A Comparative Analysis of Spectrum Alternatives for WiMAX™ Networks with Deployment Scenarios Based on the U.S. 700 MHz Band

June 2008

By

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Author's Note

Performance of wireless systems is highly dependent on the operating environment, deployment choices, and the end-to-end network implementation. Range projections in this paper are based on calculations using generally accepted propagation models. Sector and base station channel capacity is 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.

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1.0 Introduction

The Mobile WiMAX™ Release 1.0 Profiles currently cover several frequency bands ranging from 2300 MHz to 3800 MHz. For comparison purposes these bands can be grouped into two categories, 2500 MHz and 3500 MHz. To accommodate the anticipated growth in mobile services and new broadband applications, there is ongoing pressure on regulators to make additional spectrum available for mobile applications. Bands below 1000 MHz are especially interesting due to the improved propagation conditions as compared to 2500 and 3500 MHz.

The frequency band between 470 MHz and 862 MHz has traditionally been allocated worldwide for radio and TV broadcasting and encompasses the UHF TV channels. With the planned transition to digital radio and TV formats, portions of this band will become available for other services and applications. This has been commonly referred to as the "Digital Dividend". The specifics and timing for revised allocations in this band will vary country by country but it is safe to conclude that regulators will give serious consideration to providing additional spectrum for fixed and mobile broadband services. Regulators, in many cases, already recognize the potential of using the range and coverage benefits of this spectrum to cost-effectively reach consumers in underserved rural areas. Within the ITU, WRC-2007 identified frequencies in the 450 – 470 MHz range world wide, the 698-806 MHz range in Region 2 and some Region 3 countries and 790- 862 MHz range in Region 1 and 3 for IMT mobile applications. Co-primary Mobile allocations in the range 806-960 MHz were already identified in Regions 2 and 3 for IMT at WRC-2000.

Using a hypothetical mid-sized metropolitan area comprising urban, suburban, and rural demographic regions, this paper provides a comparison of WiMAX™ deployments at 700 MHz and 2500 MHz[1] from a range, coverage, capacity, and performance perspective. Since a WiMAX profile in the UHF frequency bands is still under development, a set of parameters is assumed for the purposes of this paper that is felt to be representative of a

[1] A discussion of the tradeoffs between 2500 MHz and 3500 MHz has been provided in the paper, "A Comparative Analysis of Mobile WiMAX Deployment Alternatives in the Access Network", available on the WiMAX Forum website.

WiMAX 700 MHz solution[2]. This analysis will provide insights as to the deployment challenges of having limited spectrum for high population density regions as well as the advantages of having access to the 700 MHz band for range and coverage in the more sparsely populated rural areas.

Since spectrum allocations in the 700 MHz band may support either Frequency Division or Time Division Duplexing, a deployment comparison for these two approaches is also provided for varied downlink to uplink traffic ratios.

2.0 The "700 MHz Band" in the United States

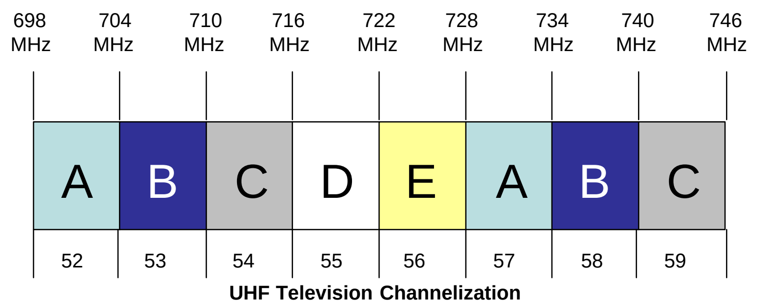
Although allocations will vary in detail from country to country, a characteristic that generally prevails is; there is less available spectrum for assignment to any single operator in the lower frequency bands than there is in the higher bands[3]. The 700 MHz allocation in the United States [Ref.1,2] represents a good example for analysis since it provides for several licenses ranging from 2 MHz of spectrum to 22 MHz of spectrum per license. This will enable us to provide some insights as to the relative value of having more or less spectrum in the same frequency band. The US 700 MHz band allocation is shown in the following two figures. The spectrum designated as the "Lower 700 MHz Band", shown in Figure 1, supports five licenses. Three of the licenses have paired 6 MHz channels for a total of 12 MHz per license and two licenses consist of a single 6 MHz channel. Many of the lower band licenses were auctioned by the FCC in the year 2003.

The FCC plan for the "Upper 700 MHz Band", shown in Figure 2, provides for four additional licenses, one with paired 11 MHz channels for 22 MHz total, one with paired 5 MHz channels for a total of 10 MHz, and two licenses with paired 1 MHz channels. The latter two licenses comprising only 2 MHz of spectrum will not be considered further in this paper since the spectrum is considered to be insufficient for a WiMAX deployment offering broadband services. The auctions for the "Upper 700 MHz Band" licenses were auctioned in the first quarter of 2008[4].

[2] The WiMAX Forum is actively engaged in the development of profiles for the UHF bands in compliance with global spectrum allocations including the "Lower and Upper 700 MHz bands" as defined by the FCC in the U.S.

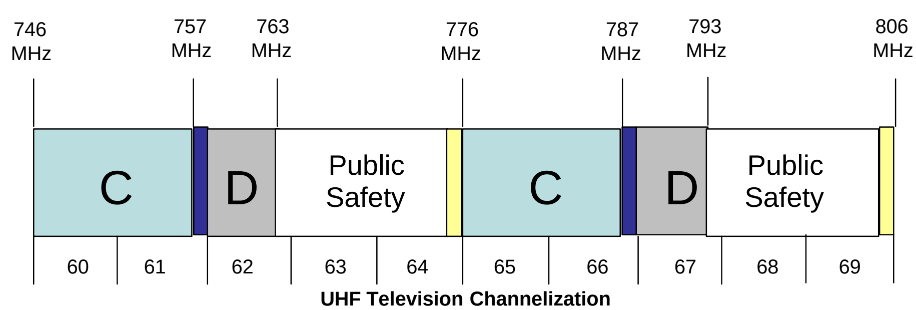
[3] Although the UHF band covers 372 MHz it not likely that regulators will allocate all of it for fixed and mobile services. Work in the regional bodies in Europe for example, are examining channel plans for mobile services restricted to the 798-862 MHz range.

[4] 700 MHz auction details can be found on the FCC website, Auction 73: 700 MHz Band



License	Amount	Channelization
A-A	12 MHz	2 x 6 MHz Paired Channels
B-B	12 MHz	2 x 6 MHz Paired Channels
C-C	12 MHz	2 x 6 MHz Paired Channels
D	6 MHz	Unpaired Channel
E	6 MHz	Unpaired Channel

Figure 1: "Lower" 700 MHz Band in the US



License	Amount	Channelization
C-C	22 MHz	2 x 11 MHz Paired Channels
D-D	10 MHz	2 x 5 MHz Paired Channels
A-A	2 MHz	2 x 1 MHz Paired Channels
B-B	2 MHz	2 x 1 MHz Paired Channels

Figure 2: "Upper" 700 MHz Band in the US

Assuming 700 MHz WiMAX equipment is available with either 5 or 10 MHz channel bandwidths, the US licenses in the 700 MHz band will support base station configurations as shown in Table 1 for TDD[5] operation. The average downlink (DL) sector capacity is based on a (1x2) SIMO[6] base station antenna configuration, a DL to UL traffic ratio of 3:1 and reuse factor of 1. It also assumes a mixed user model [Ref.3].

Table 1: Possible BS Configurations for US 700 MHz Band Plan

License	Channel BW	Maximum Channels per Sector	Average DL Sector Capacity
"Lower 700 MHz Band" D or E	5 MHz	1	4.6 Mbps
"Lower 700 MHz Band" A-A, B-B, or C-C	5 MHz	2	9.1 Mbps
"Upper 700 MHz Band" C-C	10 MHz	2	18.2 Mbps
"Upper 700 MHz Band" D-D[7]	5 MHz	2	9.1 Mbps
"Upper 700 MHz Band" A-A, B-B	Not Applicable for WiMAX Deployment		

3.0 Path Loss Comparison

3.1 Channel Models

A number of channel models can be considered for 700 MHz and higher bands that include provision for mobile communication and the usage of multiple antenna concepts. Both for MIMO and Beamforming, a channel model that can consider the effect of direction of incoming and outgoing signals is desirable. With these requirements, a suitable channel model is the COST 273 Directional Channel Model. This channel model can be considered as a parametric stochastic model. The model can be used for 13 different environments and can cover macro, micro, and pico cells. Since the concentration is given mostly to urban and suburban areas, the COST 273 channel models for macro cells can be used for the purpose of analysis for the following terrain types:

[5] TDD is the preferred mode since it has many favorable attributes including adaptation to asymmetric traffic for improved spectral efficiency.

[6] WiMAX technology supports a wide range of advanced antenna systems, (1x2) SIMO is selected for analysis in this paper as a representative initial baseline configuration.

[7] Since this allocation is adjacent to the Public Safety spectrum coordination is required as to technology choice so as mitigate the potential for interference.

a. Generalized Typical Urban (GTU)
b. Generalized Bad Urban (GBU)
c. Generalized Rural Area (GRA)
d. Generalized Hilly Terrain (GHT)

Another channel model that is available for simulations is the COST 259 model. The limitations of the COST 259 channel model are:

1. It can be used for channel BW's up to 5 MHz and possibly would be satisfactory for 6 MHz, but the usage for BW's higher than 6 MHz is not guaranteed to yield accurate results [Molisch.1206].
2. The channel model assumes only the mobile station moving while the objects between the BS and MS are stationary.

