deployment are not addressed in this paper. However, since the access portion of the network comprising the WiMAX base station equipment, the base station infrastructure, and the base station backhaul network is generally the dominant factor in the total end-to-end network investment, a comparison of base station requirements alone provides a good insight as to the economic trade-offs for any of the varied deployment options.

2. Metropolitan Area

Most reasonably-sized metropolitan areas are composed of a densely populated city center surrounded by areas of decreasing population density until such point as the next metropolitan area is encountered. For the purposes of this paper a hypothetical metropolitan area has been contrived with a total population of 1.75 million distributed over an area of 1,500 km^2. This represents a typical mid-sized city and surrounding metropolitan area generally encountered in the United States and many other developed countries. For analysis purposes it is convenient to divide this metropolitan area into the following demographic regions.

- **Dense Urban:** This is the city center where many of the businesses are located as well as high density multiple dwelling residential units. These areas represent a challenging propagation environment due to the multipath caused by the multi-storey buildings.
- **Urban:** Immediately surrounding the city center would be more businesses and moderate to high density multiple dwelling units. Average building heights may be lower but the propagation environment will be equally challenging.
- **Suburban:** This describes areas with lower density housing, primarily single family dwellings, and fewer businesses. Average building heights are lower and, on average, structures are more spread out, thus creating a more favorable propagation environment.
- **Rural:** Moving further from the city center, homes are further apart resulting in significantly lower population density with scattered small businesses.
- **Open Space:** Throughout the entire metropolitan area there will generally be areas of open space. This includes parks, greenbelts, lakes, golf courses, etc. Although there are few, if any, full time residents, these are still areas that require consideration for wireless deployment since at any given time these regions can be frequented by large numbers of people.

Since the characteristics for rural environments and open space are quite similar they can be combined for the purposes of discussion.

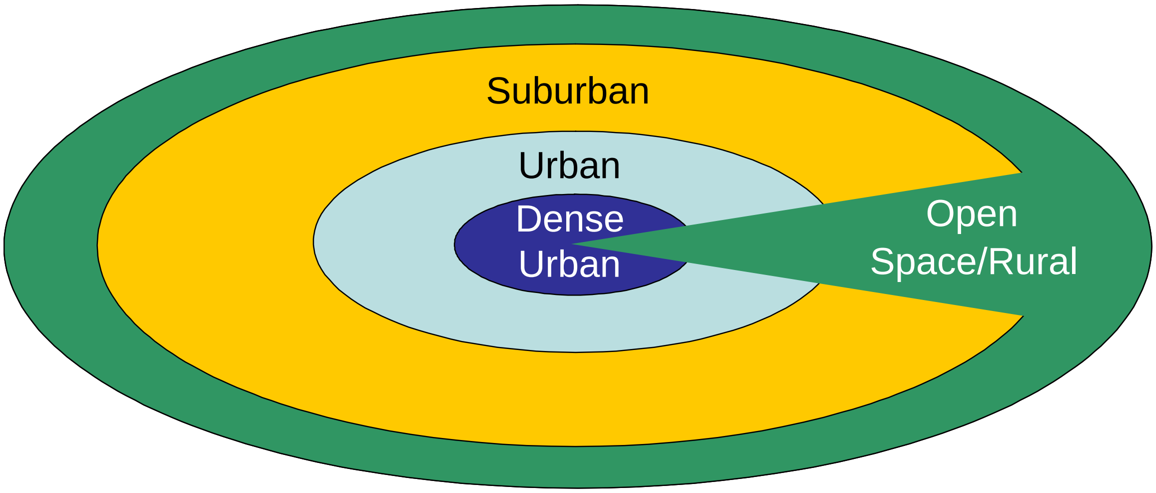


Figure 1: Typical Metropolitan Area

2.1 Demographics

Table 1 provides a summary of the relevant statistics for the hypothetical metropolitan area that will be used throughout this paper to evaluate the WiMAX deployment trade-offs.

Region	Area	Year 1 Population	Population Density
Dense Urban	100 km^2	800,000	8,000/ km^2
Urban	200 km^2	500,000	2,500/ km^2
Suburban	500 km^2	400,000	800/ km^2
Rural & Open Space	700 km^2	50,000	71/ km^2
Metro Area	**1500 km^2**	**1,750,000**	**1,166/ km^2**

Table 1: Hypothetical Metropolitan Area for Analysis

3. Determining Coverage Requirements

The key goal for an operator with any WirelessMAN deployment is to achieve ubiquitous coverage throughout the entire metropolitan area. This requires different considerations depending on the terrain, building densities, typical building heights, and other factors that can affect multipath and the link budget. Furthermore, with mobile applications it is necessary to maintain reliable coverage regardless of where users happen to be located; whether outdoors in sight of a base station, in a rapidly moving vehicle, or deep inside the interior of a building.

Traditionally, cellular deployments were based solely on achieving ubiquitous coverage with little consideration for capacity requirements. Since the only services offered were voice and the market was uncertain, this was a very reasonable approach. Moreover, the voice service offering is a low data rate application enabling traditional cellular networks to achieve wide outdoor and indoor coverage with a low data rate network (~10-15 kbps bandwidth depending on type of vocoder). As the customer base grew and more services offered, additional base stations were deployed and/or channels added to existing base stations to meet the growing capacity requirements.

With Mobile WiMAX, however, operators will want to offer a wide range of broadband services with Quality-of-Service (QoS) support. To meet customer expectations for these types of services it will be necessary to predetermine capacity requirements and deploy accordingly at the outset. Careful deployment planning in anticipation of growing customer demands will ensure a quality user experience when the network is at its busiest. This will be especially important in the higher density urban areas, as these are the deployments that are most likely to be driven by capacity requirements.

4. Determining Capacity Requirements

Arriving at an accurate estimate of capacity requirements for new broadband services is not a simple exercise. One must anticipate how users will make use of the new services being offered and how often users will be actively engaged with the network. In this section we look at one approach that can be followed.

Data density, expressed as Mbps per km^2, is a convenient metric for describing capacity requirements. Determining the required data density for a specific demographic region is a multi-step process. These steps are summarized in Table 2 along with the assumptions used for the deployment analyses that follow in later sections of this paper.

Population density and population growth rates are easily obtained for any metropolitan area by referring to readily available census data. When considering mobile services the addressable market can be assumed to be any individual within a certain age group. The specific age group targeted may differ from operator to operator based on planned services and applications but for the sake of this exercise it is assumed to be anyone between 15 and 75 years old. In a typical US city this age group ranges from 70 to 75% of the total population.

The expected market penetration, or take-up rate, at maturity is dependent on a number of factors including the competitive situation and the services offered that distinguish one service provider from another. The service provider's penetration may also vary within the metropolitan area since urban and dense urban residents will often have other broadband access alternatives from which to choose as compared to residents in suburban and rural areas. For the following analyses the mature market penetration for a single operator is assumed to range from 10 to 12%, depending on the demographic region, by the 10th year of operation. This results in a 10.4% average penetration for the total metropolitan area.

Wireless service providers will generally offer plans with varied service level agreements (SLAs) to appeal to a wide range of anticipated customer types within the targeted market segment. For capacity planning purposes we have elected to group the varied customer types into the following three categories.

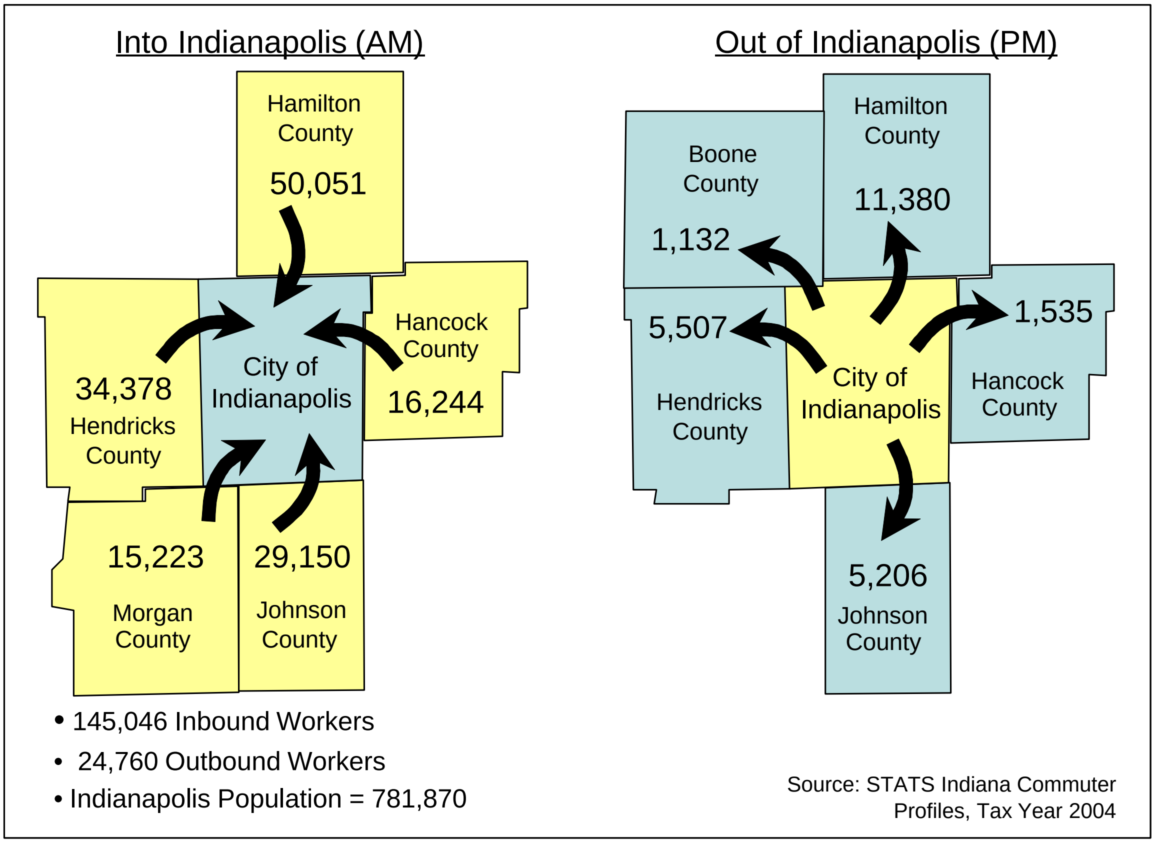
- **Professional User:** This describes the customer that requires mobile broadband access for business purposes and would also use the service for personal use. E-mail, video conferencing, file downloads, etc. would be key applications for these types of users. Although these users will be stationary much of the time, broadband nomadic and mobile access is required to maintain communications while commuting, meeting with clients, inspecting remote job sites, etc.
- **High-End Consumer:** This is a high usage customer whose primary application is for personal rather than business use. Web browsing, gaming, music downloads, etc. may be dominant applications for these types of users.
- **Casual User:** These are consumers who desire periodic access for web browsing and other data oriented services, but may only be actively connected to the network a few hours per day.

