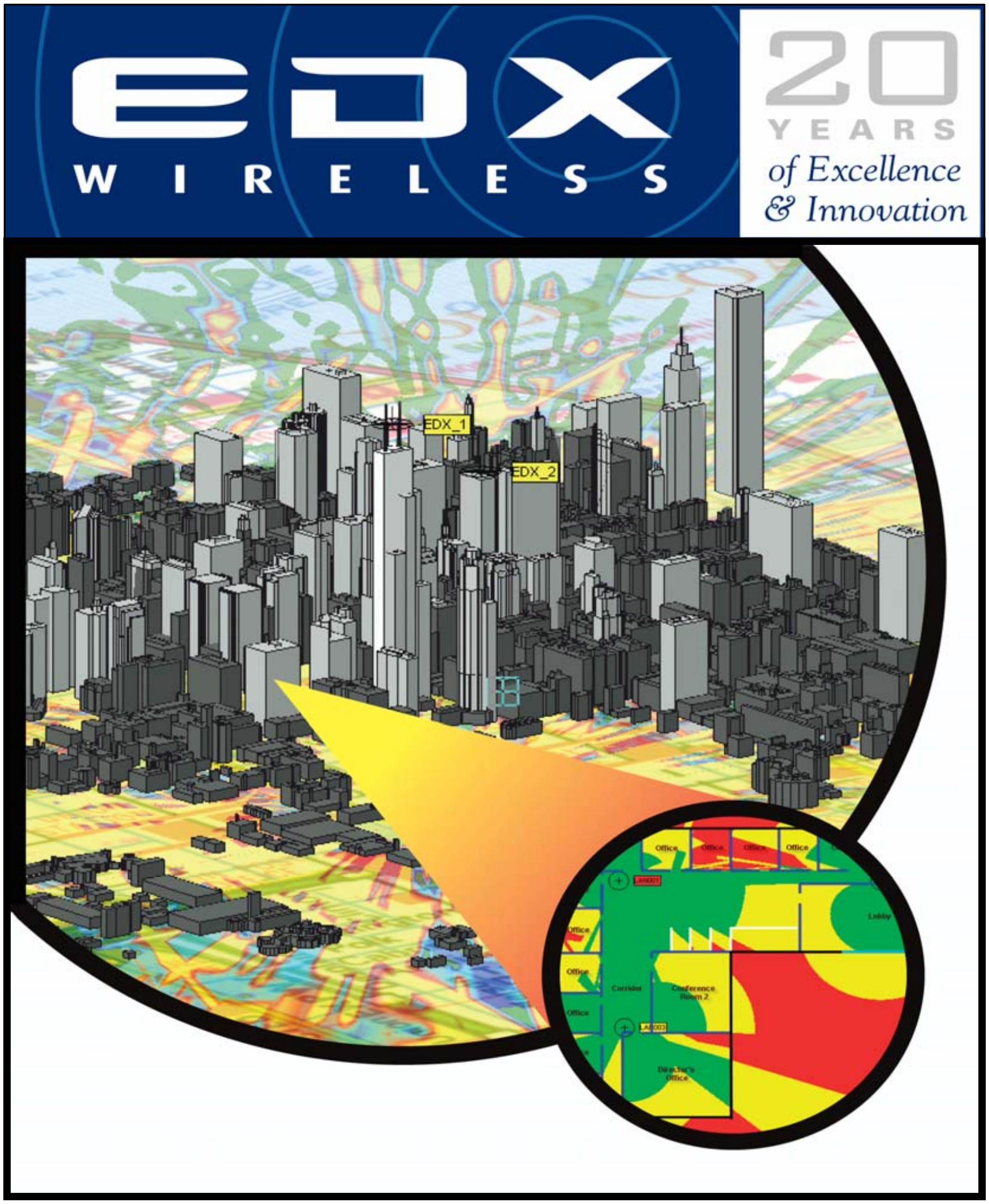
*Technology White Paper*

# WiMAX System Performance Studies

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# WiMAX System Performance Studies

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There are several ways of quantifying the performance of a broadband system. This paper will address two pressing issues of WiMAX system design which are interference and capacity analysis. This paper considers the factors affecting these two performance measures and discusses how to properly take these effects into account. The manuscript starts with an overview of WiMAX with focus on the relevant aspects in the standard that are necessary for these studies. The sections of interference and capacity analysis follow. The technical details of the 802.16e standard presented herein are based on the reports [1] and [2].