For 700 MHz applications we based our path loss simulations on the Hata model which is compared to the COST 259 and COST 273 models in the following table. In the higher bands, path loss calculations are based on the modified Hata or COST 231 model. The capacity and interference simulations in Section 5 are also based on the COST 231 model. All four models are summarized in Table 2.

Table 3 summarizes the parameters for determining the path loss differences between the two frequency bands; 700 MHz and 2500 MHz assuming a (1x2) SIMO antenna configuration at both the Base Station and the Mobile Station. The Hata propagation model is assumed for the 700 MHz band. The mobile COST 231 or modified Hata has been used extensively in the 1900 MHz band and with an appropriate frequency scaling factor[8] is also considered acceptable for range predictions to approximately 6 GHz. Another model that can be considered for the higher bands is the Stanford Pedestrian model or Erceg-Greenstein model. This model provides a more optimistic estimate for path loss and is included for reference purposes in Table 3.

Table 2: Path Loss Models

	COST-259	COST-273	Hata	COST-231
Frequency	> 500 MHz	X, >2GHz	<1500 MHz	>1500 MHz
Broadband	X	√	X	X
Directional	√	√	X	X

[8] The frequency scaling factor of $26 x \mathrm{Log}_{10}(f/2)$, where f is frequency in GHz, is used to extend the useful frequency range of the COST 231 model.

	COST-259	COST-273	Hata	COST-231
MIMO	√	√	X	X
Beamforming	√	√	X	X
Mobility	√	√	X	X
Multipath	√	√	√	√
Urban Models	√	√	√	√
Suburban/Rural models	√	√	√	√
Building Penetration Loss	+	+	+	+
Vehicle Penetration Loss	+	+	+	+
Channel Types	13	13	1	1
+ : Can be added				

Table 3: Parameters for Path Loss Comparison

Parameter	700 MHz	2500 MHz
Propagation Model	Hata	COST 231
Region	Suburban	
BS Antenna Height	32 Meters	
Height Above Average Building Height	10 Meters	
Mobile Terminal Antenna Height	1.5 Meters	
Path Loss Exponent	3.5	
Path Loss at 1 km	113.9 dB	140.6 dB
Path Loss at 1 km (Stanford Pedestrian Model)	n/a	126.7 dB

Figure 3 shows the path loss versus cell radius for the 700 MHz and 2500 MHz frequency bands assuming the Hata model at 700 MHz and the COST 231 model in the 2500 MHz band with the Stanford Pedestrian model result included for comparison.

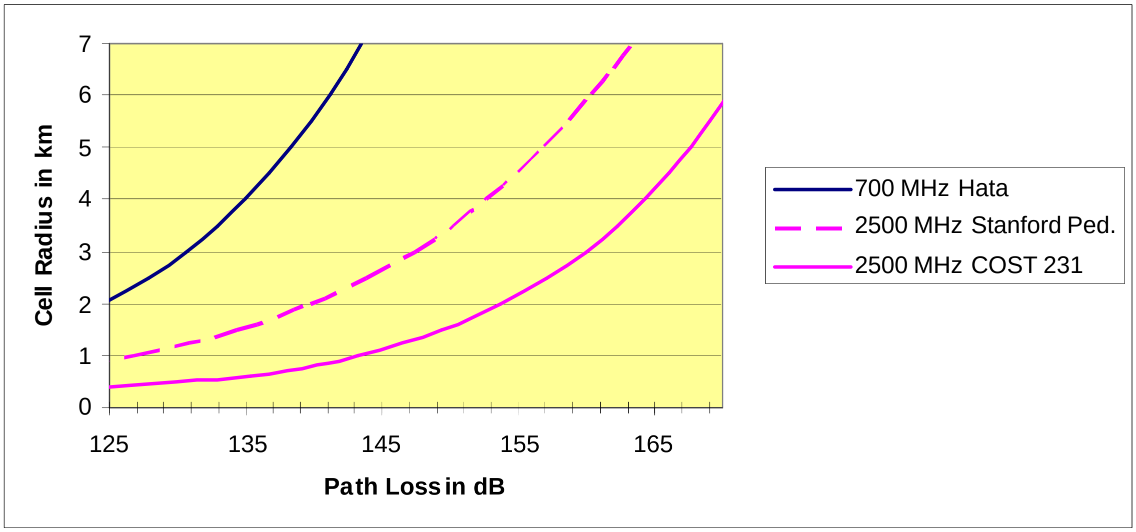


Figure 3: Suburban Outdoor Path Loss Comparison

3.2 Building and Vehicular Penetration Loss

Planning tools for dimensioning a network usually provide outdoor coverage predictions. Path loss is estimated from the BS to the center of the street. However the use of mobile terminals is not limited to outdoors, but is used at an increasing rate indoors - at times deep into buildings. Therefore extra signal attenuation due to building penetration must be modeled and incorporated in the overall path loss analysis so that it provides an accurate prediction of coverage. It is well known that building construction characteristics and city morphology have a strong impact thus making a correct adaptation of the models and predictions a difficult task. These studies therefore resort to statistical models. The measurement criteria for the study are captured below:

- Outdoor measurements were taken on both sides of the street and averaged
- Indoor measurements were acquired in the rooms in an 'X' manner.
- Attenuation for types of buildings, rooms and floors were measured and correlated
- Buildings were grouped as follows:

  High Integrated (HIn) : > 6 floors, sharing walls
  High Isolated (HIs): > 6 floors, non-sharing walls
  Low Integrated (LIn): < 6 floors, sharing walls
  Low Isolated (LIs): < 6 floors, non-sharing walls
- Rooms were classified as follows:

  Indoor Light (IL): room with windows to outdoors

Indoor (I): room without windows, one wall separation

Deep Indoor (DI): Multiple walls

Based on the study and measurements conducted by Lucio Ferreira, et al, Technical University of Lisbon, in the publication titled "Characterization of signal penetration into buildings for GSM & UMTS" it was found that, for GSM900, the mean of 5.7 dB and standard deviation of 11.1 dB is the limit to be incorporated to account for signal loss in buildings. A similar factor will be expected in the 700 MHz band. It was also found that attenuation increased as you go deeper into the building (IL ~ 5 dB, I ~ 6 dB, DI~ 9dB) and attenuation penetration decreases for higher floors (~ 0.8 dB/floor). Attenuation for GSM1800 and UMTS can be obtained by shifting GSM900 CDFs by 1.9 dB.

Table 4: Building Penetration Loss in the 900 MHz Band

Average and standard deviation values for the attenuation due to penetration into buildings, for GSM900.

	Deep Indoor		Indoor		Indoor Light		Av. per building type	
	μ [dB]	σ [dB]	μ [dB]	σ [dB]	μ [dB]	σ [dB]	μ [dB]	σ [dB]
HIn	8.8	8.9	7.2	9.3	4.5	9.4	5.6	9.5
HIs	5.8	11.5	2.0	11.7	1.2	10.1	2.0	10.8
LIn	12.3	11.5	6.2	12.9	5.5	12.9	5.8	13.1
LIs	12.3	12.2	9.0	9.0	8.3	11.2	9.1	11.2
Av. per room type	9.7	11.1	4.8	11.0	5.0	10.9	**5.7**	11.1

Values similar to those summarized in Table 4 can be assumed for WiMAX deployments in the 700 MHz band. Since subscribers will often be located in vehicles, penetration loss for these applications also must be considered. These are summarized in Table 5.

Table 5: Vehicle Penetration Loss

Type of Environment	Position of the Antenna	Mean [dB]	Standard Deviation [dB]
Urban	Drivers Hat	8.98	2.26
Urban	Passenger Seat	8.64	3.89
Suburban	Drivers Hat	8.86	3.13
Suburban	Passenger Seat	7.26	2.94

3.3 Antenna Requirements and Deployment Considerations

Emerging wireless systems require the use of multiple antennas either at the receiver, the transmitter, or both for a higher channel capacity. Advanced multiple antenna techniques such as MIMO with Space Time Coding (STC) and Spatial Multiplexing and Beamforming can provide transmit and receive diversity to enhance both range and channel capacity. In order to realize the benefit of these multi-antenna systems, certain constraints on the antenna separation must be taken into consideration.

For MIMO and receive/transmit diversity systems the level of correlation between antenna elements has a direct impact on the resulting performance of these multi-antenna techniques. Two means of achieving low correlation are common, namely polarization and space diversity. Polarization diversity typically provides very low levels of correlation and is realized by using any two orthogonal polarizations, e.g. vertical and horizontal or ±45°. Such techniques can be used at both the mobile and base station and, in principle, do not require any additional space over that required for the dual polarized antenna element itself. This approach will be equally effective at both 700 MHz and higher frequencies. For 2-branch MIMO systems using polarization diversity the base station (BS) antenna sizes are therefore likely to be the same as a conventional dual polar sector antenna - e.g. ~300 mm wide at 700 MHz or ~150 mm wide at 2500 MHz.