Step	Description	Comments and Assumptions for Analysis
1	Population Density	1.75 Million people over 1,500 km^2 (See Table 1)
2	Population Growth Rate	1 to 2% varies with region

Step	Description	Comments and Assumptions for Analysis
3	Addressable Market	Ages 15 to 75, typically 70 to 75% of population
4	Mature Market Penetration	10-12% in year 10 (Averages to 10.4% over the metro area)
5	Mature Customer Mix	• 50% Professional User • 35% High-end Consumer • 15% Casual Consumer
6	Effect of Mobility and Roaming	Must estimate customer distribution during high traffic periods (Peak Busy Hour)
7	Peak Busy Hour (PBH) Activity	Varies with customer type
8	Desired Performance During PBH	Determined by Applications, Service Level Agreements, QoS, etc.
9	Required Data Density	A simple calculation

Table 2: Calculating the Required Data Density

The impact of mobility (and roaming) throughout the metropolitan area is another important factor that must be taken into account in determining data density requirements. This is most important in the dense urban and urban areas where most of the businesses are located. These areas will typically experience a significant net influx of commuter traffic from the suburban and rural areas in the morning hours creating an additional demand on the network during the daytime hours. Commuting data is often compiled for major cities for the purposes of municipal transport and highway planning purposes and can be used for the data capacity requirements analysis. As an example, commuter data for the U.S. city of Indianapolis, Indiana is shown in Figure 2. The seven counties comprising the Indianapolis metropolitan area have a population of about 1.6 million people with about half living within the Indianapolis city limits. The daily commuter traffic flow increases the city daytime population by more than 15%, a number typical of many metropolitan areas.



Source: STATS Indiana Commuter Profiles, Tax Year 2004

Figure 2: Commuter Traffic will Increase Daytime Busy Hour Traffic in Urban Areas

It is generally safe to assume that commuting traffic will have the biggest impact on the changing distribution of active customers within the metropolitan area. The impact of other mobile customers and customers "roaming" from other networks can be expected to net to zero since it is reasonable to expect as many will be exiting a specific region as entering at any given time.

The peak busy hour (PBH) activity level is probably the most challenging for an operator to predict with any degree of accuracy. It depends on applications, customer mix, etc. The process is further complicated by the fact that there will not be any prior history for many of the new services to be offered on which the operator can base traffic estimates. Where there does seem to be consensus however, is that traffic will be increasingly more data-centric. With data-centric traffic, downlink traffic is expected to dominate. For that reason we will focus exclusively on downlink projections for capacity planning purposes.

In addition to estimating the number of customers actively on the network during the busiest periods it is also necessary to estimate the portion of time devoted to downlink (DL) activity versus uplink (UL) activity. It should be noted that there will also be idle periods. These are intervals in which the active subscriber is either reviewing what has just been downloaded or alternatively, considering what information to send. For traditional voice services the DL to UL traffic split will be close to 50/50 with very little idle time. With data-dominated web traffic however, the traffic patterns will be bursty in nature with each user experiencing idle periods interspersed with large blocks of data transfers while "actively" engaged with the network. The "Desired Performance During PBH" is quite arbitrary and depends on what the type of experience the operator wishes to provide for the end-user during the times when the network is busiest. Once this "minimal" performance level is determined, calculating the required data density is a straightforward process.

Table 3 summarizes the assumptions made for customer mix, PBH Activity Level, DL Duty Cycle, and the "Minimal per End-User Rate[1] during PBH"[2]. The 75 kilobyte/sec minimal PBH data rate for a professional user would enable a typical 30 page E-mail attachment[3] to be downloaded in about 4 seconds during PBH or "worse case" traffic conditions. It is important to emphasize that the minimal rate for the peak busy hour is not truly a guarantee unless it is programmed in conjunction with a specific service level agreement (SLA), it only holds if the combination of activity level and DL duty cycle are as shown in Table 3. It should also be noted that this is intended to be worse case, i.e. during periods of peak activity on the network. The chart in Figure 3 provides a view of the "available" DL rate[4] based on other activity and downlink duty cycle levels than those assumed for the peak busy hour. For example, if the duty cycle were to drop from 25% to 15% with an activity level of 10%, a subscriber would have access to 1.3 megabits per second. This would enable a download of a typical 30-page E-mail attachment in less than a second.

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[1] Not to be confused with "Committed Information Rate" or CIR

[2] The values in table 3 are not based on any statistical evidence or surveys but felt to be reasonable for illustrative purposes.

[3] A 30 page document with a number of graphs and figures would typically be between 250 and 350 kilobytes.

[4] Not to be confused with "Peak" DL data rate. Peak DL rates are a function of user location with respect to the base station and can be more than 30 Mbps for a 10 MHz channel with a (1x2) SIMO base station deployment.

If guaranteed minimal rates were built into the customer SLA as a Committed Information Rates (CIR) for the high usage customers, i.e. “Professional” and “High-End Consumers”. “Casual” customers would experience a decline in service, i.e. Best Effort (BE), if the assumed PBH activity and duty cycle levels were exceeded. These factors are typically built into operator business models using prioritized class of service designations to distinguish between the various types of customer.

Customer Type	Mature Customer Mix	Peak Busy Hour Activity: 1 of “N” active	DL Duty Cycle	Minimal per End-User DL Rate During PBH
Professional	50%	N = 5	25%	75 kilobytes/sec (600 kbps)
High-End Consumer	35%	N = 7	25%	60 kilobytes/sec (480 kbps)
Casual Consumer	15%	N = 20	25%	30 kilobytes/sec (240 kbps)
Overall Customer Average Over Metro Area		N = 7.9	25%	63 kilobytes/sec (504 kbps)

Table 3: Estimated Peak Busy Hour Data Rate Requirements

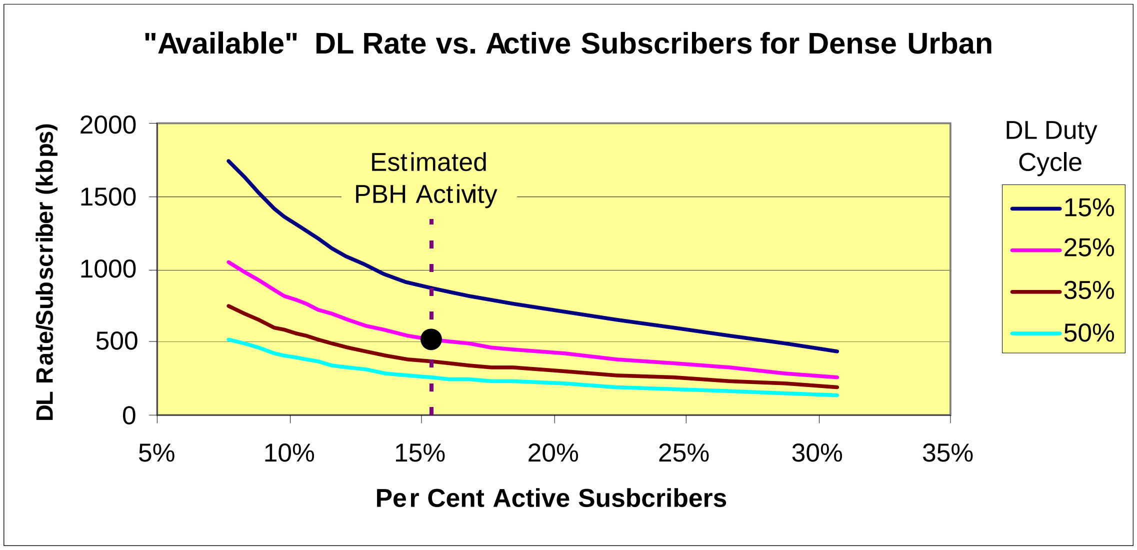

Figure 3: "Available" Data Rate vs. Activity and DL Duty Cycle

The PBH assumptions in Table 3 combined with an estimate for customer mobility during PBH and an estimated 2% per year growth in activity levels, results in downlink data density requirements for the tenth year of operation as summarized in Table 4. Although data density requirements for the suburban, rural, and open space areas will undoubtedly be met by simply deploying for ubiquitous coverage, the dense urban and possibly, urban areas will require a phased deployment plan that adds capacity over time to match the growing customer base and increasing activity levels.

Metro Region	Number of Customers	Adjustments to Account for Mobility During PBH	Downlink Data Density Requirements in 10th Year
Dense Urban	66,000	+15%	20 Mbps/km^2 over 100 km^2 area
Urban	42,000	+15%	5.8 Mbps/ km^2 over 200 km^2 area
Suburban	37,000	0%	1.6 Mbps/ km^2 over 500 km^2

Metro Region	Number of Customers	Adjustments to Account for Mobility During PBH	Downlink Data Density Requirements in 10th Year
Rural & Open Space	5,000	0%	0.12 Mbps/ km^2 over 700 km^2 area

Table 4: Mid-Sized Metro Area Data Density Requirements

Although the data density requirements arrived in this section are reasonable for the demographics and other assumptions made for the hypothetical mid-sized metropolitan area assumed for this paper, they should not be arbitrarily applied to other metropolitan areas. In urban centers of many larger cities, such as New York City, Chicago, London, etc. much higher user densities can be encountered that will result in numbers larger than those in Table 4. As an example, the urban center of New York City has a population density that is almost 2.5 times what was used to generate the numbers in Table 4. Even lowering the market penetration to reflect the more highly competitive environment that would exist in a larger city, data density requirements in the range of 30-40 Mbps/ km^2 would not be unrealistic for cities of that type.

5. Mobile WiMAX™ Base Station Deployment Alternatives

Mobile WiMAX base station equipment will be available from many different vendors and, although all will be WiMAX compliant and meet performance and interoperability requirements, a great many different configurations will be available from which service providers can choose. The availability and timing of optional features also adds to the equipment variability. Additionally, there are different frequency bands that can be considered and varied amounts of spectrum availability within these bands. The spectrum choices will, in many cases, affect the frequency reuse factor and the channel bandwidths that can be employed in the access network. This section provides an overview of some of the performance and operational tradeoffs associated with these varied WiMAX base station deployment alternatives.

5.1 Antenna Configurations

In addition to multiple input, multiple output antenna configurations, (SIMO and MIMO), Mobile WiMAX technology supports a full range of smart antenna technologies [1] to enhance both coverage and channel throughput. The advanced antenna features supported in the Release-1 profiles include Adaptive Beamforming, Space Time Coding (STC) and Spatial Multiplexing (SM). A summary of the WiMAX-supported advanced antenna options are provided in Table 5.

Although many of these Base Station advanced antenna features are optional, the Mobile Station is required to support all of the base station options that might be deployed to ensure inter-vendor interoperability. For the discussions that follow, the Mobile Station will be assumed, in all cases, to be configured with one transmit antenna and two receive antennas, (1x2) SIMO.

Link	Space Time Coding (STC)	Spatial Multiplexing (SM)	Adaptive Beamforming
DL	Nt=2, Nr≥1[5] Matrix A	Nt=2, Nr≥2 Matrix B, Vertical Encoding	Nt≥2, Nr≥1
UL	n/a	Nt=1, Nr≥2 Two-User Collaborative	Nt ≥1, Nr≥2

Table 5: Advanced Antenna Options

5.1.1 (1x2) SIMO Base Station

A typical WiMAX baseline base station antenna configuration will be (1x2) SIMO. Even with only single transmit antenna at each end of the link this configuration takes advantage of multipath to improve both the downlink and uplink received signal strength as compared to a single input single output (SISO) configuration. With dual receive antennas at both the base station and the mobile station the received signal is enhanced through the use of diversity and the use of maximal ratio combining techniques.

5.1.2 (2x2) MIMO Base Station

Adding a second base station antenna provides a (2x2) MIMO configuration. This offers the possibility for two additional modes for improved downstream performance. With Space Time Coding (STC) also known as MIMO Matrix A, identical downlink data streams are sent from each transmit antenna providing space and time diversity. In an environment with rapid fading and multipath, STC enhances the signal to noise ratio

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[5] Nt = number of transmit antennas; Nr = number of receive antennas

(SNR) of the received signal at the mobile station to enable support of higher modulation efficiency bursts and thus enhance DL capacity as well as DL range.

With Spatial Multiplexing (SM), also known as MIMO Matrix B, each of the base station transmit antennas sends a different downlink data stream. This technique uses multipath to distinguish between the different data streams and theoretically has the potential to double the DL capacity under favorable channel conditions. To take best advantage of STC and SM Mobile WiMAX also supports Adaptive MIMO Switching. This enables dynamic switching between Matrix A and Matrix B depending on existing channel conditions at any given time.