## Overview of WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is based on the IEEE 802.16 standard for Metropolitan Area Networks (MAN). Its goal is to deliver wireless broadband access to customers using base stations with coverage distances in the order of miles. Originally, the standard considered only fixed and nomadic links (802.16-2004) that could be used for “last mile” connectivity providing an alternate to T1 and DSL wired lines or as a backhaul for cellular or Wi-Fi networks. In order to address mobile subscribers, WiMAX was expanded to include portable devices (802.16e) such as personal digital assistants (PDAs), laptops, or phones. Supporting mobility required including provisions for roaming and inter-cell handoff and incorporating more flexibility into the standard to sustain multiple users demanding various types of services. In mobile WiMAX, the system’s resources are dynamically allocated to deliver high data rates seamlessly to terminals traveling at vehicular speeds.

The frequencies allocated for WiMAX span the 2-66 GHz range. The exact frequency of operation for any given system is dependent on the propagation conditions that are encountered during its use. The frequencies higher than 10 GHz are practical only for fixed line-of-sight (LOS) type services. Non-line of sight (NLOS) communications perform better when the frequencies of operation are kept under 10 GHz. The frequencies below 6 GHz have better propagation properties and are better suited for mobile communications because they most likely guarantee service to all the niches of the coverage area.

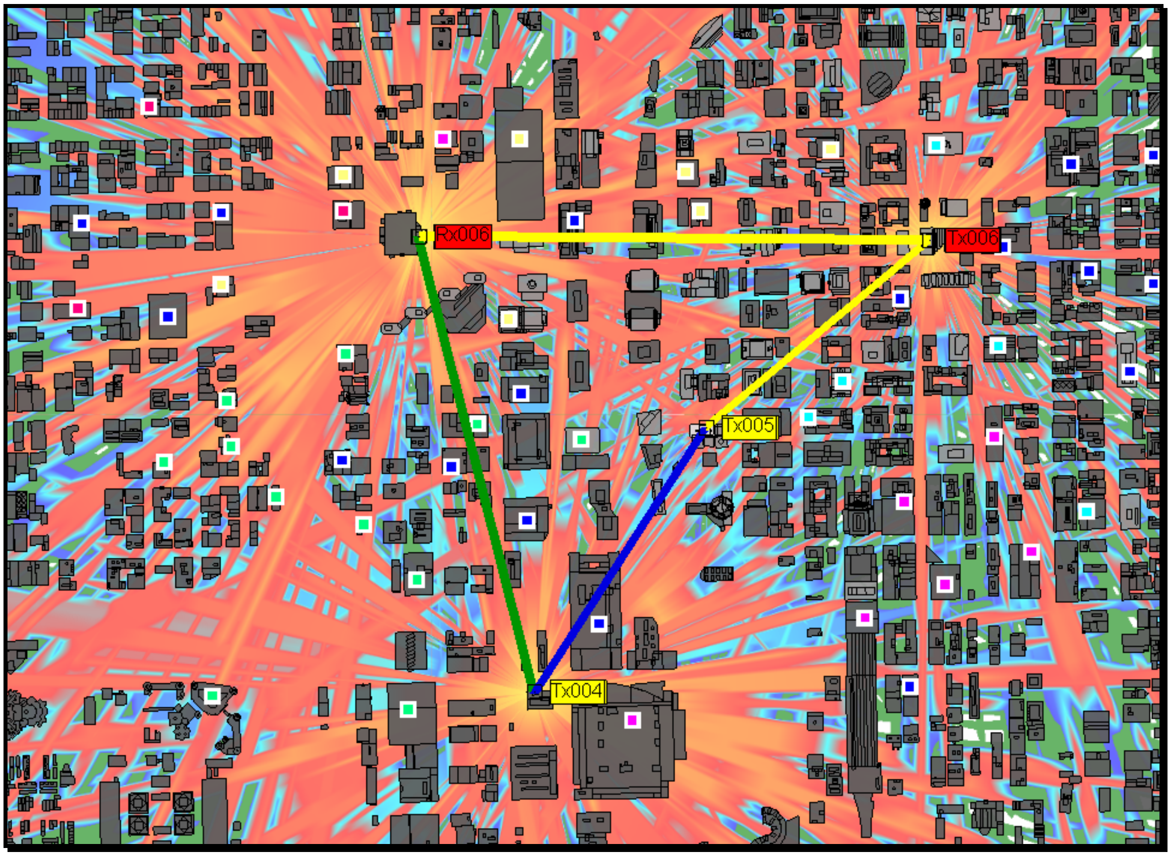


**Figure 1 WiMAX Network including Backhaul, Fixed Customer Premise Equipment, and Mobile/Nomadic Coverage Area produced in EDX® SignalPro®**