The difference between the frequency bands is more pronounced however when both space and polarization diversity is implemented, such as might be necessary for higher order MIMO implementations. Here the antenna spacing is dictated by the level of de-correlation required for effective MIMO operation which in turn is determined by the degree of scattering present in the environment. Considering a dense urban channel, for example, where there is a high degree of scattering about the mobile which in turn subtends an appreciable angle at the BS antenna, a relatively modest antenna separation might be adequate - perhaps 1 to 2 wavelengths for example. In a suburban channel however the angle spread subtended at the BS by the multipath is much reduced and far greater antenna separation will be required to achieve the same level of de-correlation, perhaps 5 wavelengths, while still greater separations would be required in rural deployments. The necessary physical spacing is then determined by the wavelength, with those at 700 MHz being roughly 3.5 times as great as those required at 2500 MHz. The practicality of such spatial techniques at 700 MHz will then depend on the details of the deployments involved and the performance benefits offered.

Beamforming schemes can be realized using a variety of antenna configurations including the combinations of the polarization and space diverse arrangements discussed above. In these cases the overall antenna dimensions will depend on the number and spacing of the antennas involved. Beamforming techniques however also include the case of what might be termed 'classic' directional beamforming which typically employs closely spaced antenna elements of the order of 0.5 wavelengths apart within a single aperture to allow controlled radiation patterns to be generated. Such an array might comprise as many as 4 or 8 closely spaced columns of elements within a single aperture. Here again the antenna width will be dictated by the wavelength with a 4 column antenna being approximately 900 mm wide at 700 MHz but only 250 mm wide at 2500 MHz.

Similar correlation requirements exist at the mobile station (MS) where physical space is likely to be limited regardless of the frequency. Here polarization and pattern diversity are effective means of achieving the necessary low levels of correlation and while the design challenge no doubt increases as the frequency drops, effective 2-element design should be achievable for all the bands being considered here.

In conclusion antenna spacing considerations may, in general, limit the use of some of the advanced multiple antenna systems supported by WiMAX technology in the 700 MHz band when compared with 2500 MHz deployments. In practice however the specifics of individual deployments and the performance gains offered by the techniques in question will dictate what is acceptable.

3.4 Other Parameter Differences

- **Cable Losses:** Network operators typically prefer base-mounted transmitter power amplifiers rather than tower-mounted amplifiers for ease of maintenance. The amplifier transmit power must therefore be sufficient to overcome cable losses. In the 2500 MHz band cable losses can range from approximately 2 dB for a high performance cable to almost 6 dB for a lower cost cable for a 32 meter tower height. For the same types of cable in the 700 MHz band these losses will range from 1 dB to about 3 dB. To achieve the same transmit power at the base station antenna port, 700 MHz deployments can use lower power base-mounted amplifiers or alternatively lower cost cable. In either case this cost savings would help to mitigate the cost impact of the larger antennas and associated mounting structures.

- **Line of Sight:** True line-of-sight (LOS) is defined as a path free of obstructions within the 1st Fresnel zone[9] to minimize the simultaneous reception of reflected out–of-phase signals and excess losses due to signal diffraction. Although in practice it is common to tolerate obstructions in 30-40% of the 1st Fresnel zone it would still require higher base station heights at 700 MHz to achieve the same Fresnel zone clearance that can be achieved at 2500 MHz.
- **Other Relevant Parameters**: For the purposes of this paper it is reasonable to assume that other parameters and factors that impact range such as mobile station antenna gain, transmit power, noise figures, etc. are comparable for each of the bands.

3.5 System Path Loss Model

The system model below shows path-loss and penetration losses for fixed and mobile applications. For nomadic instances a fixed model will suffice.

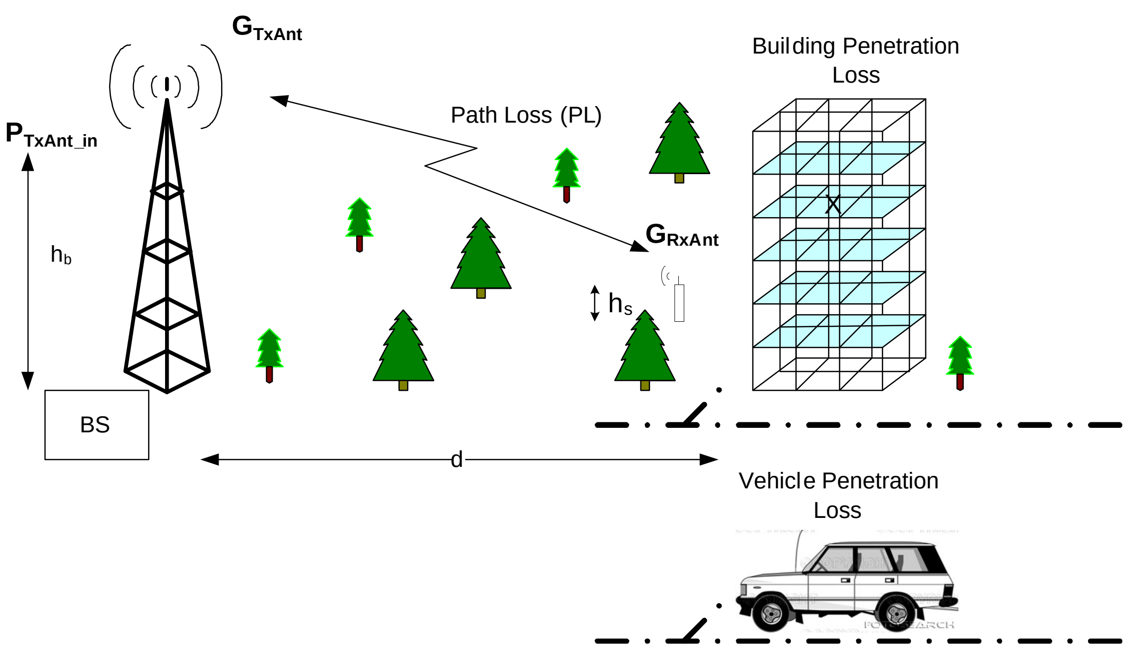


Figure 4: System Model

[9] The radius of the first Fresnel zone is maximum at the midpoint of the LOS path and is directly proportional to the square root of the wavelength times the path length.

3.6 System Gain and Range

Table 6 provides a summary of the parameters used to estimate the range and coverage for the frequency bands of interest. A (1x2) SIMO base station and mobile station implementation is assumed for the 700 MHz band and a base station beamforming array assumed for the 2500 MHz band. This reflects the fact that the use of these types of antenna arrays would not be readily adaptable to the 700 MHz band due to the size and antenna spacing requirements, but will be quite common in the higher bands. The more conservative COST 231 propagation model is also assumed for 2500 MHz.

Table 6: Parameters for Range Estimation

Parameter	700 MHz	2500 MHz
Duplex	TDD	
Channel BW	10 MHz	
BS Antennas	Tx=1, Rx=2 (1x2 SIMO)	Beamforming Array
BS Antenna Gain	15 dBi	21 dBi[10]
BS Tx Power (at antenna)	10 Watts (+40 dBm)	
BS Antenna Height	32 meters	
MS Antennas	Tx=1, Rx=2 (1x2 SIMO)	
MS Antenna Gain	-1 dBi	
MS Tx Power	200 mw (+23 dBm)	
MS Antenna Height	1.5 meters	
BS Noise Figure	4 dB	
MS Noise Figure	7 dB	
Building Penetration Loss	8 dB	10 dB
Propagation Model	Hata	COST 231

[10] Assumes a 4-element beamforming array

The relative range, with 2500 MHz as a reference, for a suburban deployment with indoor mobile terminals for the two band alternatives is summarized in Figure 5. The UL link budget is the determining factor in the 700 MHz band whereas the DL MAP range, not the beamforming gain, determines the link budget in the 2500 MHz band. Beamforming therefore, does not appreciably impact the range but does have significant impact on DL channel capacity resulting from the increased link margin and improved interference control. The lower path loss in the 700 MHz band provides a significant range advantage. In range-limited or noise-limited deployments it would take considerably more base stations in the 2500 MHz band to achieve the same area coverage as a 700 MHz deployment. It should be noted however, that this range analysis only takes into account AWGN and does not include the impact of the interference that would normally be encountered in a typical multi-cellular deployment. In addition to interference, capacity requirements must also be taken into account to gain a true comparison between the two frequency bands. Since many demographic regions with high population densities will be constrained by capacity rather than by range, it is important to look at a more typical large-scale wide area deployment scenario with variable demographic conditions to gain a more accurate assessment of the deployment differences. Various deployment scenarios will be analyzed later in the paper to provide greater insights as to the tradeoffs between the lower and higher frequency bands.