With (2x2) MIMO the UL channel capacity is also increased by enabling two mobile users to transmit collaboratively in the same time slot, a technique known as uplink collaborative spatial multiplexing.

MIMO is particularly effective in urban and suburban area deployments where there is considerable multipath. Dual polarization diversity can also be supported with (2x2) MIMO to provide two orthogonal signals for improved performance when there is not sufficient multipath. MIMO is also equally effective in both stationary and high mobility environments.

The addition of a second antenna and associated high-power power amplifier chain adds to the WiMAX base station complexity but nevertheless, can be considered a cost-effective upgrade over (1x2) SIMO in capacity-limited scenarios since the downlink channel capacity is typically enhanced by as much as 55% or more [2].

Figure 4 provides a more visual overview of the SIMO and MIMO base station and mobile station antenna options that will be analyzed for the purposes of this paper.

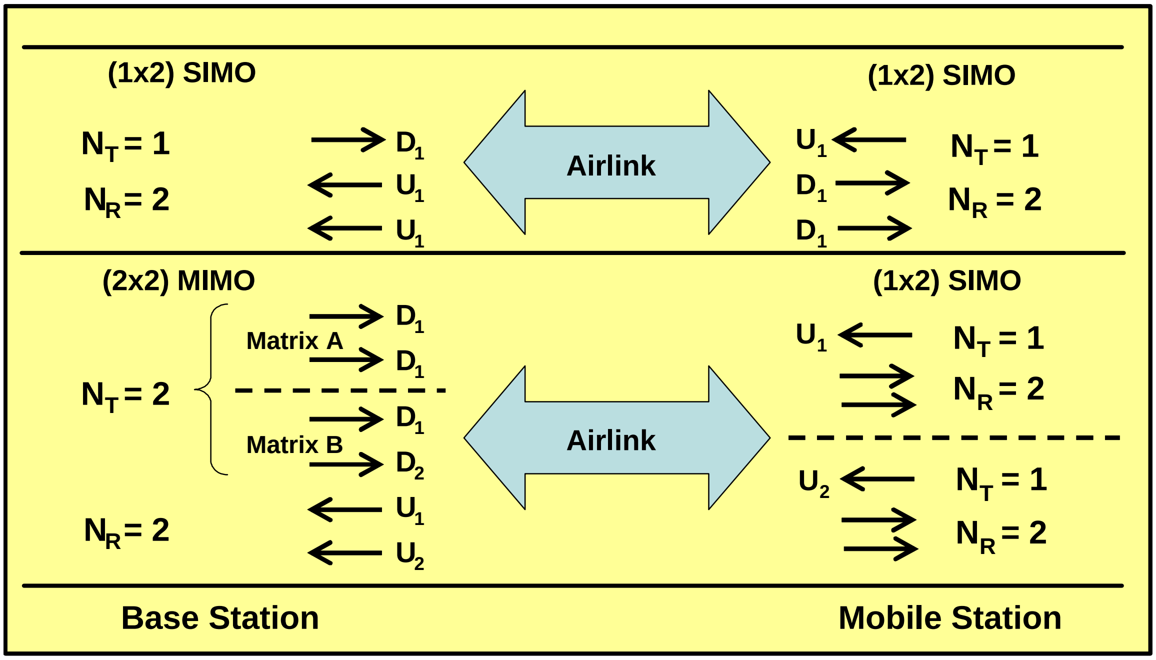

Figure 4: SIMO/MIMO Base Station & Mobile Station Options

5.1.3 Base Station with Adaptive Beamforming

Beamforming is another advanced antenna option supported by WiMAX technology. This antenna technology also commonly referred to as Smart or Adaptive antenna systems can be implemented in a variety of ways [3]. The simplest approach, known as “Switched Beam”, provides the ability to switch between several narrow beam antennas or between different beams in an antenna array. A second approach, known as “Dynamically Phased Array”, employs a Direction of Arrival (DoA) algorithm from the user to dynamically direct the beam. Both of these approaches enhance the received signal strength and therefore can provide range and channel capacity improvement but are also subject to angle spread due to scattering and multipath, especially prevalent in urban and many suburban environments [4]. A third approach to beamforming is known as “Adaptive Array” or “Adaptive Beamforming”. With this approach the beamforming parameters are adaptively determined based on both channel and interference conditions. This can also enable the array to not only maximize signal strength to the desired user but also provides a mechanism to null out interference. With Adaptive Arrays or Adaptive Beamforming, other algorithms can be employed to constructively enhance both signal to noise and signal to interference ratios in all propagation environments. Although high mobility makes it more challenging to get accurate channel estimation due to the rapidly changing channel conditions, experimental results have reported an average SIR increase up to 10 dB in an urban mobile environment [5].

The electronically steerable antenna patterns are implemented by providing the appropriate amplitude and phase to each feed of an n-element[6] base station antenna array. Digital signal processing techniques are used to analyze the link performance in real-time and adjust the weighting factors for both amplitude and phase to each of the antenna feeds to maintain optimal performance. Signals received in the UL are used to determine the link characteristics and since Mobile WiMAX uses TDD, channel reciprocity is assured. Since the antenna elements in the array are typically spaced at a half wavelength or less, the aperture size is limited, nevertheless, element gains of 14 to 16 dBi are realizable in the 2500 MHz band. It should also be noted however, that close spacing antenna to antenna coupling can also cause some degradation in the achievable element gain.

In range-limited situations, beamforming provides greater range capability due to the improved link budget in both the DL and UL direction. To what extent this added DL range capability can be utilized however, depends on the Media Access Protocol (MAP) range. To support multiple simultaneous users within the coverage area a (MAP) message must be transmitted to all users in the sector. Since the MAP message is broadcast, the DL range benefit provided by the added link budget with beamforming may not be fully realized without using multiple repetitions to assure reliable reception of the message. In addition, with mobile handsets the UL link budget is most often the limiting factor in determining the range so it too must be taken into account. For the analyses that follow the range will be determined by the MAP or the UL range whichever is lower.

A comparison of Adaptive Beamforming with (1x2) SIMO is provided in Table 6. An implementation factor of -1 dB is assumed to account for mutual antenna coupling for an 8-element array[7]. At the time of this writing simulation data was not available for Beamforming based on the same set of assumptions that were used for SIMO and MIMO in earlier WiMAX Forum® white papers. It is possible however, to calculate the beamforming benefit based on the expected SNIR improvement. Since the increase in SNIR will enable bursts with higher efficiency modulation to a greater number of users

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[6] Beamforming arrays for mobile WiMAX are expected to range from 2 to 8 elements.

[7] Although it is possible, it is not likely that arrays of more than eight elements will be considered in these frequency bands due to the added tower mounting complexities necessary to deal with the increased size and weight.

throughout the base station coverage area, the net channel throughput gain can be estimated. Figure 5 shows the net throughput gain versus the SNIR improvement assuming a uniform distribution of users throughout the base station coverage area. This is a reasonable assumption, particularly during periods of high activity. This approach provides a throughput gain, for an 8 dB SNIR improvement, of approximately 67%.

It is important to emphasize that this throughput comparison is based on the assumed operating parameters listed in Table 6 which result in a SNIR difference of 8 dB between the two base station configurations. Both the (1x2) SIMO and Beamforming parameters can vary from vendor to vendor. As already mentioned the number of elements in a beamforming array may vary from 2 to 8. Vendors may also choose different antenna element gains and/or Tx Power levels for either the SIMO or the beamforming solution. Additionally, local regulations may impose different EIRP constraints[8] that may indirectly favor one technology over another. The graph in Figure 5 provides the reader a view of the beamforming throughput gain for different values of SNIR improvement as compared to a (1x2) SIMO configuration.

Parameter	Value
(1x2) SIMO	
Antenna Gain	15 dBi
Tx Power at Antenna	40 dBm (10 watts)
Base Station EIRP	55 dBm
Adaptive Beamforming	
Beamforming Elements	8
Antenna Gain per Element	15 dBi
Tx Power per Element	+31 dBm (1.25 Watt)
Implementation	-1 dB

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[8] In the US, 47CFR Part 27.50 specifies a peak EIRP of 2000 watts (63 dBm) in all but the middle part of the 2500-2690 MHz band. In the 2620-2686 MHz portion of the band higher EIRP limits are allowed for channel BWs greater than 6 MHz and/or sectored antennas. In many other countries regulators adopt recommendations of the ECC (Electronics Communications Committee). For the 3400-3800 MHz band, ECC Decision of 30March 2007 recommends an EIRP limit of 25 dBm/MHz. This results in a 65 dBm EIRP limit for a 10 MHz channel and 62 dBm for a 5 MHz channel.

Parameter	Value
Effective Array Gain	23 dBi
Base Station EIRP	63 dBm
Adaptive Beamforming Relative to (1x2) SIMO	
Net DL SNIR Improvement[9]	~8 dB
DL Channel Capacity Gain	~67%
Range Improvement	~22%[10]

Table 6: Adaptive Beamforming vs. (1x2) SIMO at 2500 MHz

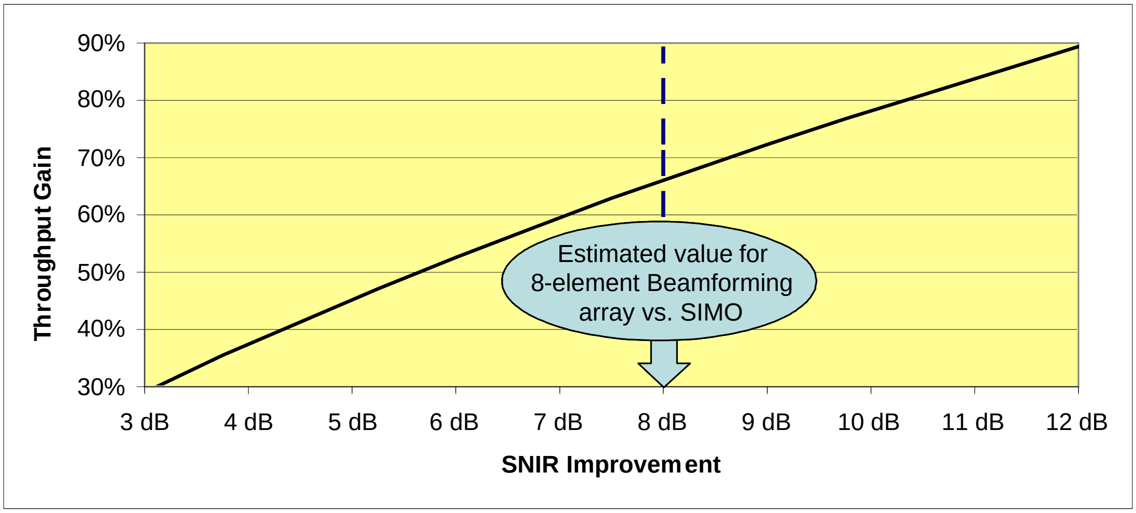

Figure 5: Beamforming Throughput Gain vs. SNIR Improvement

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[9] With simpler beam steering approaches, as opposed to Adaptive Beamforming, the SNIR improvement would be less due to beam spreading in high multipath environments typically encountered in urban and many suburban environments.

[10] The range improvement in this case is limited by the MAP range.

5.1.4 Base Station with Adaptive Beamforming and MIMO

With an n-element adaptive beamforming array in place various partitioning techniques can be considered to further enhance performance. Implementing MIMO Matrix A with beamforming can increase the channel robustness in environments with rapid fading and the use of MIMO Matrix B enables multiple data streams for added throughput performance. This added capability can enhance the channel throughput by an additional 10 to 15%.