WiMAX is a part of the evolution from voice-only wireless communications systems to ones that provide additional services like web browsing, streaming media, gaming, instant messaging, and other content. Being able to deliver a wide variety of services also requires a delivery system that is flexible and can efficiently allocate system resources. The 802.16 standard offers adjustable data rate to and from each user while maintaining the required quality of service (QoS). Certain applications require higher error resilience and latency requirements that directly factor into the QoS. Real-time services, for example, have strict latency tolerances. The system resources are allocated and scheduled dynamically by the base station on a frame by frame basis to keep up with the need of the users in the environment.

To approach the theoretical capacity of the system, WiMAX uses a combination of adaptive modulation schemes and coding ranging from 1/2 rate QPSK to 5/6 rate 64QAM. The amount of error correction applied to each transmission is adjustable and can be changed depending on the required QoS and based on the reliability of the link between each user and the base station. The higher modulation constellations offer a larger throughput per frequency-time slot but not all users receive adequate signal levels to reliably decode all modulation types. Users that are close to the base station that exhibit good propagation and interference characteristics are assigned with higher modulation constellations to minimize the use of system resources. At the other end, users that are in less favorable areas use the lower order modulations for communications to ensure data is received and decoded correctly at the expense of additional frequency/time slots for the same amount of throughput. Assigning modulations based on the link conditions increases the overall capacity of the system. The use of variable or adaptive modulations to increase capacity is a trend also observed in other recently developed mobile phone and data standards like WCDMA.

Provisions have been made to include advanced antenna systems in the WiMAX standard to improve throughput and link reliability. 802.16 allows for several antennas to be used at the transmitter and the receiver to create a Multiple-Input Multiple-Output (MIMO) system. Techniques such as space-time coding (STC) can be used to reduce the occurrence of deep fades in the signal level across the transmission band. An increase in throughput can be achieved by spatially multiplexing (SM) different data streams on each of the transmit antenna elements at the same time on the same frequency. A multiple antenna receiver (with at least the same number of elements as unique transmitted data streams) could separate these signals resulting in an increase in data rate proportional to the number of antennas at the receiver. Antenna beam forming is a third supported option in the standard in which pattern maximas are electronically steered in the direction of the desired source while nulls are placed in the direction of the interfering sources. Beam forming can be performed on transmit or receive as long as more than one antenna is available for spatial processing. The number and the degree by which interferers can be rejected is dependent on the number of antennas at the terminal. Beam forming is useful in improving coverage as well as reducing interference levels and has the potential of improving throughput by reusing frequency-time slots through Spatial Division Multiple Access (SDMA) techniques.

The extensive flexibility introduced into the WiMAX standard also makes it harder to model correctly. In the following sections, the challenges of modeling the interference and capacity in a WiMAX system will be examined.

## Interference in WiMAX Systems

Before addressing the interference of a deployed WiMAX system it is best to review how the sub-channels are divided among users in the uplink (UL) and downlink (DL). More specifically, the Time Division Duplex (TDD) transmission scheme of the 802.16e standard will be considered. In the initial working group release, the standard supports 5 and 10 MHz bandwidth allocations for each radio frequency channel. The available channel bandwidth is made up of sub-carriers each of which can be modulated individually with information. WiMAX uses Orthogonal Frequency Division Multiple Access (OFDMA) to assign sub-carriers to different users. The number of sub-carriers available for assignment in the UL and DL are a function of the channel bandwidth, the frame size, and the UL/DL transmit ratio. In mobile WiMAX, the smallest unit of frequency-time allocation available is a slot which contains 48 data sub-carriers. The sub-carriers comprising a slot can be made up of adjacent sub-carriers or can be allocated in a distributed fashion throughout the available carrier space. In general, distributed carrier allocations perform better in mobile environments, while adjacent sub-carriers are better suited for fixed links. The number of slots assigned to a particular user per frame is a function of their data needs.