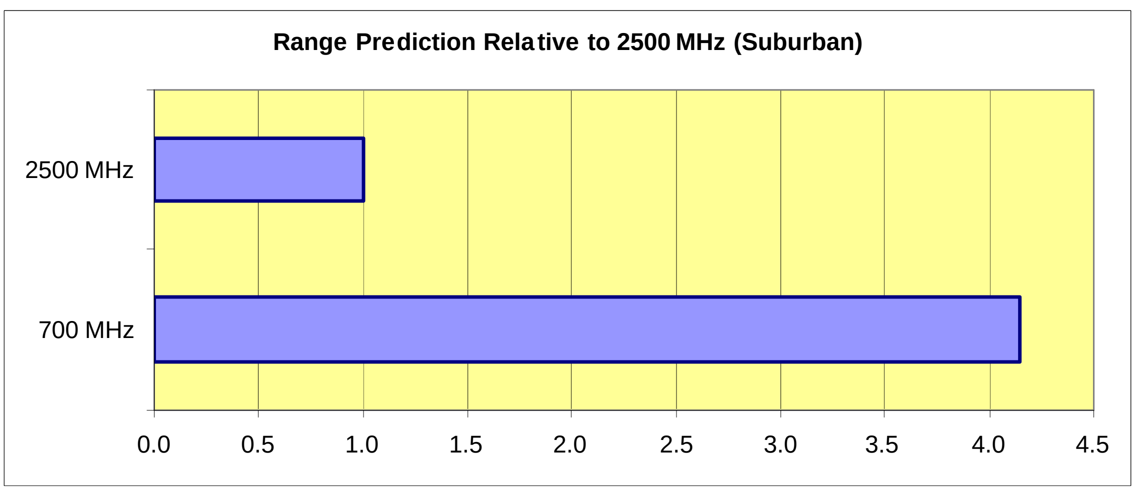


Figure 5: Suburban Range Comparison for Indoor Mobile Station

4.0 High Mobility Support Based on Doppler Spread

With the ever-increasing interest in broadband connectivity combined with high mobility it is important to assess the tradeoffs that exist between the various frequency bands for this important metric. This is evaluated by analyzing the Doppler Spread.

Multiple independent frequency offsets exist within the received signal due to the variable Doppler shift that occurs with multi-path propagation and a moving MS. This is known as Doppler Spread since only the main path offset can be tracked. The actual impacts of the other paths' offsets depend on the relative frequency offsets and their relative powers.

An upper and lower bound has been developed for the inter-carrier interference power as a function of velocity and symbol period for different time varying models [Ref. 4]. The upper and lower bound respectively is given by:

$$P_{ICI} \leq \frac{\alpha_1}{12}\left(2\pi f_d T_s\right)^2 \qquad (1)$$

And

$$P_{ICI} \geq \frac{\alpha_1}{12}\left(2\pi f_d T_s\right)^2 - \frac{\alpha_2}{360}\left(2\pi f_d T_s\right)^4 \qquad (2)$$

Where P_{ICI} is the inter-carrier interference power relative to the received signal power, f_d is the Doppler frequency and T_s is the symbol period. The α factors are dependent on the particular Doppler spectrum values for which, are provided in the table below:

Table 7: Alpha Factors for Determining Inter-Carrier Interference

Model[11]	α_1	α_2
Classical	1/2	3/8
Uniform	1/3	1/5
Two-path	1	1

[11] The models are defined in reference [4]

Figure 6 shows the signal to lower-bound inter-carrier interference ratio introduced by the Doppler Spreading, which is derived from equation (2), for a carrier frequency of 2500 MHz and 700 MHz. The X-axis in the figure represents that MS velocity divided by 10 so effectively covers the velocity range from 10 to 300 km/hr.

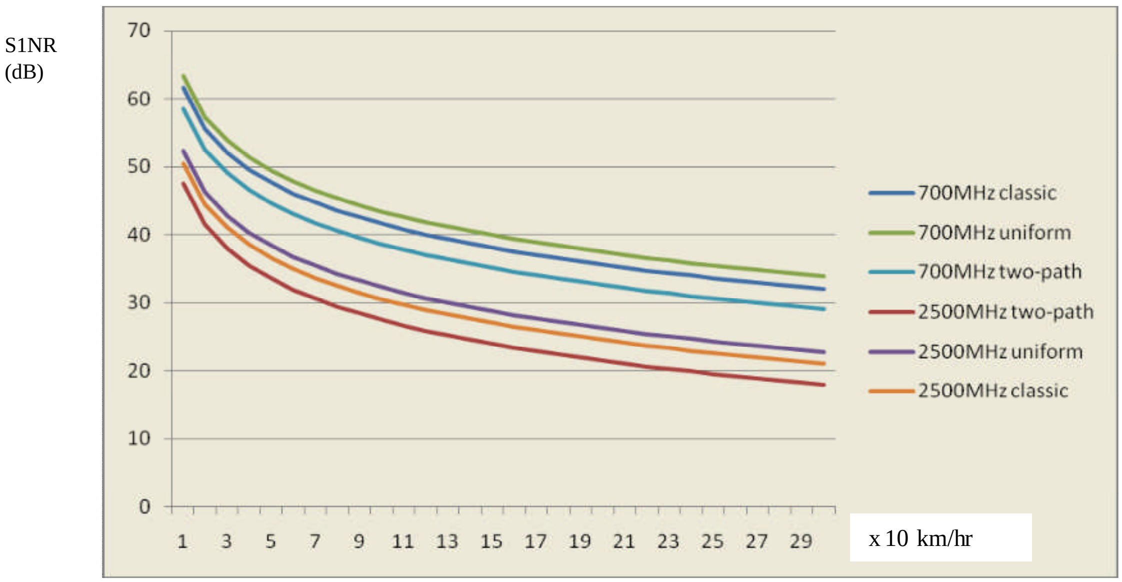


Figure 6: Doppler Spreading Impact on SINR

It is clear that the inter-carrier interference for the 700 MHz OFDMA system will be approximately 11 dB better than the 2500 MHz system on the average. Considering that the required SINR for Convolutional Turbo Code (CTC) 64QAM ¾ at the Bit-to-Error-Rate (BER) of 10^{-6} is 20 dB in an AWGN channel, the 2500 MHz system would be difficult to use 64QAM ¾ scheme when the velocity is high, such as >250 km/hr. Obviously, the 700 MHz system would exhibit better performance in high velocity applications.

5.0 Coverage and Capacity Simulations

System level simulations are done to provide a comparison of coverage, interference, and channel capacity performance between 700 MHz and 2500 MHz WiMAX Systems. The simulation time is about 100 seconds, which contains 20,000 5 ms frames. Also, the wrap around model is used in the simulation, thus the effective simulation period would be much longer. Table 8 shows the key parameters used for these simulations.

Table 8: Key Simulation Parameters

Key Simulation Parameters		
Parameter	**Value**	**Note**
FFT Size	1024	
Bandwidth	10 MHz	
Carrier Frequency	700 MHz, 2500 MHz	
Permutation	PUSC	
CP Size	1/8	
Duplexing	TDD	
DL:UL	2:1	
Modulation	QPSK1/2, QPSK ¾, 16QAM1/2, 16QAM3/4, 64QAM1/2, 64QAM2/3, 64QAM3/4	
BS Tower HAAT (m)	32 m	
CPE or Mobile Height (m)	1.5 m	
Building Loss(dB)	12.8 dB	
Body Loss(dB)	0 dB	
BS MAX TX Power (Watt)	10 Watt	
CPE TX Power (Watt)	0.2 Watt	
BS Antenna Gain (dBi)	15 dB	
CPE Antenna Gain (dBi)	-1 dB	
BS Rx Implementation loss including NF (dB)	5 dB	
CPE Rx Implementation loss including NF (dB)	7 dB	
Fading Channel Model	ITU Pedestrian B	
Velocity for Users	3 km/hr	
Packet Scheduler	PF (Proportional Fair)	
Traffic Model	Full Buffer	
Cell deployment	3 sector cell with segmentation; Cell radius = 2 km;	10 users per sector
Number of tiers	2	7 cells (3*7=21 sectors) , Wrap around model
Path loss channel model	COST 231	

Key Simulation Parameters		
Parameter	**Value**	**Note**
Simulation time	20,000 frames	5x20,000 ms = 100 sec Since the wrap around model is used, the effective simulation period would be 7x100s.

5.1 Simulation Results for Pedestrian B Channel with 3 km/hr Velocity

5.1.1 Average Interference Margin

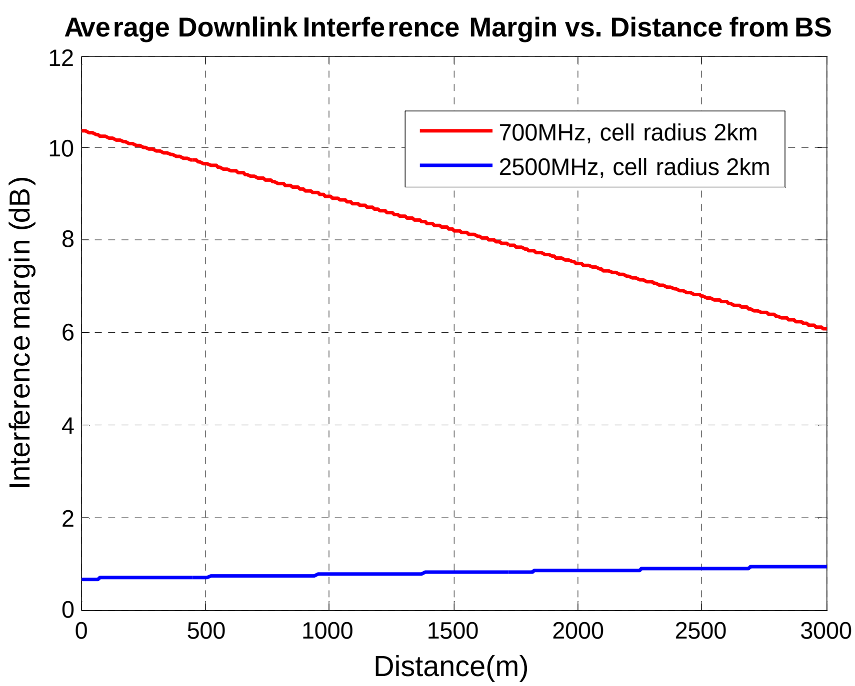


Figure 7: Downlink Interference Margin

Figure 7 shows the average downlink interference margin, which is defined as the difference between SNR and SINR in the simulation. To obtain the averaged trend, we plot the linear fitting lines, which show that the 700 MHz systems have a higher interference margin because the interference signal experiences the lower path loss.