WiMAX solutions with beamforming will generally be architected quite differently from SIMO and MIMO solutions. A typical SIMO or MIMO configuration will have power amplifiers mounted at the base of the tower to facilitate cooling and maintenance. The amplifiers in this case would have to be sized to compensate for cable losses, which can range from 2 to 4 dB depending on tower height and frequency. Beamforming solutions require good phase and amplitude control between transmitting elements and will often be architected with their power amplifiers integrated with the antenna elements in a tower-mounted array. The larger size and weight of these structures will also require more robust mounting. There is additional signal processing requirements for beamforming solutions with Adaptive Beamforming being the most computational intensive.

5.2 Frequency Reuse

Traditional reuse patterns for conventional cellular deployments used cell frequency reuse factors as high as seven (7) to mitigate intercellular co-channel interference (CCI). These deployments assured a minimal spatial separation of 5:1 between the interfering signal and the desired signal but required seven times as much spectrum. With technologies such as CDMA, introduced with 3G, and OFDMA, introduced with WiMAX [6], more aggressive reuse schemes can be employed to improve overall spectrum efficiency.

Two common frequency reuse configurations for a multi-cellular deployment with 3-sector base stations are a sector reuse of 3, i.e. (c, 3, 3)[11] and a sector reuse of 1, (c, 1, 3) also referred to as universal frequency reuse. With a frequency reuse of 1 the same channel is deployed in each of the three (3) base station sectors[12] as shown in Figure 6.

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[11] Nomenclature for describing the frequency reuse pattern in this paper is (c, n, s); where c is the number of base station sites in a cluster, n is the number of unique frequency channels required, and s is the number of sectors per base station site.

[12] Another deployment alternative with a single channel is to “share” the channel over all 3 sectors. This approach effectively splits the channel into 3 subchannels and assigns each subchannel to a specific sector making it roughly equivalent to a reuse of 3 with 1/3 the channel bandwidth.

This approach has the advantage of using the least amount of spectrum and in many cases, may represent the only deployment reuse alternative due to limited spectrum availability. With Reuse 1, a pseudorandom subcarrier permutation scheme along with channel segmentation is employed to mitigate CCI at the sector boundaries and at the cell-edge. As a result some downlink channel capacity is sacrificed since some subcarriers will not be fully utilized throughout the entire cell. Nevertheless, the downlink spectral efficiency for WiMAX with universal reuse is still quite high and generally preferred over reuse 3.

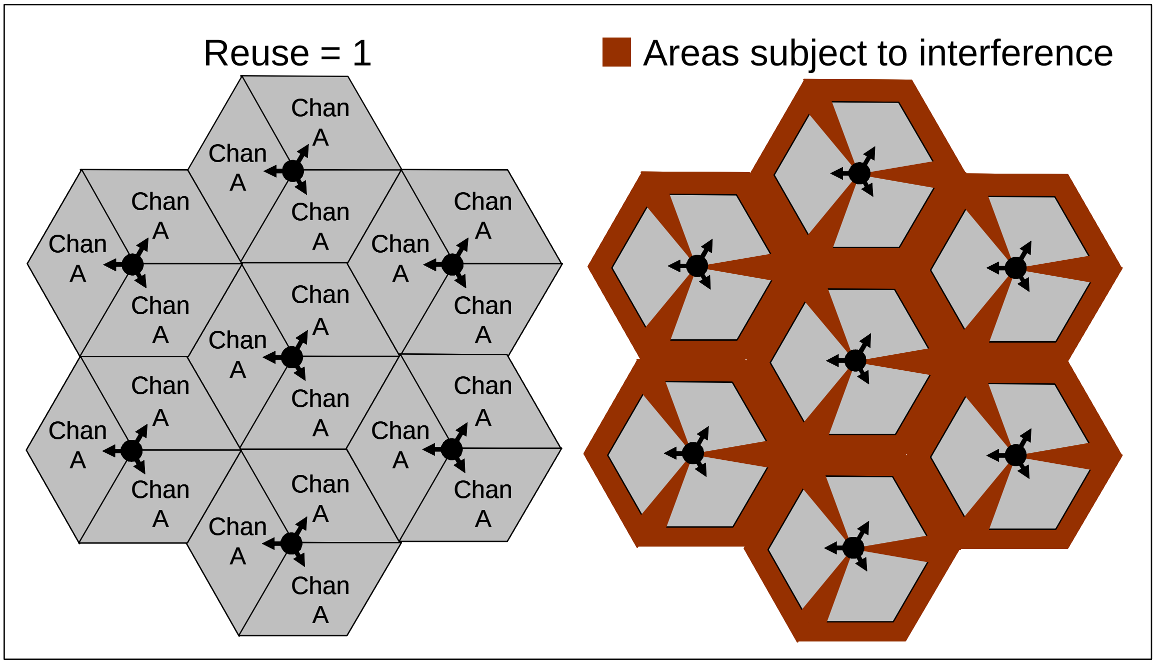

Figure 6: Frequency Reuse of 1 with 3-Sector Base Stations

With reuse 3, each sector is assigned a unique channel as shown in Figure 7. Thus, assuming the same channel bandwidth, a 3-sector base station deployment requires three times as much spectrum as reuse 1. Reuse 3 eliminates CCI interference at the sector boundaries and significantly decreases CCI between neighboring cells due to the increased spatial separation for channels operating at the same frequency provided that the cell sector boundaries are properly aligned. Adjacent Channel Interference (ACI) at the sector boundaries is controlled by the orthogonal nature of the subcarriers inherent with OFDMA. A reuse of 3 enables greater use of all of the subcarriers thus increasing the spectral efficiency of each channel but requires three times as much spectrum.

Although the improvements in channel spectral efficiency with reuse 3 can be significant, the overall spectral efficiency will always be lower when the added spectrum requirements are taken into account. Moreover, in some markets there may also be an added capital investment associated with the acquisition of the additional spectrum. Since the cost-effectiveness and overall spectral efficiency will almost always make reuse 1 the preferred deployment approach, reuse 1 will be assumed for all of the WiMAX deployment alternatives analyzed in the following sections.

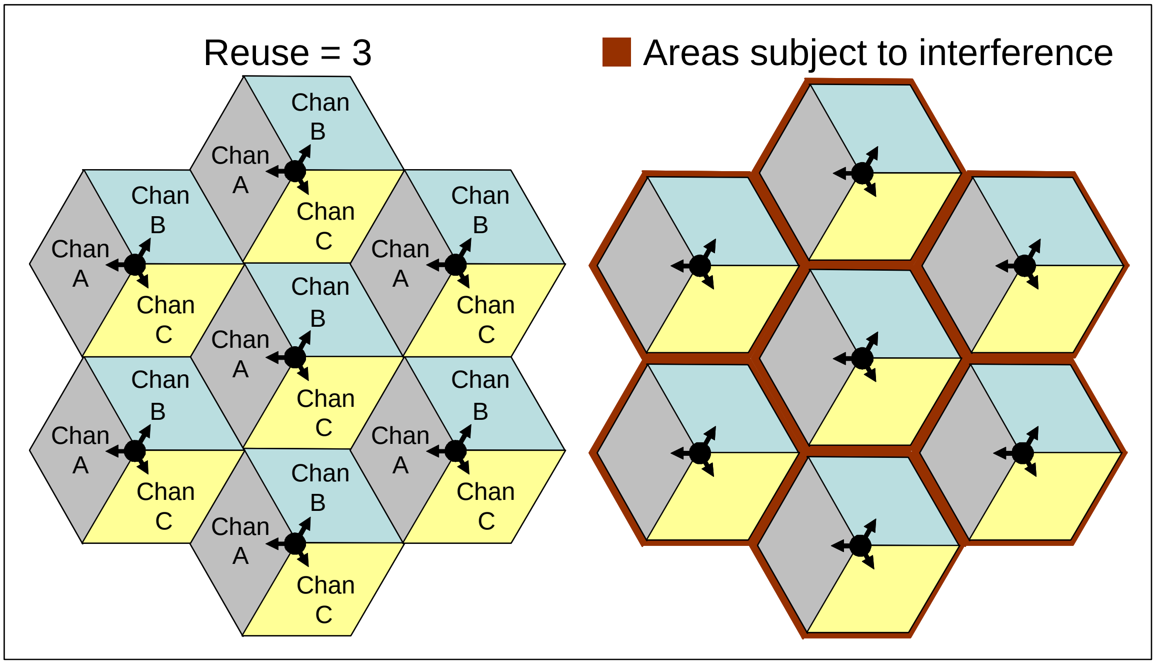

Figure 7: Frequency Reuse of 3 with 3-Sector Base Stations

5.3 Relative Channel Capacity

Figure 8 provides a summary of the predicted relative downlink channel capacity or relative channel spectral efficiency for all of the base station antenna configurations discussed in the previous sections. The predictions for (1x2) SIMO and (2x2) MIMO are based on a simulation methodology developed by 3GPP2 [1,7,8]. The traffic is assumed to be full buffer FTP traffic and proportional fair scheduling is assumed. The simulations assume a deployment of nineteen 3-sector base stations with a spacing of 2.8 km and a heterogeneous mix of mobile users as summarized in Table 7. Other relevant assumptions for the simulations are summarized in Table 8.

ITU Channel Multipath Model	Paths	Speed	Fading	Per Cent of Users
ITU Pedestrian A	1	3 km/hr	Jakes	30%
ITU Pedestrian B	3	10 km/hr	Jakes	30%
ITU Vehicular A	2	30 km/hr	Jakes	20%
ITU Pedestrian A	1	120 km/hr	Jakes	10%
Single Path	1	0, $f_{Doppler}$=1.5 Hz	Jakes	10%

Table 7: Multipath Models for Performance Simulation

Parameters	Value
Frequency Band	2500 MHz
Duplex	TDD
Channel Bandwidth	10 MHz
BS to BS Spacing	2.8 kilometers
BS Tx Maximum Power per Element (SIMO and MIMO)	+40 dBm (10 Watts per Element)
Mobile Station Maximum Tx Power	+23 dBm (200 Milliwatts)
Base Station Antenna Gain per Element	15 dBi
Mobile Station Antenna Gain	-1 dBi
Mobile Station Antenna	Tx: 1; Rx: 2
Base Station Antenna Height	32 meters
Mobile Station Antenna Height	1.5 meters
Propagation Model	COST 231 Suburban
Log-Normal Shadowing	8 dB
Base Station Shadowing Correlation	0.5
Penetration Loss	10 dB
Interference Margin	2.0 dB

Parameters	Value
Overhead Symbols	7 DL, 3 UL, 1 TTG (11 total out of 48)
DL/UL Symbols	28/9 (~3/1) and 19/18 (~1/1)
Frame Duration	5 milliseconds
Permutation	PUSC
Traffic	Full Buffer FTP

Table 8: Relevant Parameters for Performance Simulation.