Channel planning in WiMAX systems can be performed in several ways. Channel allocation is left up to the service providers and is based upon the amount of available spectrum and the density of the users requiring service. When enough bandwidth is at hand, the channels (5 or 10 MHz portions of spectrum) can be allocated and reassigned among the available sectors in such a way as to minimize the co-channel interference at neighboring sites. This procedure corresponds to the traditional form of channel planning where a channel frequency re-use factor (FRF) can be picked to appropriately balance the trade off between spectral efficiency and interference. The interference between sectors operating on the same frequency is typically minimized through the use of directional antennas, sector spacing, and transmit power control in order to reduce the co-channel interference levels experienced by the users in the service area. Lower interference levels result in higher reliabilities and prevent the system from becoming unduly interference limited.

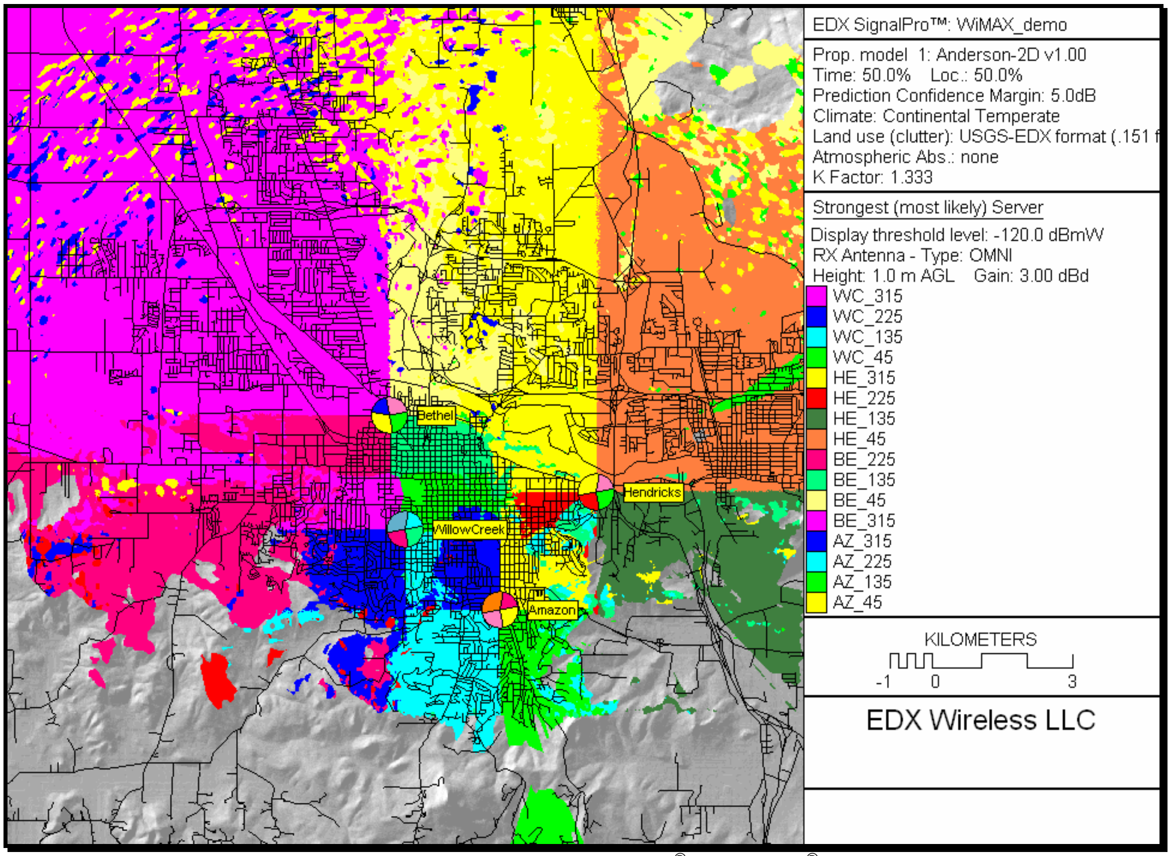


**Figure 2 Most Likely Server Prediction Calculated by EDX® SignalPro®**

For maximum spectral efficiency, however, WiMAX supports a cell frequency re-use factor of one using an assignment algorithm that minimizes the probability that the same sub-carriers are used in adjacent sectors or cells. The problems of using a FRF of one is that the users at the outer edges of the cell could experience poor carrier-to-interference (C/I) ratios since the neighboring cell could potentially be using the same sub-channel assignment (and be comparable in strength) as the signal received from the desired base station. To get around this problem, WiMAX supports dividing up the available sub-channels among the different sectors of the cell creating a virtual higher FRF while maintaining a channel re-use factor of one. This can be done in the 802.16 standard through its built in zone switching capability. This allows the base stations to dynamically change their FRF during a frame by dividing up the transmission time into different FRF segments. It could, for example, connect to the users at the edges of the cell during the first transmission zone using a larger sub-channel frequency re-use factor (to mitigate the high C/I ratios there) and in a second zone service the users close to the base station with all available sub-channels. These options are provided to help systems with a limited amount of channels serve a larger population. Using this technique, however, requires that the neighboring cells synchronize their scheduling and sub-channel allocation tables and therefore requires system wide planning at the sub-carrier level.

When analyzing the performance of a system using any level of FRF or sub-channelization the DL-only and UL-only interference cases are of the most significant concern. During the DL, a mobile experiences interference from neighboring sectors that use the same sub-carriers. This type of analysis requires information on the channel and slot allocations at each sector and, if used, their frame frequency re-use factor zones. Since the cells and sectors are fixed in location and given a set of allotted time-frequency resources, a C/I ratio could be estimated or measured for each point in space the system is deployed. In some cases there will be regions where the received C/I is not sufficient for reliable service. These areas could be identified and, if necessary, additional base stations erected to cover the affected areas. Note that this type of analysis is non-stochastic in nature once the resources are allocated to the different sectors and the locations of the sectors are fixed.