Figure 8 further illustrates the data subcarrier CINR vs. distance from the BS. It is clear that the 700 MHz systems have better CINR comparing to the 2500 MHz systems.

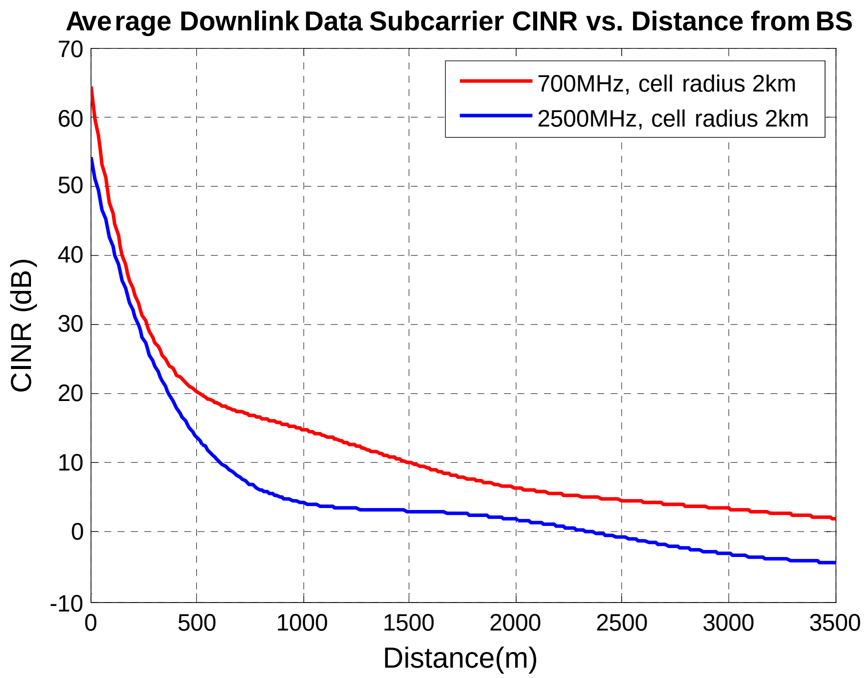


Figure 8: Downlink Data Subcarrier CINR

5.1.2 Coverage Comparison Based on Data CDF Curves

Figure 9 shows the Cumulative Distribution Function (CDF) curves of the received DL data subcarrier CINR. It is observed that 90% of MSs have a DL data subcarrier CINR greater than -4 dB in a 2500 MHz system, while, in the 700 MHz system, 90% of MSs have a DL data subcarrier CINR greater than 0 dB, which indicates the 700 MHz system could achieve greater coverage. (e.g. assume the minimum CINR requirement for maintaining a connection is 0 dB, then 90% of MSs would have coverage in a 700 MHz system, while only 72% MSs would have coverage in a 2500 MHz system).

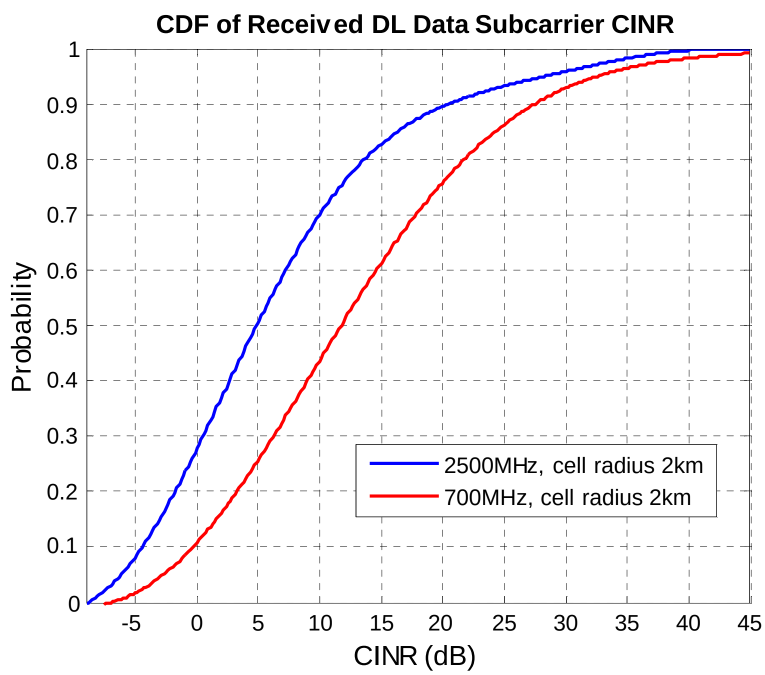


Figure 9: CDF of Received DL Data Subcarrier CINR

5.1.3 Modulation & Coding Scheme Utilization Comparison

Figure 10 shows the probability of DL MCS (Modulation and coding scheme) usage from QPSK ½ to 64QAM ¾. It shows that the higher order modulation scheme would be more likely in the 700 MHz systems thus resulting in higher spectral efficiency. In the simulation, the MCS is chosen based on the required CINR at a PER (Packet Error Rate) of 10%.

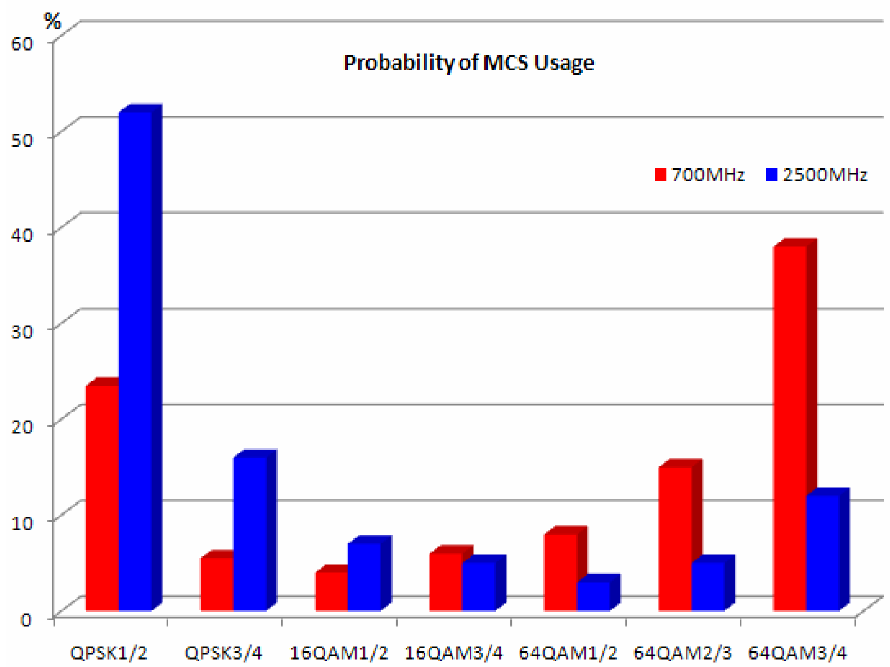
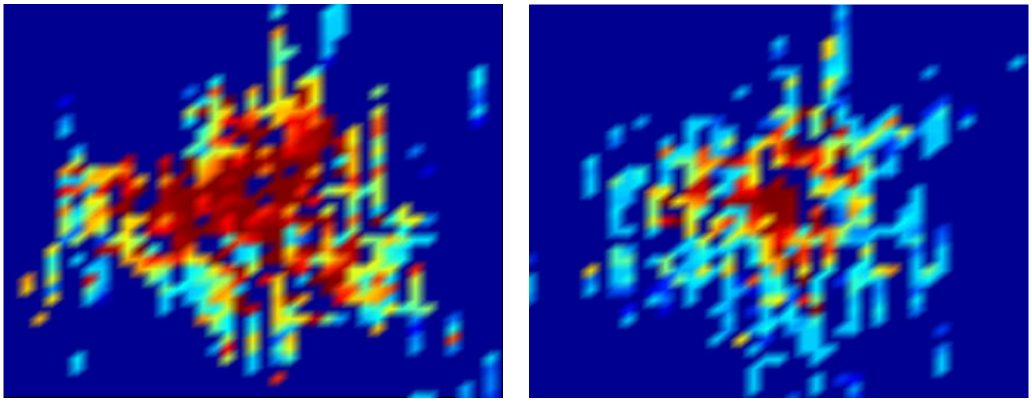


Figure 10: Probability of Channel Modulation Scheme

5.1.4 User Throughput Distribution

Figure 11 compares the user throughput distribution for a 2 km radius cell between 700 MHz (Fig. 11a) and 2500 MHz (Fig. 11b). Warmer color (red) indicates higher user throughput. It can be observed that, for a 2 km radius cell[12], the red zone coverage is greater in the 700 MHz than that of 2500 MHz, thus illustrating that the 700 MHz system has both higher user throughput and better area coverage.