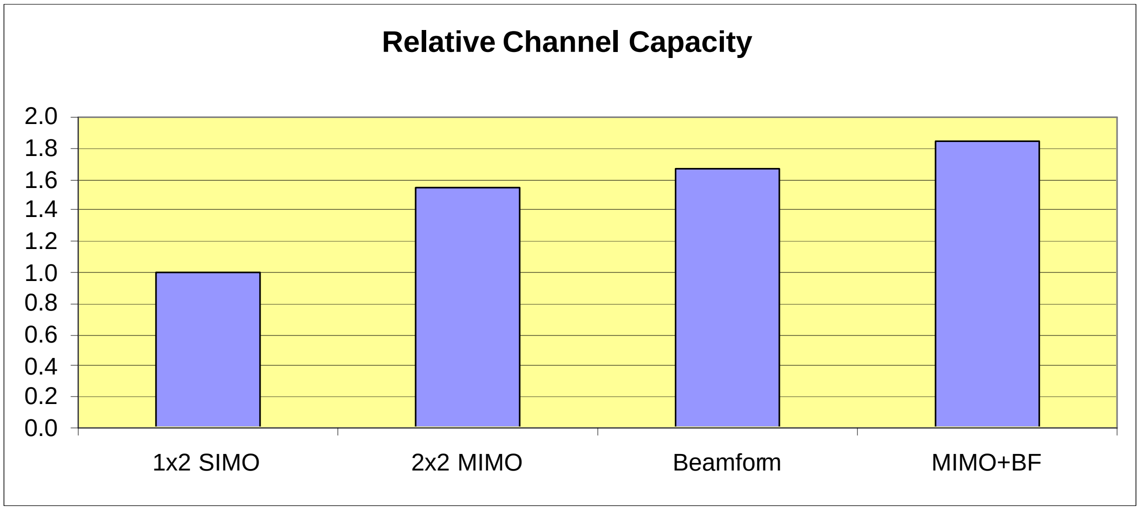

Figure 8: Relative Channel Capacity for Varied BS Antenna Configurations

5.4 Frequency Band and Other Range-Related Considerations

The WiMAX Forum has plans to support several profiles for Mobile WiMAX. Release-1 profiles include various channel bandwidths from 5 MHz to 10 MHz in frequency bands ranging from 2300 MHz to 2690 MHz and 3300 MHz to 3800 MHz [1, 3][13]. For

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[13] Profiles in other frequency bands will be considered by the WiMAX Forum to align with future spectrum allocations and market demand.

discussion purposes in this paper the 2300 to 2690 MHz band will be referred to as the 2500 MHz band and the 3300 to 3800 MHz band will be referred to as the 3500 MHz band.

In discussing the relative performance between frequency bands, range difference is generally the parameter of greatest interest and this, of course, is a function of the link budget. Before looking at the spectrum differences however, it is important to understand the link budget characteristics that are common to any of the frequency bands in the 2300 to 3800 MHz range. For mobile services the range will usually be limited by the uplink not the downlink. Since subscriber station devices have to be small and lightweight to be truly mobile, battery and antenna size are limited. This limits the transmit power and the antenna gain. Devices for portable and nomadic use, such as laptops will often have higher antenna gains and, since in many cases will have access to AC power, will also be capable of higher transmit power. Subscriber devices for fixed applications will have even greater antenna gains.

The location of mobile subscribers also plays a key role in determining the link budget. Active subscribers may be in an outdoor location, a moving vehicle, or deep inside a building requiring that signals have to penetrate multiple walls. The subscriber station antenna height relative to the base station antenna height can also impact the link budget by several dB. Subscriber location alone can result in a 20 to 25 dB variation in the link budget. Figure 9 provides a view of the relative ranges for different customer terminals in varied locations that would be applicable to either the 2500 MHz or 3500 MHz frequency band. A chart like this is useful in providing potential operators insights as to the trade-offs between different business plans. An operator who elects to address only fixed applications can get by with far fewer base stations than one who chooses to address mobile services. In the latter case, an operator with a deployment sufficient to serve mobile customers is also in a position to offer fixed services as well. In the deployment scenarios analyzed in the following sections the range estimates will always assume a mobile usage model.

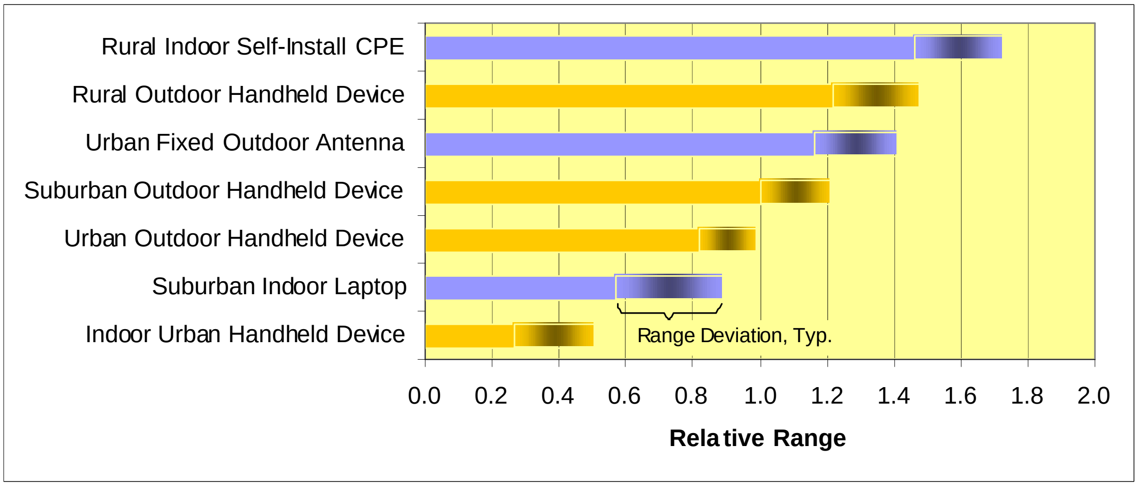

Figure 9: Range Relative to Device Type and Location

In comparing 2500 MHz performance with 3500 MHz, there are some important frequency-dependent differences that must be considered. For example:

- **Building/Vehicle Penetration Loss:** For mobile applications in-building and in-vehicle services are required, therefore penetration loss must be taken into account. Expectations are that penetration losses will be higher at the higher frequencies. This is a valid assumption when considering frequencies ranging from UHF to mm waves however, one study has show that the penetration losses vary very little in the range from 1 to 6 GHz [9], noting a difference of only 3.5 dB. Therefore, for the purposes of comparing 3500 MHz with 2500 MHz it is reasonable to assume no difference in the penetration loss.
- **Propagation Model:** The Modified Hata COST 231 model is generally accepted as a suitable propagation model for mobile applications in the 1900 MHz band and is assumed, in this case, to be acceptable for 2500 and 3500 MHz. Although the COST 231 model has not been empirically verified for mobile applications in the 3500 MHz band it was felt for the purposes of this paper to be a reasonable choice to assure consistency between 2500 and 3500 MHz predictions[14].

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[14] The COST 231 model predicts a higher path loss at both 2500 MHz and 3500 MHz than either the ITU M.2225 Vehicular Model or the Stanford Pedestrian Model. It predicts a lower path loss than the M.2225 Pedestrian Model.

- **Antenna Gains:** For a fixed antenna size and type, the antenna gain is inversely proportional to the square of the operating wavelength. It is easier therefore, to achieve higher antenna gains at the higher frequencies with low profile antennas. This gain advantage is partially offset by higher cable and antenna interface losses but nevertheless nets an improved antenna gain relative to the lower bands. To compare 3500 MHz with 2500 MHz the same aperture is assumed for both bands with an assumed net increase in antenna gain of 2 dB.
- **Other Link Margins:** For the following analysis the other link parameters including fade margins and interference margins are assumed to be the same for each of the two frequency bands.
- **Other Link Budget-Related Equipment Parameters:** Although, in practice, other equipment related parameters such as transmit power, noise figure, etc. may vary from band to band they are assumed to be the same 2500 MHz and 3500 MHz for the purposes of the comparisons that follow.

Based on the above assumptions the chart in Figure 10 shows the relative range predictions for 3500 MHz and 2500 MHz referenced to the range at 2500 MHz in a suburban environment assuming a net 2 dB greater system gain for 3500 MHz due to the increased base station antenna gain.

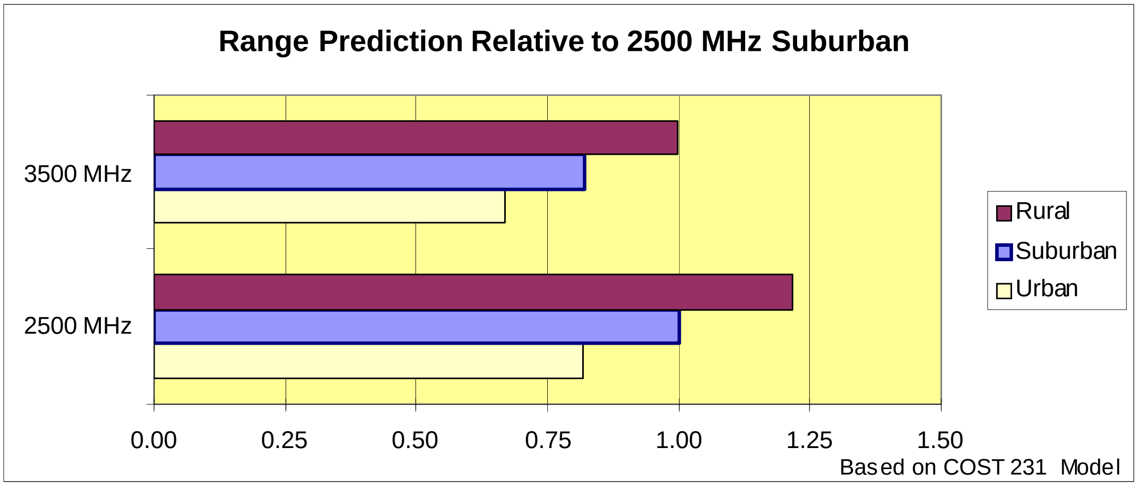

Figure 10: Relative Range for Suburban Environment

5.5 Other Deployment Factors

The selection of channel bandwidth and duplexing method can also have an economic impact on the varied WiMAX deployment alternatives. In addition the desired "worse case" UL rate will affect the UL link budget and therefore, impact the range and coverage of the base station.

5.5.1 Channel Bandwidth

The approved WiMAX Forum® profiles for Mobile WiMAX currently support channel bandwidths of 5, 7, 8.75, and 10 MHz. The IEEE 802.16e-2005 standard, on which Mobile WiMAX technology is based, supports channel bandwidths from 1.25 to 20 MHz, leaving open the possibility for additional WiMAX channel profiles in the future. In some cases local regulatory requirements will dictate the choice of channel bandwidth by limiting the amount of spectrum available to individual licensees or by specifying a specific channel plan. From an equipment-complexity and cost point of view there will be little or no difference in selecting a 5 MHz versus a 10 MHz channel bandwidth. Since the wider channel bandwidth will have greater capacity it will, in most cases, be more cost-effective to deploy the largest channel bandwidth supportable by local regulatory requirements, the desired reuse factor, and desire to conserve spectrum for future overlays.

5.5.2 UL Link Budget

As indicated earlier the UL link budget is often the limiting factor in determining the range and coverage area of a WiMAX base station. An exception to this would be in the case of adaptive beamforming where the MAP range may be the key factor in determining coverage. Range-imposed limitations in mobile devices are driven by key customer and operator requirements for hand-held mobile devices. These requirements are:

- Small size and low weight for ease of portability
- Low power consumption for prolonged battery life
- Low cost to minimize operator subsidization cost and price to the consumer

To maximize battery life while minimizing battery size, transmit powers are limited and to keep within the size, weight, and cost constraints, antenna gains are lower and the use of advanced antenna options are limited. Fortunately uplink user data rate requirements are, for most applications, lower than downlink requirements. This enables the use of narrower sub-channels in the UL direction thus maintaining a reasonable transmit power spectral density even with the lower power amplifier transmit power. Nevertheless, under most mobile usage scenarios, the UL link budget will generally be somewhat lower than the DL link budget. In the analyses that follow, where the UL is the limiting factor for range an UL data rate at the cell edge of 115 kilobits per second is assumed. This requires an UL sub-channel BW of approximately 1.6 MHz.

5.5.3 Duplexing: TDD or FDD

Time Division Duplex (TDD) is called for in all of the current performance profiles for Mobile WiMAX. TDD has several advantages over Frequency Division Duplex (FDD) [1] and generally will be the preferred duplexing approach where local rules allow. One key advantage of TDD is that it assures channel reciprocity between the uplink and downlink. This is especially important for Adaptive Beamforming which depends on the UL transmissions to control and optimize the weighting factors for the amplitude and phase for each antenna element in an n-element array at the base station. With FDD there would be some performance degradation due to the varied link conditions between the DL and UL channels which, in some cases, may be separated by 100 MHz or more.