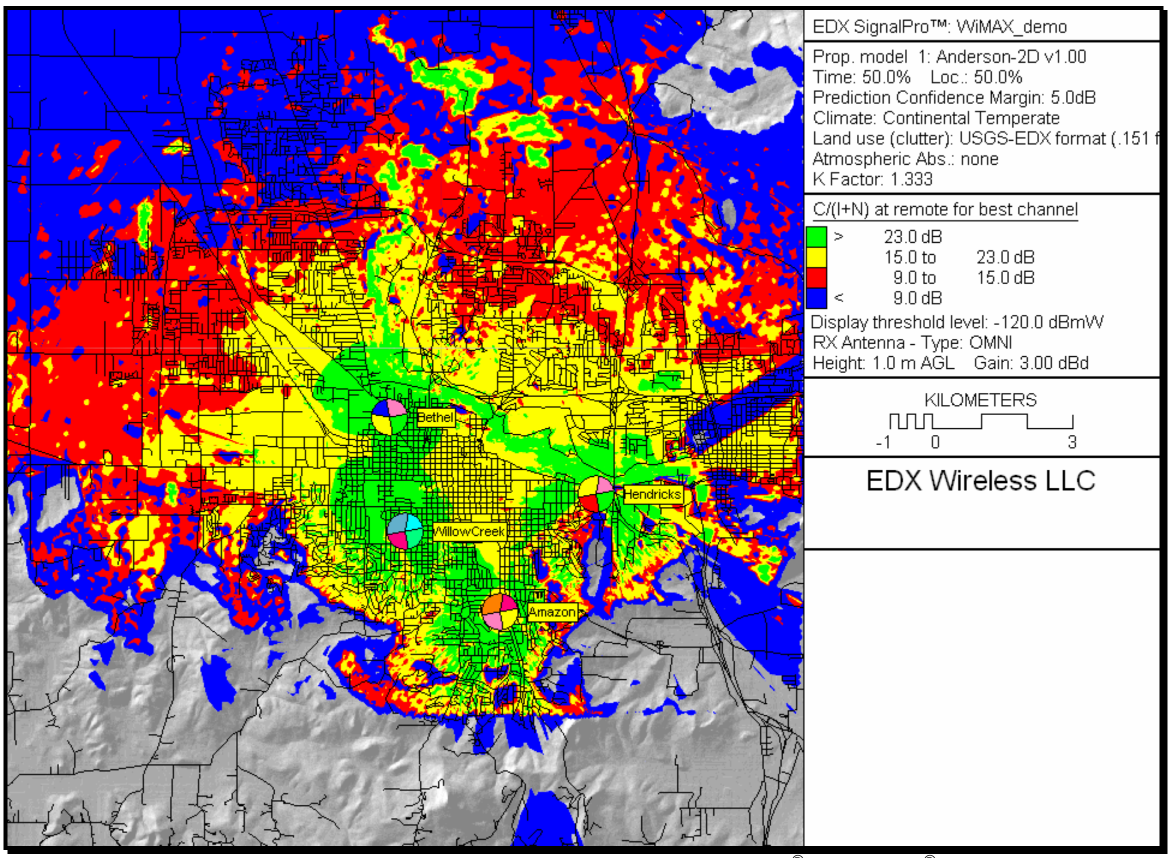


**Figure 3 Downlink C/(I+N) Based on Best Channel Predicted by EDX® SignalPro®**

The UL interference is the interference experienced at the base stations from neighboring mobiles transmitting on the same sub-carriers as the desired user. This second type of interference, however, is stochastic in nature because the mobiles can at any given time be at any location within their cell service area. Each of the possible combinations of interference and desired mobile locations could result in different C/Is at the base stations. Some C/I ratios will occur more frequently than others based on the size, the terrain, as well as the population density of the service areas of both the interfering cells and the cell of interest. The probability distributions of the C/Is at each sector can either be measured or they can be estimated using a prediction tool. Under these circumstances, the performance of a system is better quantified by using reliabilities. For example there might be a requirement that for 90% of the time the C/I ratios experienced at all sectors be above a given threshold. This information can be extracted from the cumulative distribution functions (CDF) of the C/Is at each of the sectors or cells. The figure below graphically represents the CDF of the C/I at a base station where the C/I exceeds 15.6 dB 90% of the time.