[12] It should be noted that 2 km radius is close to the maximum achievable range for an outdoor MS at 2500 MHz. If a smaller radius were used for this simulation the differences in user throughput between 700 MHz and 2500 MHz would not be as great as interference limitations would tend to shrink the red zone in the 700 MHz case.



a. 700 MHz, 2 km cell radius b. 2.5 GHz, 2 km cell radius

Figure 11: Higher Order Modulation Coverage

6.0 Metropolitan Area Deployment Comparisons

In this section we look at various deployment scenarios to provide additional insights as to how these frequency bands compare in a typical WMAN. For a deployment comparison, a hypothetical mid-sized metropolitan area is assumed having a total population of approximately 1.75 million people over a demographically varied area of 1,500 km^2. The demographic regions for this assumed metropolitan area are broken down as shown in Table 9. The table also provides some market and usage assumptions to estimate average downlink (DL) data density requirements. For any broadband wireless access deployment it is important to plan the network to meet the projected peak busy hour (PBH) demand. This is a function of population density, market penetration, and the desired performance during the period when the network is most heavily loaded [Ref. 5].

In addition to different population densities each of the demographic regions will have region-specific propagation conditions due to the varied number of buildings, building heights, and terrain differences. These variations result in varied range estimates as predicted by the Hata and COST 231 models. The range predictions for these regions are summarized in Figure 12, assuming indoor mobile stations.

Table 9: Estimating Data Density Requirements

	Dense Urban	Urban	Suburban	Rural/Open Space
Area	100 km^2	200 km^2	500 km^2	700 km^2
Population	800,000	500,000	400,000	50,000
Addressable Market	70%	70%	75%	75%
Population Growth	1%/yr	1%/yr	2%/yr	2.5%/yr
Net Customers in Year 10	76,000	48,000	39,000	5,000
Estimated PBH Activity	1 out of 5	1 out of 6	1 out of 7	1 out of 7
DL Duty Cycle	25%			
Desired DL Data Rate During PBH	30 kilobytes per second per user for "casual" subscribers to 75 kilobytes per second for "professional/high-end" subscribers[13]			
Required Data Density in Year 10	~20 $Mbps/km^2$	~5.5 $Mbps/km^2$	~1.5 $Mbps/km^2$	~0.1 $Mbps/km^2$

[13] The values in the table are selected for illustrative purposes. In practice an operator will determine the appropriate value for PBH performance based on the offered services and customer expectations and may result in data density requirements higher or lower than those shown.

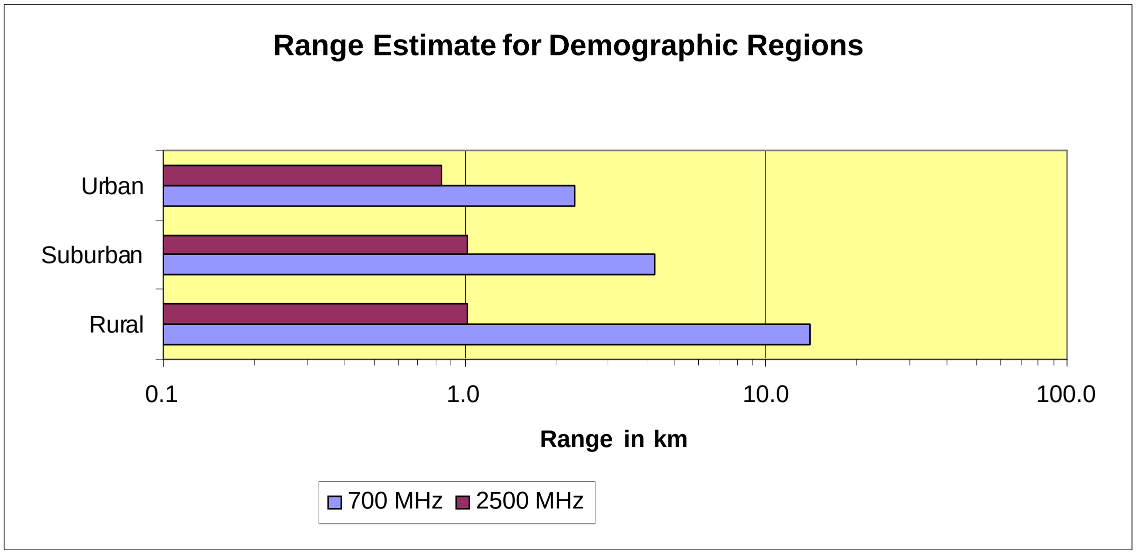


Figure 12: Range Predictions for Indoor Mobile Station

Figure 13 provides a view of the data density at the predicted maximum range that would result for each frequency band assuming one 10 MHz bandwidth channel per base station, and how it compares with the required downlink data density shown in Table 9. The base station antenna configuration for this comparison is assumed to be (1x2) SIMO for both frequency bands. The channel capacity is based on simulations assuming a mixed usage model [Ref. 3] with a 3:1[14] DL to UL traffic ratio. As expected, the dense urban deployment is constrained by capacity rather than range regardless of the frequency band. Due to its range capability, the 700 MHz solution, when deployed to utilize its maximum range, is capacity constrained not only in the urban and suburban regions but also in the rural region since at full range in these areas the resulting DL data density is only 0.01 $Mbps/km^2$ while the desired DL data density is 0.1 $Mbps/km^2$.

[14] With expected traffic demand trending towards data versus voice, downlink traffic is expected to be dominant for most users.

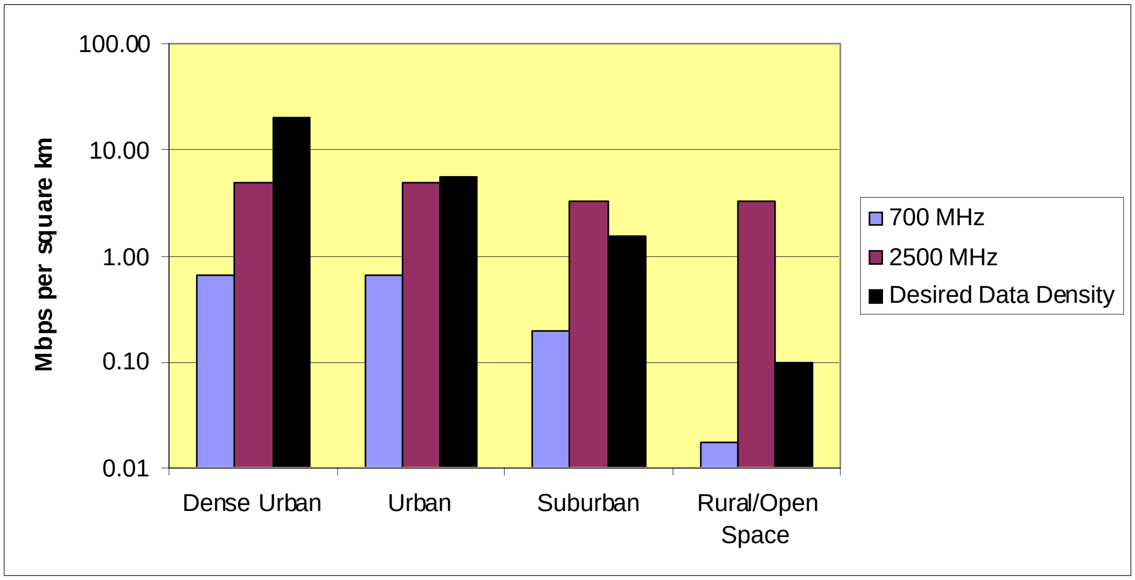


Figure 13: DL Data Density for Indoor Mobile Stations vs. Data Density Requirements

Several deployment scenarios are used to assess the deployment differences between the two spectrum choices. Cases 1, 2, and 3 assume spectrum availability of 6 MHz, 10 MHz and 22 MHz respectively in the 700 MHz band to be consistent with the license assignments in the Lower and Upper 700 MHz Band in the United States. Case 4 uses the same amount of spectrum as Case 3 at 2500 MHz while Case 5 assumes the availability of 30 MHz of spectrum in the 2500 band. For each case, TDD is assumed with a frequency reuse factor of 1, and the channel BW and number of channels per base station are selected to be the maximum supportable by the available spectrum. The assumptions and required number of base stations for the metropolitan area deployment are summarized in Table 10. The results clearly show the advantage, from a BS deployment perspective, of having more available spectrum. Having a metropolitan area-wide 30 MHz license in the 2500 MHz band enables a deployment with fewer base stations[15] than having only 6 or 10 MHz of spectrum in the 700 MHz band. On the other hand with 22 MHz in the 700 MHz band the lower band solution proves to be more BS-efficient than 2500 MHz with (1x2) SIMO base stations. For a more complete business case analysis

[15] Although there may be some WiMAX equipment cost differences between the three bands the base station infrastructure cost will be dominant in a typical deployment. These costs include site acquisition, towers, equipment enclosures, backhaul, etc. Any deployment cost savings due to the requirement for fewer base stations will be offset by the cost of acquiring a greater amount of spectrum.

differences in spectrum cost must also be taken into account, especially in markets such as the US where spectrum licenses are generally awarded by an auction process.