Another important advantage is the ability of TDD to adapt to asymmetric traffic conditions. In TDD mode, Mobile WiMAX supports downlink to uplink ratios from 1:1 to 3:1. This provides a significant throughput advantage for data-centric traffic that is expected to be more dominant in the downlink direction. This is shown in Figure 11, which shows the downlink channel capacity for both a 1:1 and 3:1 downlink to uplink ratio for a 10 MHz channel BW. Note that this represents a 50% increase in the downlink data throughput for a 3:1 downlink to uplink traffic ratio as compared to 1:1 for the same channel bandwidth. If this were an FDD solution with two 5 MHz channels in the same occupied spectrum, the downlink channel capacity would be limited to the 1:1 values independent of the traffic asymmetry and the uplink channel would be underutilized. It should be noted that the channel capacity values are based on the simulation assumptions described earlier and summarized in Tables 7 and 8. As stated earlier these simulations are based on full buffer FTP traffic. The added scheduling overhead to support a more varied mix of traffic types such as VoIP, real-time gaming, etc. can result in a net throughput reduction of 5 to 10%. The relative values however, would not change.

Despite the cited advantages of TDD, it is anticipated that future Mobile WiMAX profiles will also include FDD to address specific market opportunities where TDD is not allowed due to local regulatory requirements or where FDD is a better fit for the channelization scheme that has been specified.

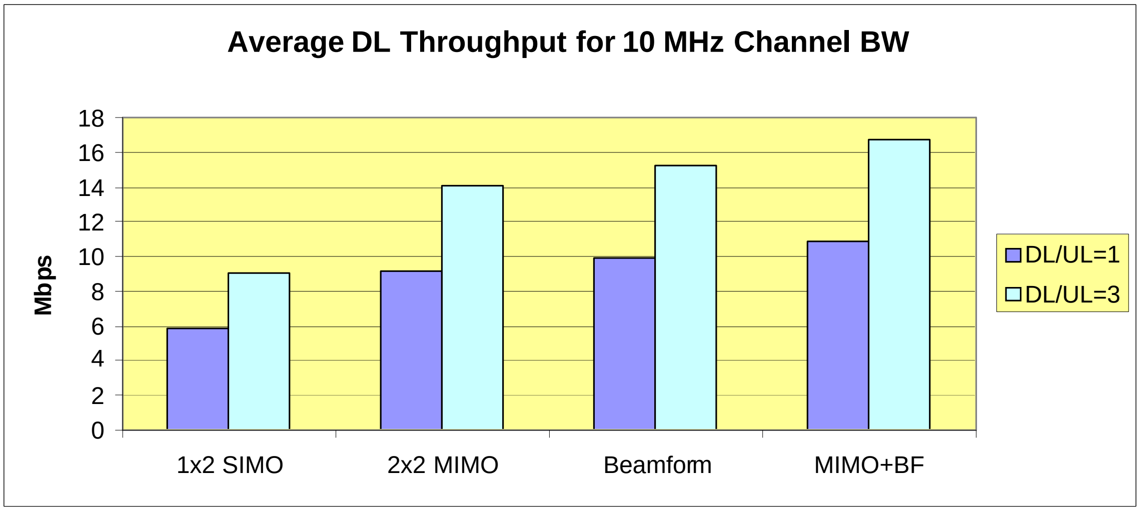

Figure 11: Downlink Throughput for TDD with 10 MHz Channel BW

6. Key Metric: Number of Base Stations

As mentioned earlier, the focus of this analysis is on the access portion of the network so the key metric for the quantified comparison will be the number of WiMAX base stations required to meet both capacity and coverage requirements in the varied demographic regions of the hypothetical metropolitan area described in the previous sections. The WiMAX base station is a key network element in connecting the core network to the end-user in that it determines the coverage of the network and defines the end-user experience. If too few base stations are deployed the coverage will not be ubiquitous and the end-user may experience drop outs or periods of poor performance due to weak signal levels as he moves throughout the coverage area. And since the base station investment will tend to be a dominant contributor to the total end-to-end network costs, deploying too many base stations can result in unnecessary start-up costs for the operator leading to a weaker business case.

6.1 Base Station Components

To better understand the base station investment it is convenient to break the base station into its three major components:

- Base Station Infrastructure
- WiMAX Base Station Equipment
- Backhaul Connection

6.1.1 Base Station Infrastructure

A major base station cost contributor for facilities-based operators, is the investment necessary to establish and prepare the base station site prior to the installation of the WiMAX equipment. This includes site acquisition, antenna towers, environmentally controlled enclosures for the indoor electronics, primary and back-up power, conduits, cabling, etc. Many of these items are often combined into what is called civil works. Based on cellular service provider surveys these costs can run as high as $200K to $250K for a Greenfield installation. Even the reuse of existing mobile sites can result in an investment of $50K to $70K for upgrades necessary to accommodate additional equipment or to phase out old equipment. At a minimum, existing sites will generally require adding to the size of the electronics enclosure to accommodate the WiMAX equipment, adding power supply capacity, and additional conduits and cabling.

For a non-facilities-based operator the entire base station infrastructure including the backhaul capacity can be leased, in which case the entire base station infrastructure cost (not including the WiMAX equipment) is captured as OPEX.

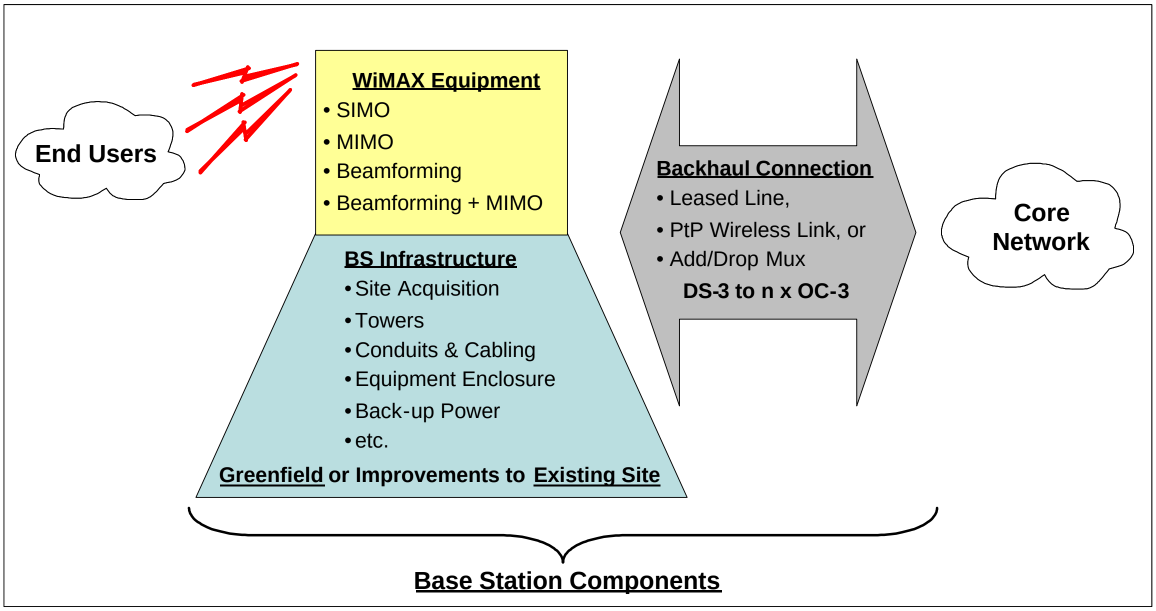

Figure 12: WiMAX Base Station in the Access Network

6.1.2 WiMAX™ Base Station Equipment

Base station equipment for Mobile WiMAX will be available from many vendors with a variety of architectures, performance, and features. This will be the case even though the base station antenna configurations may be the same. Although all WiMAX Forum Certified™ equipment will meet specific baseline performance levels as dictated by the WiMAX Forum certification testing profiles, individual manufacturers can elect to offer various optional features and attributes that will affect equipment complexity and impact equipment cost. Vendors will also offer a range of equipment architectures to fit varied deployment scenarios. These architectures will range from single-channel, self-contained, mini-base stations for economical, low capacity rural deployments and short range urban macro base station deployments to scalable multi-channel, card-based platforms for high capacity environments. Operators may also elect to implement various equipment redundancy options offered by vendors to minimize service downtime due to equipment malfunction. Some equipment architectures will require tower-mounting of active components. Although this relaxes power and noise figure requirements by circumventing cable losses it requires more robust mounting structures and potentially increases maintenance expense. Due to the wide range of variables, WiMAX equipment cost projections are not provided in this paper. It is reasonable to conclude however, that, in general, equipment costs will tend to increase with increasing equipment complexity and performance.

6.1.3 Base Station Backhaul

The third major component to the base station is the backhaul connection. The backhaul connections can be by means of leased lines, resulting in a monthly operating expense (OPEX), or a non-redundant or fully redundant point-to-point (PtP) wireless link to an aggregation node or fiber node, resulting in a capital expense (CAPEX). Some base station sites may be co-located with a fiber node requiring only an interface card to connect to the core network. Many multi-cellular metro area deployments will use a combination of all of these backhaul approaches.

Whatever approach is used, the backhaul capacity must be sized in accordance with the base station capacity. A high-capacity base station in an urban environment may require an OC-3 or 2xOC-3 backhaul whereas a DS-3[15] would suffice in a suburban and rural area deployment. Backhaul costs therefore, will also increase with higher throughput, higher performance base stations.

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[15] This is in contrast with n x T1/E1 backhaul connections which generally provided sufficient capacity in traditional cellular networks.

7. Comparing Mobile WiMAX™ Deployment Alternatives

In this section, the 1,500 km^2 hypothetical metropolitan area with a population of 1.75 million, as described earlier (refer to Table 4 for capacity requirements), is used as a basis for analyzing each of the following deployment scenarios.

1. Spectrum Comparison: 2500 MHz with 3500 MHz
2. Comparison of WiMAX Base Station Antenna Alternatives: (1x2) SIMO, (2x2) MIMO, Adaptive Beamforming, and Beamforming plus MIMO[16]
3. Channel Bandwidth Comparison: 7 MHz and 10 MHz
4. Available Spectrum: 10, 20, 30, and 40 MHz

7.1 Spectrum Comparison: 2500 MHz and 3500 MHz

This scenario compares deployments at 2500 MHz and 3500. The reuse factor is 1 and 10 MHz channels are assumed for both bands. As shown earlier, 2500 MHz has a range advantage of about 10% compared to 3500 MHz with the assumption of a higher base station antenna gains in the higher band. For this comparison three deployment alternatives are analyzed as summarized in Table 9. A breakdown of the required base stations to meet the capacity and coverage requirements for the metro area deployment is provided in Figure 13.

	Case 1	**Case 2**	**Case 3**
Frequency Band	2500 MHz	3500 MHz	
BS Antenna Gain	15 dBi	17 dBi	
Available Spectrum	30 MHz		
Channel Bandwidth	10 MHz		
Dense Urban	(2x2) MIMO	(2x2) MIMO	Beamforming
Urban	(1x2) SIMO	(1x2) SIMO	Beamforming
Suburban	(1x2) SIMO	(1x2) SIMO	Beamforming

---

[16] All of the beamforming alternatives considered in these sections assume an 8-element Adaptive Beamforming array with a 15 dBi element gain and +30 dBm (1 watt) transmit power per element.