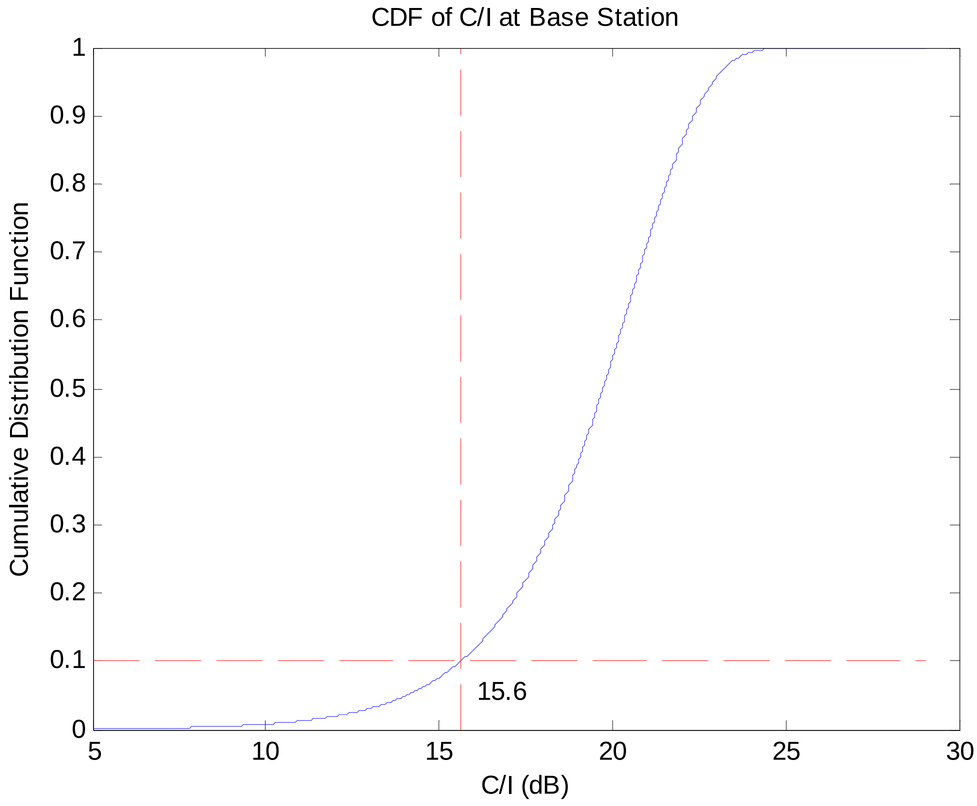


**Figure 4 Cumulative Distribution Function of C/I at Base Station**

There are, however, other interference possibilities in a TDD system. The 802.16 standard allows for each base station to adaptively set the amount of time that the DL and UL transmissions take up in a frame based on demand in that cell or sector. This means that at some point, a base station could be transmitting in the DL while a neighboring cell is in the UL part of the frame. Under these circumstances there are two additional interference scenarios. The DL/UL interference occurs when a mobile is being interfered by a neighboring mobile transmitting on the UL while receiving information on the DL. Similarly, UL/DL interference could occur at the base station while it is receiving transmissions on the UL and a neighboring cell is interfering on the same sub-carriers while in the DL mode. These two additional cases, however, usually happen only over a limited time around the transition band between the UL and DL portions of the frame. At the early adoption of WiMAX, the dynamic allocation of the UL and DL time will most likely not be necessary until the systems get more heavily loaded at which point the added spectral efficiency of partitioning the frame becomes useful.

## Capacity of WiMAX Systems

Another important factor affecting the performance of a WiMAX system is capacity. Capacity determines the amount of data that can be delivered to and from the users. There is a limit on how much data can be reliably sent through any given channel. There are several ways of quantifying the capacity of a wireless system. The traditional way of quantifying capacity is by calculating the data rate per unit bandwidth that can be delivered in a system. An alternate way of looking at capacity is by quantifying the number of users that can be supported by a system, by a sector, or per channel to name a few. A channel can also be defined in several ways; it can be defined as a frequency range, a time slot, or as a frequency-time combo slot.

In a WiMAX system, not all users are of the same type. Browsing the web, emailing, sending/receiving video, downloading files, or using VoIP are all activities that might be performed simultaneously within the population of users. Each of these operations places varying demands on the system. Some might require a higher data rate on download than on upload, while others are about evenly distributed. In