Since beamforming solutions will also be prevalent in the higher bands it is important to also take into account the impact of beamforming on the base station count in the 2500 MHz band. By deploying beamforming in the higher density urban regions, the resulting 40 to 50% increase in DL channel capacity will result in a reduction in the number of required base stations in those regions [Ref. 5]. Under these conditions, the BS count is comparable between the two bands. The total metro area base station deployment requirements are summarized for this scenario in the last line in Table 10.

Table 10: Deployment Scenarios and Summary for Comparative Analysis

	Case 1	Case 2	Case 3	Case 4	Case 5
Frequency Band	700 MHz			2500 MHz	
Base Station	3-Sector, 1 Tx Antenna and 2 Rx Antennas (1x2 SIMO)				
Available Spectrum	6 MHz	10 or 12 MHz	22 MHz	20 MHz	30 MHz
Channel BW	5 MHz	10 MHz		10 MHz	
Duplex	Time Division Duplex (TDD)				
DL to UL Ratio	3:1				
Reuse Factor	(c, 1, 3)				
Total BS requirements with (1x2) SIMO	**1191**	**596**	**299**	**404**	**350**
Total BS requirements with BF in the 2500 MHz Band	**n/a**	**n/a**	**n/a**	**314**	**285**

Figure 14 summarizes the base station deployment requirements for each of the demographic regions. As shown in the figure, 700 MHz does have a deployment advantage, even with limited spectrum availability, in the lower population density regions. Despite still being capacity-constrained, the range advantage of 700 MHz does come into play in reducing the number of base stations required to cover these regions.

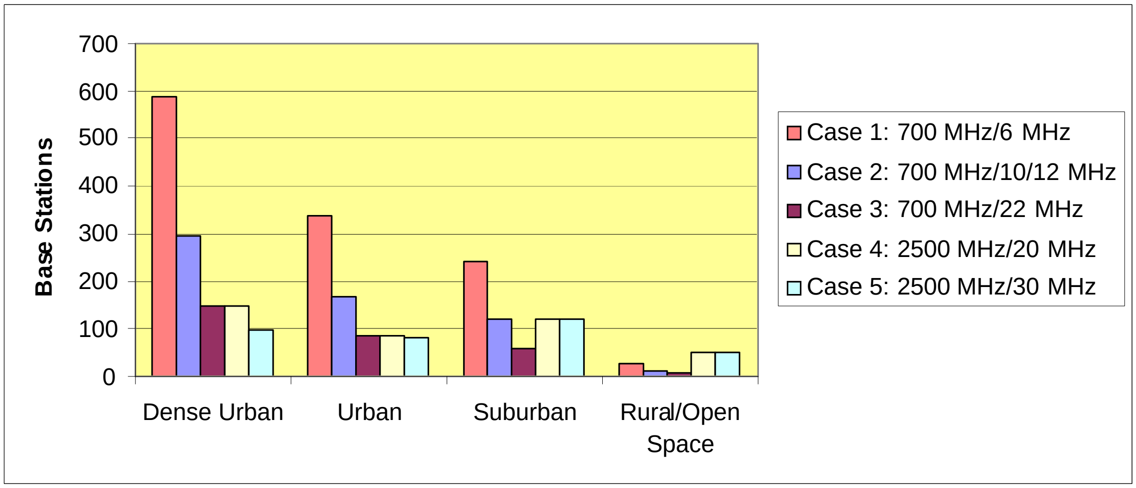


Figure 14: Metropolitan Area Base Station Deployment Breakdown

6.1 TDD or FDD

Since they consist of two paired channels, all but two of the licenses allocated in the US lower and upper 700 MHz band will support either Frequency Division Duplex (FDD) or Time Division Duplex (TDD). Further, since the FCC rules allow for flexible use in this band[16], operators holding these licenses have an additional degree of deployment flexibility. Generally the attributes of TDD make it the preferred duplexing approach. This is especially true when the traffic is expected to be asymmetric and spectrum is limited [Ref. 3]. With asymmetric traffic, one of the channels will be underutilized with FDD whereas TDD can adapt DL and UL frames to match actual traffic conditions. Table 11 provides a comparison of the attributes for the two duplexing approaches when working with a spectrum allocation comprising paired channels.

[16] From time to time regulators will establish rules for bands or portions of bands stipulating either FDD or TDD operation but not both.

Table 11: Comparative Attributes of TDD and FDD

TDD	FDD
• Adaptive DL to UL ratio for better spectral efficiency with asymmetric traffic • Channel reciprocity for easy support of closed loop advanced antenna systems • Greater flexibility with frequency reuse schemes with two independent paired channels • Easy adaptation to varied global spectrum assignments • Simple transceiver design	• Dedicated DL and dedicated UL channel • Single transceiver to cover two paired channels • Does not require Tx-Rx transition gap with full duplex FDD[17] mobile stations • More flexibility in dealing with interference issues

Figure 15 provides a deployment comparison for TDD relative to FDD for the same metropolitan area used in the previous section. This analysis illustrates the TDD advantage for DL to UL traffic asymmetries ranging from 3:2 to 3:1. If on the other hand, traffic is projected to be symmetric or nearly so, FDD, with its more flexible interference control may prove to be a better choice. This will be an important consideration in the 700 MHz band with respect to coexistence with high power TV and public safety systems.

[17] Half Duplex FDD (HD-FDD) at either the BS or the mobile station does require a transition gap between UL and DL transmissions

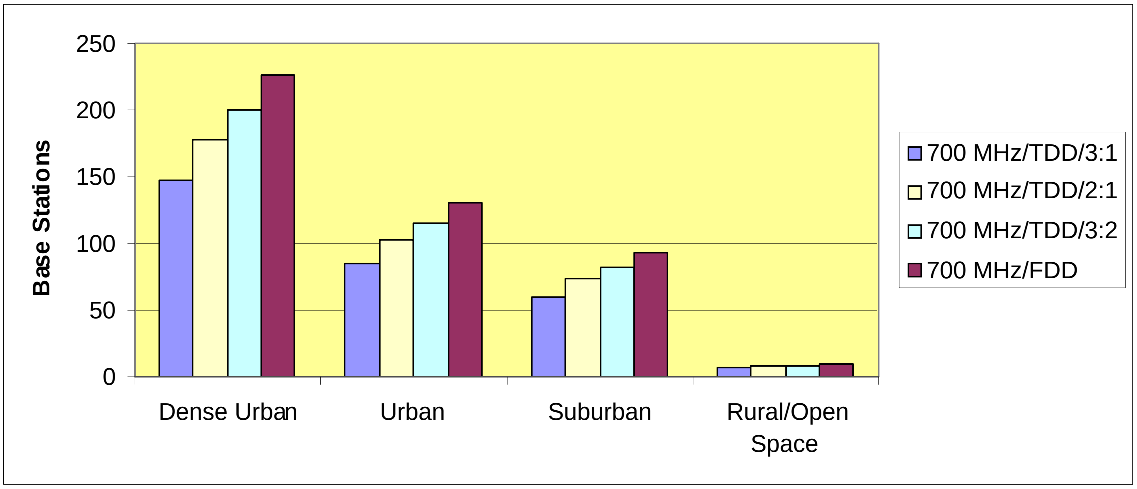


Figure 15: FDD vs. TDD for 700 MHz with 2 x 10 MHz Paired Channels and Varied Traffic Asymmetry

6.2 Other Mobile WiMAX™ Usage Models

In assessing the business opportunity for a Mobile WiMAX™ deployment an operator may also want to consider alternative usage models. The previous analysis assumed mobile handheld WiMAX devices and indoor operation. An operator can also elect to limit customers to outdoor operation thus eliminating the building penetration loss or address a market that only includes fixed roof-mounted outdoor subscriber antennas. The latter usage model eliminates building penetration loss and also adds the benefit of an outdoor mounted subscriber station with a high gain directional antenna. When considering this usage model however, an operator must also take into account the added expense of a truck-roll and professional installation for the fixed outdoor subscriber terminals. Either of these options will increase the range capability in any of the bands being considered with the fixed outdoor model providing a 3.5 to 5 times range advantage over an indoor mobile station. The range estimates relative to the indoor mobile station usage model for the 700 MHz band is summarized in Figure 16.

Although these alternative usage models reduce the addressable market, they can still offer a viable business case for the operator due to the lower initial infrastructure cost to cover the geographical area of interest. As a market entry strategy, an operator may choose this approach to gain a time-to-market advantage and later deploy additional base stations to expand the addressable market to include other usage models.