	Case 1	Case 2	Case 3
Rural/Open Space	(1x2) SIMO	(1x2) SIMO	Beamforming
Total BS Required	316	438	311

Table 9: Deployment Options for Frequency Band Comparison

Both the 2500 MHz and 3500 MHz deployments are capacity-limited only in the dense urban area. There is no difference therefore, between 2500 and 3500 MHz in this area for the same base station antenna configuration. Deploying Adaptive Beamforming in the 3500 MHz band however, reduces the number of required base stations by about 8 % in the dense urban area due to the increased throughput and reduces the base station count in the other areas due to the increased range capability. The analysis indicates that deploying with adaptive beamforming in the 3500 MHz band will result in a base station count that is similar to a deployment in the 2500 MHz band with (2x2) MIMO.

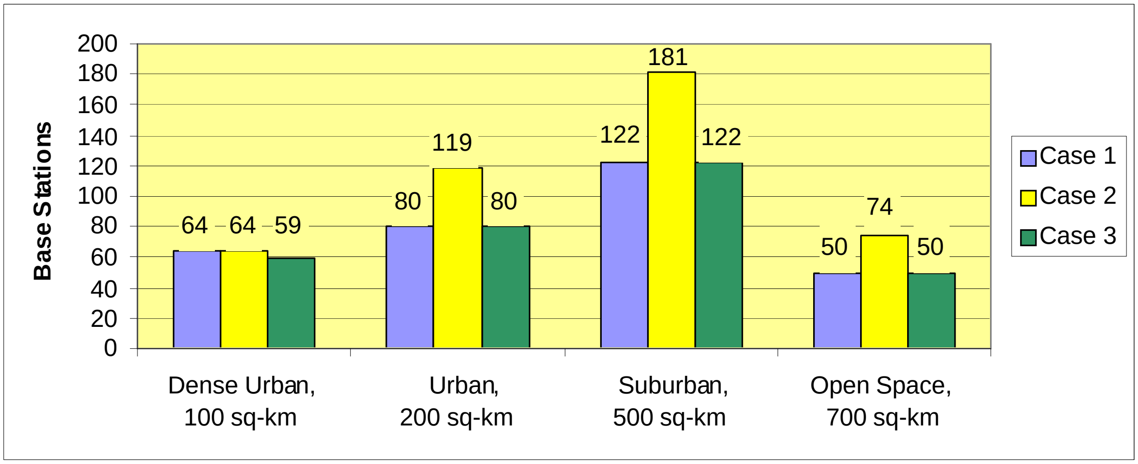

Figure 13: 2500 MHz to 3500 MHz Comparison

7.2 Comparison of WiMAX™ Base Station Antenna Alternatives

The deployment assumptions used to compare the different base station configurations in the 2500 MHz band are summarized in Table 10. The results for this analysis are summarized in Figure 14.

	Case 1	Case 2	Case 3	Case 4
Frequency Band	2500 MHz			
Available Spectrum	30 MHz			
Channel Bandwidth	10 MHz			
Dense Urban	(1x2) SIMO	(2x2) MIMO	Beamforming	BF + MIMO
Urban	(1x2) SIMO	(1x2) SIMO	Beamforming	Beamforming
Suburban	(1x2) SIMO	(1x2) SIMO	Beamforming	Beamforming
Rural/Open Space	(1x2) SIMO	(1x2) SIMO	Beamforming	Beamforming
Total BS Required	350	316	229	224

Table 10: Scenarios with Varied BS Antenna Configurations

For all of the cases the dense urban deployment is capacity-limited. Therefore, in this region there is a continuous reduction in the number of required base stations moving from SIMO to MIMO and finally to Adaptive Beamforming and Beamforming plus MIMO. In the other deployment regions, which are range-limited, a reduction in base station count is only realized with the added range provided by Adaptive Beamforming. In case 4, with Beamforming plus MIMO deployed in the dense urban region with Beamforming in all the other regions there is a 36% reduction in total base station requirements as compared to (1x2) SIMO deployed throughout the metro area. The net economic benefit will be reduced somewhat due to the potentially higher costs of the higher complexity solutions but nevertheless is expected to prove out to be a cost-effective investment.

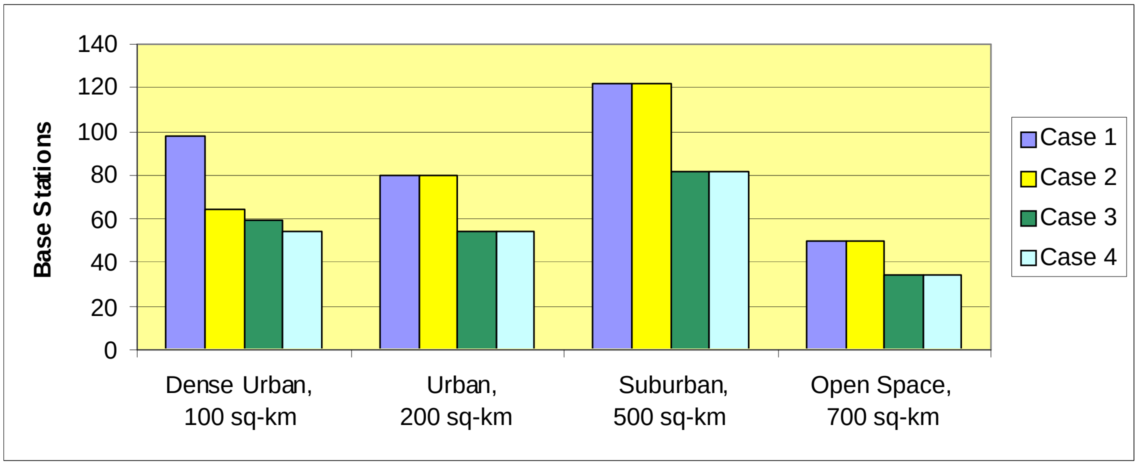

Figure 14: Base Station Count for Alternative BS Configurations

7.3 Channel Bandwidth Comparison

Table 9 provides a comparison between deployments with 7 MHz and 10 MHz channel bandwidths. Cases 1 and 2 assume the operator has access to a 21 MHz block of spectrum. Deploying with 7 MHz channels and reuse of 1 would assure that the entire 21 MHz of spectrum is utilized to meet capacity requirements in the dense urban and urban regions with a deployment comprising 9 channels per base station. The use of 10 MHz channels in case 2 reduces the base station complexity since it takes only 6 channels per base station to achieve maximum BS throughput. However, since 5% of the spectrum is not used the base station count is almost 3% higher. But with approximately 30% fewer channels per base station the base station costs will be lower. In comparing these two cases, the economic trade-off is not obvious without additional details about WiMAX equipment costs. Figure 15 provides the potential investment savings for a range of WiMAX equipment costs expressed in $K per channel and a varied investment for the base station infrastructure plus backhaul and other “fixed” base station costs[17]. The graph shows that even in a Greenfield situation there is a net savings in having fewer channels per base station when the cost of adding a WiMAX channel is higher than $5K per channel.

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[17] Other “fixed” base station costs would include WiMAX indoor equipment that is independent of the number of WiMAX channels deployed. The cost per channel covers the tower-mounted antennas, transceiver chains and installation cost.

	Case 1		Case 2		Case 3		Case 4	
Band	2500 MHz							
Base Station	(1x2) SIMO							
Avail. Spectrum	21 MHz				28 MHz		30 MHz	
Channel BW	7 MHz		10 MHz		7 MHz		10 MHz	
	BS	Chan	BS	Chan	BS	Chan	BS	Chan
Dense Urban	140	9	147	6	105	12	98	9
Urban	81	9	85	6	80	12	80	9
Suburban	122	6	122	6	122	6	122	6
Rural/Open Space	50	3	50	3	50	3	50	3
Totals	393	7.3 Avg.	404	5.6 Avg.	357	8.7 Avg.	350	7.1 Avg.

Table 11: Channel Bandwidth Comparisons

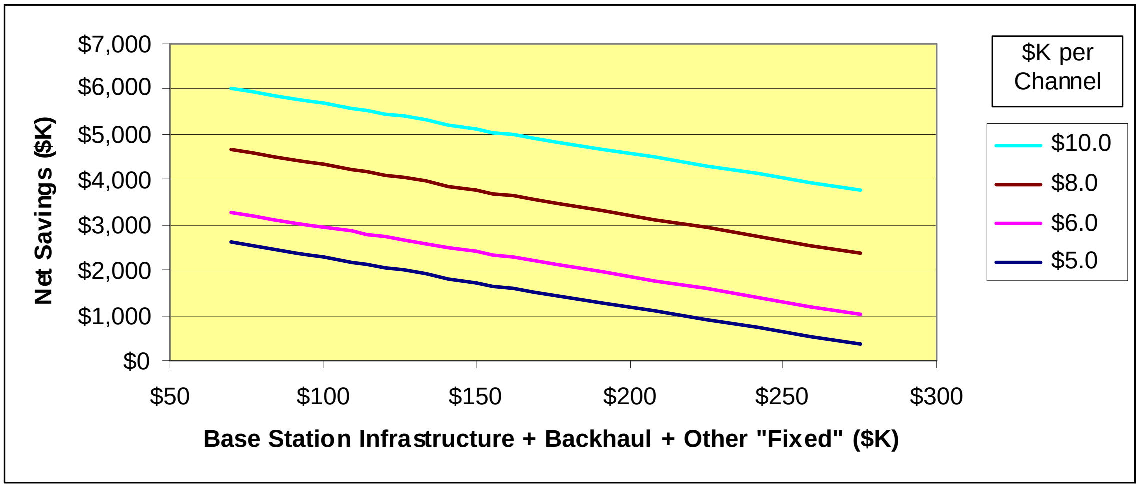

Figure 15: Benefit of Deploying with Wider BW Channels for Cases 1 & 2

Cases 3 and 4 provide a comparison between a 28 MHz assignment with 7 MHz channels and a 30 MHz assignment with 10 MHz channels. This comparison illustrates the advantage of having an additional 2 MHz of spectrum available for deployment. Both cases make full use of the spectrum available but the additional 2 MHz of spectrum enables support for wider bandwidth 10 MHz channels. Case 4, with the 10 MHz channels has both a lower base station count as well as fewer channels per base station resulting in a more cost-effective solution with a modest increase in available spectrum.

7.4 Spectrum Allocation

In the previous section we saw how a slight increase in the available spectrum from 28 MHz to 30 MHz can improve the deployment economics. In this section spectrum assignments ranging 10 to 40 MHz are evaluated and compared. For the purposes of this analysis the focus is only on the dense urban area which has an average data density requirement equal to 20 mbps per km^2 over 100 km^2 for our hypothetical metropolitan area. Table 12 provides details of the required BS to BS spacing and coverage area for the comparisons and Figure 16 summarizes the required base stations necessary to meet the dense urban area data density requirements for the varied spectrum assignments.

Unquestionably, having a spectrum assignment of 30 or 40 MHz ensures a much stronger business case for the operator. An assignment of 10 or 20 MHz on the other hand, not only necessitates a higher front-end investment for the operator but results in a base station density requirement that is not likely to be viewed as environmentally friendly.