order to predict capacity users should be classified based on their demands and how much load they place on the system. For example, streaming video requires considerably more data rate than VOIP so a user receiving video uses up more system resources. At any given time there will be a mixture of services that are being requested and the system is able to support several voice users with the same resources it takes to serve one video user.

An alternate way of looking at capacity is to establish the load that a typical number of users place on a system and then determine at what point the load surpasses each sector's ability to deliver. The number of system resources that are consumed in a given area depends on its demographics and the type of users that are present in that location (factors such as terrain and time of day can also affect demand). Additionally, in the case of WiMAX, the signal levels received at the mobile and base station terminals are important since users that achieve better C/I ratios can be reached using higher order modulation schemes therefore consuming less of available slots in a given sector.

It can be useful to examine capacity in the extreme cases where a sector can achieve the maximum or minimum of both the number of supported users and spectral efficiency (bits/second/Hz) in a sector. The worst case occurs when all the users are at the edge of the coverage area of the cell and are only reachable by the lowest order modulation (QPSK with ½ rate coding) and at the same time have the greatest demand on the system (all demand high resolution video). On the other hand, the most number of supported users and the best spectral efficiencies occur when all users are close to the base station (and can attain the highest order modulations; 64QAM with 5/6 rate coding) and demand low data rate services like email. Both of these cases are possible scenarios and all other cases that achieve varying numbers of sustained users and spectral efficiencies will fall in between these two extremes . The data rate that a sector should be able to deliver is therefore a random variable that is dependent on the distribution of the type of users in the service area as well as their achievable modulations. A similar argument can be made about the number of supported users in a sector which is also stochastic and is a function of the achievable modulation order as well as the distribution of the type of users over the coverage area.