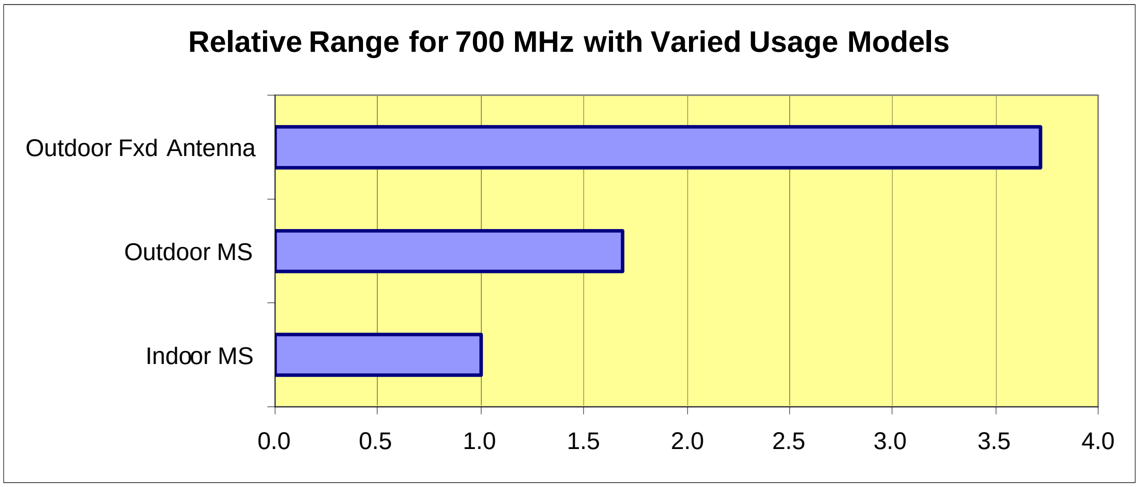


Figure 16: Relative Range for Varied Usage Models

6.3 The 700 MHz Advantage in Rural Deployments

The previous analysis clearly shows the advantage of a WiMAX deployment in the 700 MHz band in lower population density regions. In these areas the range capability is more effectively utilized whereas in the more heavily populated areas, base station channel capacity is the more important metric in determining base station deployment requirements. Looking at the results of the previous analysis for the suburban and rural demographic regions in more detail (Table 12) helps to better quantify the deployment benefits of 700 MHz in these lower population density regions. The findings in this analysis would of course, also be applicable for other bands in the UHF frequency range.

Table 12: Base Station Deployment Requirements for Suburban and Rural

	Case 1	Case 2	Case 3	Case 4	Case 5
Band	700 MHz			2500 MHz	
Available Spectrum	6 MHz	10 or 12 MHz	20 MHz	20 MHz	30 MHz
Channel BW	5 MHz		10 MHz	10 MHz	
Required Suburban BS for DL DD = 1.5 Mbps/km^2	240	120	60	122	122

	Case 1	Case 2	Case 3	Case 4	Case 5
Required Rural BS for DL DD = 0.1 Mbps/km^2	26	13	7	50	50

Although the demographic assumptions used for this specific analysis result in a capacity-constrained deployment for 700 MHz in the rural region there will certainly be areas in which the demographic factors result in a significantly lower data density requirement. Deployments in these regions will enable a greater use of the WiMAX range capability in the 700 MHz band.

Flat open terrain characteristics, often encountered in rural environments, can also enable line-of-sight to many customers to further increase the range potential. True LOS at 700 MHz however, may be difficult to achieve due to the size of the 1st Fresnel zone. This is illustrated in Figure 17 for a 10 km path length assuming a BS antenna height of 32 meters and a subscriber station (SS) height of 8 meters. The 8 meter SS height is consistent with a fixed roof-mounted subscriber antenna. Even with no obstacles above ground level, the BS and SS antenna heights would have to be increased significantly to clear the 1st Fresnel zone of obstacles or reflective surfaces to enable true LOS in the 700 MHz band. Obstacles within the 1st Fresnel zone will result in excess loss due to signal diffraction or reflected signals arriving out of phase at the receiver. Nevertheless, even though true LOS may not be readily achievable, the non-LOS and near-LOS range at 700 MHz with favorable terrain characteristics and strategic antenna tower locations should be well over 10 km with an indoor MS and over 30 km[18] with fixed outdoor mounted subscriber antennas. The data density of course would be low but may be quite sufficient for baseline services in sparsely populated areas.

[18] TDD and HD-FDD will require a larger Transmit/Receive Transition gap at these distances resulting in a nominal increase in overhead.

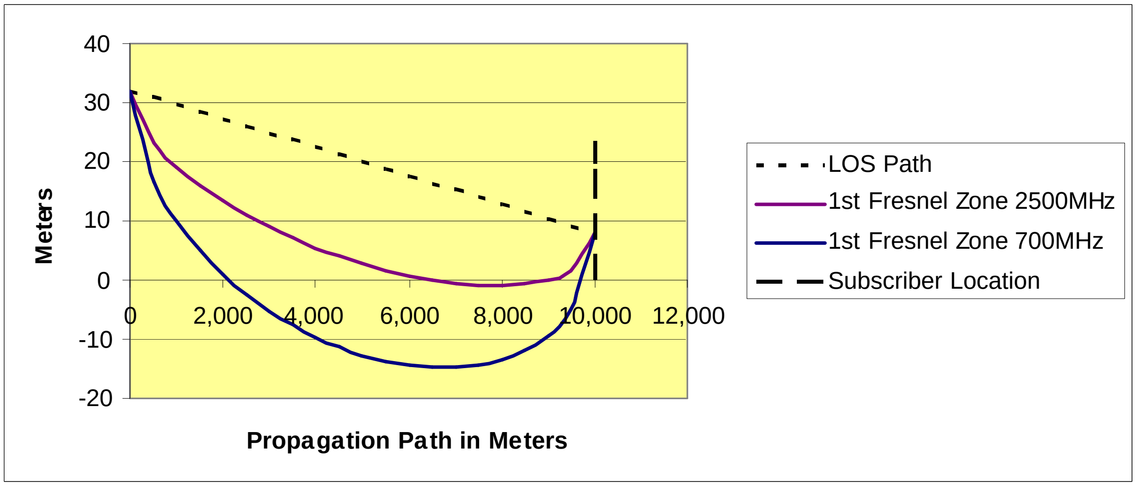


Figure 17: Fresnel Zone Comparison

6.0 Coexistence Considerations

As was mentioned in the Introduction section as well as in Section 2 where US 700 MHz spectrum was discussed; in general sub 1 GHz spectrum is shared by various wireless applications such as mobile TV, Digital TV, public safety and mobile broadband. Therefore, with the exception of some greenfield scenarios where coexistence is not an issue, detailed interference analysis and sharing studies are required to develop recommendations and guidelines on frequency planning, duplexing modes, directionality, channel bandwidth and guard bands, and minimum receive and transmit radio requirements.

More specifically, coexistence considerations and interference analysis are performed to

a) determine the interference impact of systems operating in adjacent channels such as high power Digital/Mobile TV broadcast on Mobile WiMAX system as the victim and

b) determine the interference impact of Mobile WiMAX system as the aggressor on adjacent systems such as other unsynchronized mobile broadband technologies or public safety networks.

Depending on the scenario under study, a combination of recommendations on frequency planning and inter technology coordination, duplexing mode (TDD or FDD) with proper UL/DL assignment, collocation options, guard band considerations, receive and transmit radio requirements, and proper site engineering designs are needed to optimally address coexistence requirements.

7.0 Conclusion

There is global interest in allocating portions of the spectrum between 470 MHz and 862 MHz for broadband wireless services. In recognition of the value this spectrum offers for WiMAX deployments, the WiMAX Forum® is developing TDD and FDD system profiles for this general band to address market opportunities globally.

Compared to Fixed or Mobile WiMAX solutions in the 2500 MHz frequency band, 700 MHz deployments provide a considerable range benefit. More specifically, in the case that at least 20 MHz of spectrum is available; the range benefit of 700 MHz band translates to a deployment advantage even in urban and suburban regions in an interference limited scenario. On the other hand, there is a significant deployment advantage with 700 MHz deployments in the lower population density regions (rural) even when, as little as 6 MHz of spectrum is available.

Although many spectrum allocations will support either Time Division or Frequency Division Duplexing, the asymmetric traffic expected in broadband data-oriented networks will generally favor WiMAX solutions based on TDD. This enables optimal spectral efficiency resulting in higher DL base station capacity and a more cost-effective deployment with fewer base stations. In some regions however, FDD may prove to be a better approach to effectively address interference issues due to coexistence with high power Digital TV, high power Mobile TV and Public Safety systems. This can be especially important in the US 700 MHz band.

The WiMAX Forum believes that the 700 MHz and other bands in the UHF range will be very important bands for WiMAX deployments. Even with limited spectrum assignments, WiMAX in the UHF band can provide a cost-effective solution for providing services to residents in areas that would be uneconomical to serve with conventional wire-line or other wireless access technologies. WiMAX deployments in this band can be expected to play a key role in helping to bridge the digital divide.

Acronyms

AAS	Adaptive Antenna System
AWGN	Additive White Gaussian Noise
BS	Base Station
BW	Bandwidth
CDF	Cumulative Distribution Function
CINR	Carrier to Interference + Noise Ratio
COST	COoperation in Scientific and Technical research
CP	Cyclic Prefix
CTC	Convolutional Turbo Code
DD	Data Density
DL	Down Link
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
GBU	General Bad Urban
GHT	General Hilly Terrain
GRA	General Rural Area
GTU	General Typical Urban
GSM	Global Standard for Mobile communications
HAAT	Height Above Average Terrain
HD-FDD	Half Duplex Frequency Division Duplex
IMT	International Mobile Telecommunications
ITU	International Telecommunications Union
LOS	Line of Sight
MAP	Media Access Protocol
MCS	Modulation Coding Scheme

MIMO	Multiple Input Multiple Output
MS	Mobile Station
PBH	Peak Busy Hour
PUSC	Partially Used Sub-Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SINR	Signal to Interference + Noise Ratio
SNR	Signal to Noise Ratio
SS	Subscriber Station
TDD	Time Division Duplex
UHF	Ultra High Frequency
UL	Up Link
UMTS	Universal Mobile Telephone System
WRC	World Radio Conference
WiMAX	Worldwide Interoperability for Microwave Access

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