	Case 1	Case 2	Case 3	Case 4	Case 5
Total Coverage Area	100 km^2				
Req. DL Data Density	20 mbps/ km^2				
Available Spectrum	10 MHz	20 MHz	30 MHz	30 MHz	40 MHz
Channel BW	10 MHz				
BS Antenna	(2x2) MIMO	(2x2) MIMO	(2x2) MIMO	MIMO+ BF	MIMO+ BF
BS to BS Spacing	0.78 km	1.10 km	1.34 km	1.46 km	1.70 km
Area per BS	0.53 km^2	1.05 km^2	1.56 km^2	1.85 km^2	2.50 km^2

Table 12: Scenarios for Analysis of Spectrum Availability

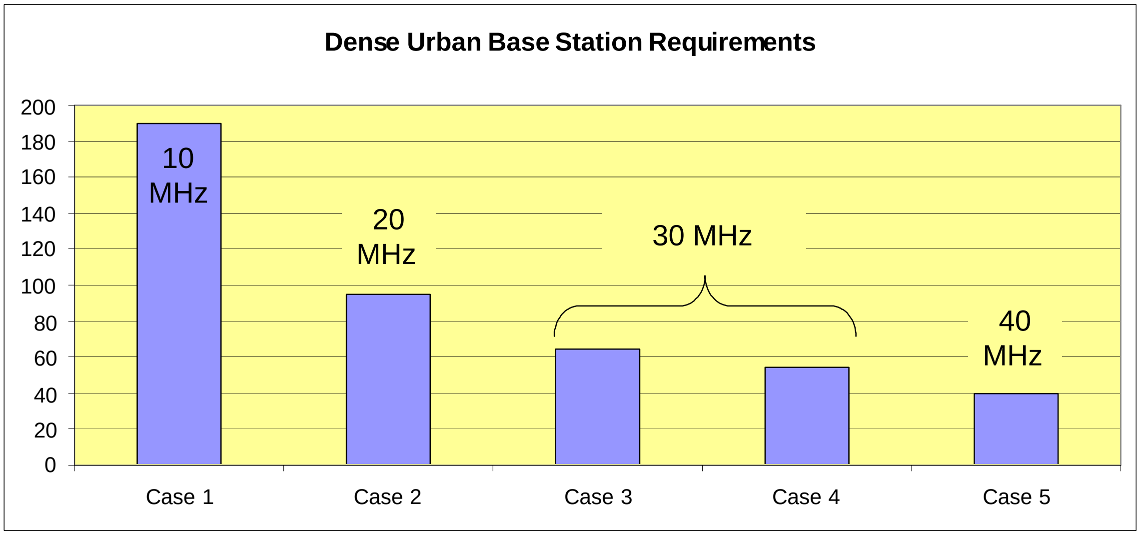

Figure 16: Base Station Requirements for Varied Spectrum Allocations

7.5 Other Deployment Considerations

The comparative analyses presented in this paper clearly indicate that in the long term, the higher performance base stations with wideband channels provide a potentially more cost-effective deployment solution as measured by the number of required base stations. Based on these results, one might conclude that it would be worth waiting for antenna technologies such as beamforming and beamforming + MIMO and possibly even 20 MHz channels, before deploying a Mobile WiMAX network. This however, is not the case. All of the above analyses are based on an assumed mature market penetration of 10 to 12% in the hypothetical metropolitan area assumed for this paper. In most markets, achieving this penetration can take several years depending on the competitive environment and the availability of other alternatives and, in all likelihood, will follow a market adoption curve similar to that shown in Figure 17. In the early years therefore, deployment can begin with range-limited base stations using (1x2) SIMO or (2x2) MIMO base station configurations to get ubiquitous coverage over the entire metropolitan area. These base stations can then be upgraded in the following years with beamforming and beamforming + MIMO as necessary to meet the capacity requirements in anticipation of a growing customer base. In most metropolitan area deployments this will only be necessary in the dense urban and urban areas.

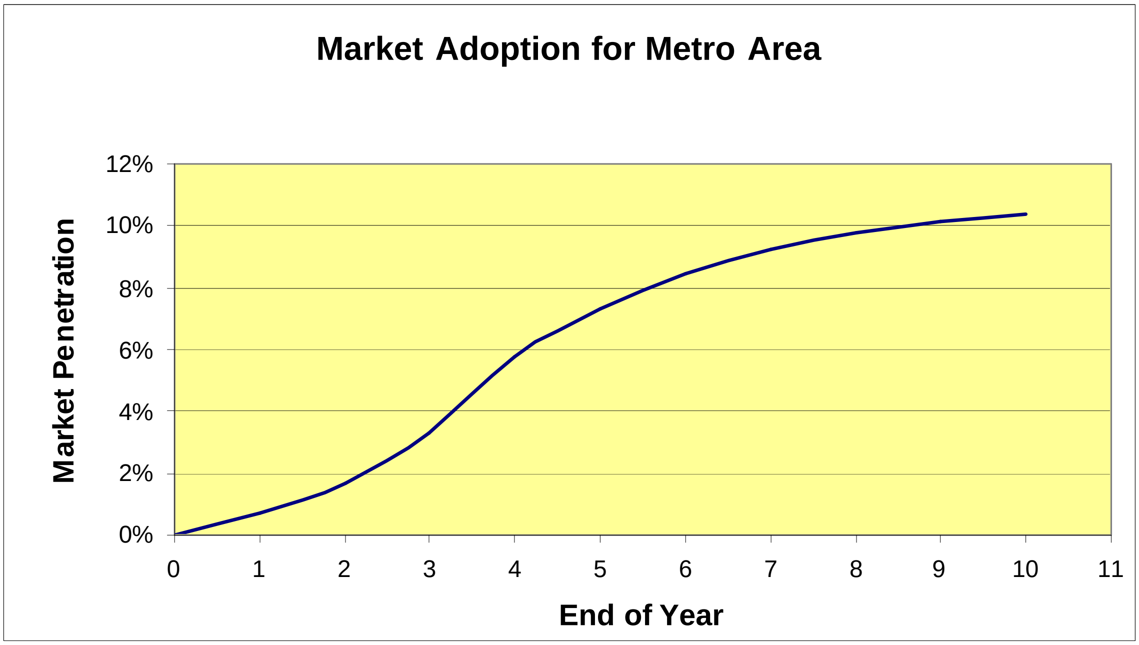

Figure 17: Typical Market Adoption Rate

Assuming a 30 MHz spectrum allocation and 10 MHz channels, Figure 18 shows the (1x2) SIMO base station requirements in the dense urban area over a 10 year period to match the customer adoption rate shown in Figure 17. Rather than adding more SIMO base stations in year 3, an alternative approach would be to upgrade existing sites with MIMO, beamforming and, in the later years, beamforming + MIMO. Only 11 base stations would have to be added from year 3 to year 10 rather than 58 required for SIMO. In the lower population density areas, where there is sufficient data density with SIMO, base station upgrades would not be necessary. Although this approach requires additional follow-up truck-rolls for the upgrades it is a solution that offers a lower front-end investment and greater deployment flexibility. It may also enable a faster time-to-market market; another essential ingredient for a successful business case.

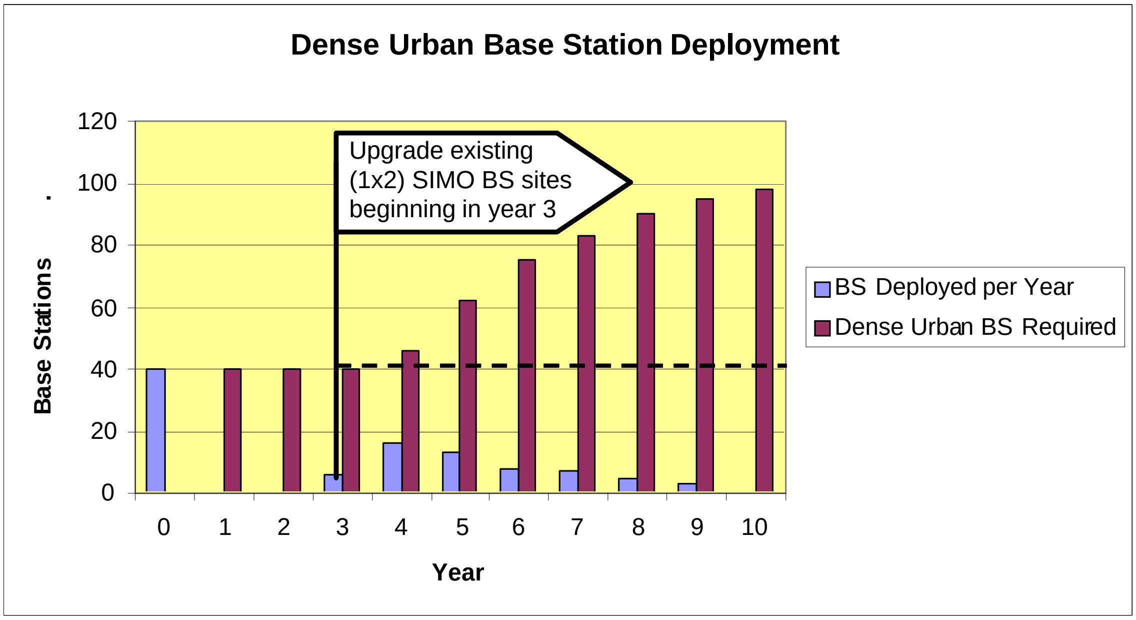

Figure 18: 10-Year Dense Urban Deployment for (1x2) SIMO

8. Conclusion

Using a consistent set of assumptions for a hypothetical mid-sized metropolitan area with a population of 1.75 million over a 1,500 km^2 area, the analyses in this paper provide a quantitative comparison between the various deployment alternatives using base station count as the key differentiator. Base station infrastructure, backhaul costs, and WiMAX equipment costs were not included in the analyses but some insights on these costs and their impact were provided. Obviously for Greenfield deployments the combination of base station infrastructure and backhaul costs will tend to dominate, whereas the WiMAX equipment costs will have bigger economic impact with deployments that reuse existing cell sites.

Additionally, a methodology was presented for estimating peak busy hour downlink capacity requirements. An estimate of data density requirements is especially important in the higher population density regions to ensure there is adequate base station capacity to meet customer demand during the network's busiest periods.

The results show that advanced antenna techniques such as MIMO with Space Time Coding, Spatial Multiplexing and Beamforming, are viable alternatives for the higher density, capacity-limited deployments to meet mature market capacity demands with a reasonable base station count. It was also pointed out that the lower complexity base station configurations can be very adequate to meet demands in the early years with a migration path to more advanced base station antenna systems in later years to match customer growth.

In comparing 2500 MHz with 3500 MHz it was shown that Adaptive Beamforming with an 8-element array could reduce the 3500 MHz base station count to levels comparable to 2500 MHz deployments with (2x2) MIMO. The paper also shows the importance of having access to sufficient spectrum for WiMAX deployment to help ensure a winning business case for the operator.

Acronyms

3GPP2	3rd Generation Partnership Project 2
AAS	Advanced (or Adaptive) Antenna System
ACI	Adjacent Channel Interference
AMC	Adaptive Modulation and Coding
BE	Best Effort
BF	Beam Forming
BS	Base Station
BW	Bandwidth
CAPEX	Capital Expense
CCI	Co-Channel Interference
CDMA	Code Division Multiple Access
CFR	Code of Federal (US) Regulations
CINR	Carrier to Interference + Noise Ratio
CIR	Committed Information Rate
DL	Downlink
DL/UL	Downlink to Uplink (traffic) Ratio
DoA	Direction of Arrival
ECC	Electronics Communications Committee
EIRP	Effective Isotropic Radiated Power
FDD	Frequency Division Duplex
FTP	File Transfer Protocol
ITU	International Telecommunications Union
MAP	Media Access Protocol
MIMO	Multiple Input Multiple Output
OPEX	Operating Expense
PBH	Peak Busy Hour
PtP	Point-to-Point
PUSC	Partially Used Subchannel

QPSK	Quadrature Phase Shift Keying
SIMO	Single Input Multiple Output
SIR	Signal to Interference Ratio
SISO	Single Input Single Output
SLA	Service Level Agreement
SM	Spatial Multiplexing
SNR	Signal to Noise Ratio
SNIR	Signal to Noise plus Interference Ratio
SS	Subscriber Station
STC	Space Time Coding
TDD	Time Division Duplex
UL	Uplink
WiMAX	Worldwide Interoperability for Microwave Access

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