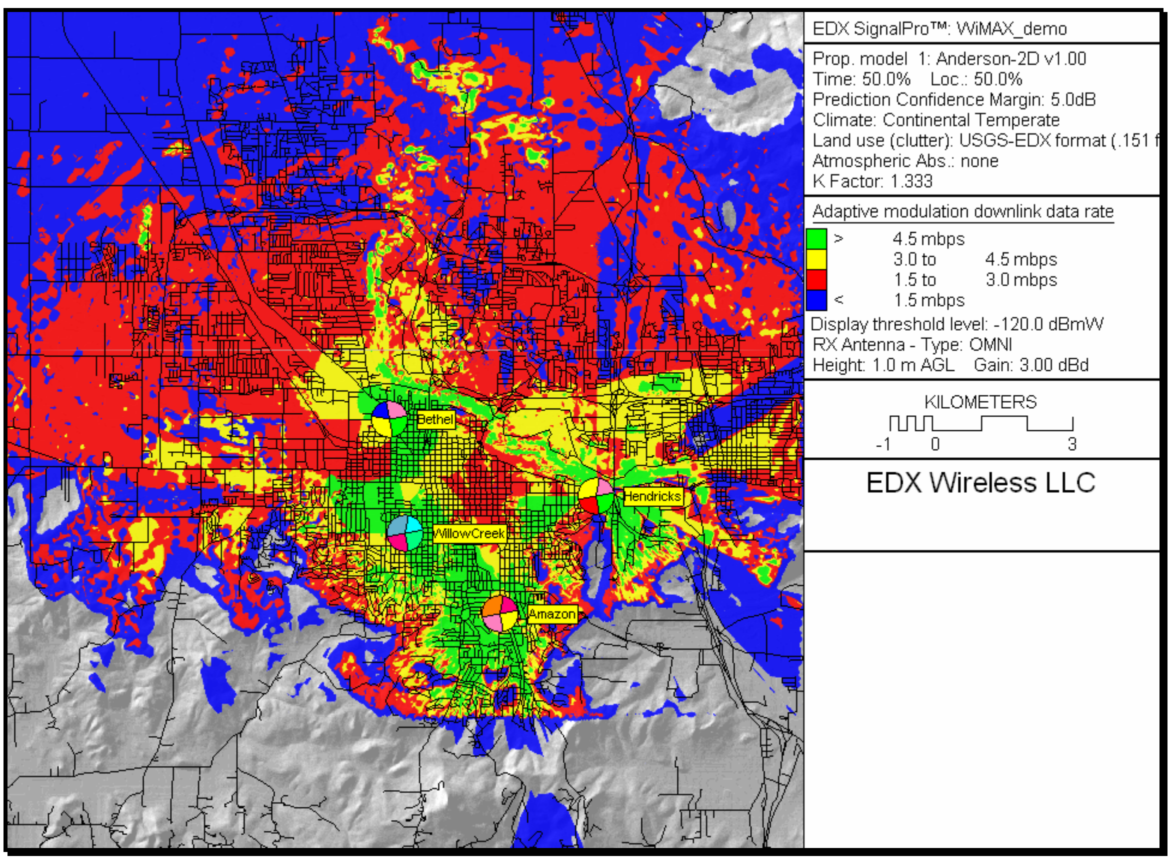


**Figure 5 Adaptive Modulation Downlink Data Rate Study based on OFDM Modulation Types defined in EDX® SignalPro®**

An additional consideration is the frequency re-use factor of the zones within each channel. As mentioned in the previous section, some portions of the frames can be allocated with different FRF zones to improve C/I ratios for users at the edge of cells. These improvements come at the expense of a reduced number of slots that are available in a frame that can be allocated to users in that sector. This diminishes the throughput a sector can deliver as well as reduces the number of supported users.

The use of adaptive modulation results in an interesting limiting effect on system capacity. As discussed earlier, users at the edge of sector's coverage area are more likely to be using a lower-constellation modulation type which is less efficient in terms of frequency/time slot usage. This implies that base stations need to be located within the areas where the majority of the users are found in order to maximize the number using the more efficient modulation types.

## Summary

This paper considered the factors affecting interference and channel capacity in a WiMAX system. As discussed in this manuscript, uplink and downlink interference analysis have to be approached and analyzed differently. Downlink interference analysis can be computed or measured at each location in the service area and is therefore deterministic in nature. On the uplink, however, the randomness of the distribution of the users in the sectors introduces also a stochastic behavior on the received C/I ratio at the base stations. Channel planning, sub-channel allocations, as well as the use of frequency re-use factor zones all have effects on system wide interference levels.

System capacity is dependent on the distribution of the users in the service area as well as the type of service that is requested. In systems that employ adaptive modulation such as 802.16, capacity is also a function of the C/I ratio since higher modulation orders can achieve higher spectral efficiencies. Channel and, if necessary, sub-channel planning also has an effect on the data rate that can be supported per unit bandwidth. The flexibility in the WiMAX standard allows a system designer to perform tradeoffs between overall system capacity and interference levels to best allocate the resources to supply the customers with their data needs.

## References

[1] "Air Interface for Fixed and Mobile Broadband Wireless Access Systems," IEEE IEEE P802.16e/D8, May, 2005.

[2] "Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation," WiMAX Forum, March, 2006.