

# Evaluating WiMAX for Public Safety

Jim Martin, James Westall  
School of Computing  
Clemson University  
Clemson, SC 29634, USA  
jim.martin, westall@cs.clemson.edu

*Abstract—Public safety agencies traditionally use mobile radio systems for communications although cell phones for voice and data are also now widely used. Most law enforcement officials would agree that these communications systems are not sufficient to meet the needs of law enforcement. Consequently there is significant interest in broadband wireless technology. In the research presented in this paper, we have evaluated WiMAX communications technology for use by public safety. Worldwide Interoperability for Microwave Access (referred to as WiMAX) is a MAC and physical layer wireless communications technology for outdoor broadband wireless coverage. We have deployed an 802.16d WiMAX network that operates at 4.9 GHz (spectrum reserved for public safety) at Clemson University. In this paper, we present the results from a performance analysis we have conducted of our WiMAX network. To the best of our knowledge the work reported in this paper is the first academic study of WiMAX in an operational network in which controlled experiments could be conducted. The WiMAX standard leaves key areas of the protocol, including packet scheduling, frame packing, and modulation/coding adaptation, unspecified. In order to accurately model and analyze WiMAX, realistic assumptions must be used. Because WiMAX systems have not been widely studied, there is a disconnect between theoretical WiMAX systems and real-world deployed systems. This motivates the research presented in this paper. Using knowledge of the equipment's implementation choices, we derive theoretical application throughput for both TCP and UDP protocols and correlate expected results with empirical results.*

## 1. INTRODUCTION

Public safety wireless networks traditionally have involved voice-centric, agency-owned land mobile radio (LMR) networks. However advances in technology are giving agencies new and more powerful options. Future 3G/3G+/4G public networks will be able to provide broadband access sufficient to support voice, video and data to desired coverage levels throughout a state. However, excessive reliance on these systems is unwise. Because their complex infrastructure relies extensively on both the electric power and wired telephone grids, they are highly vulnerable to man-made and natural disasters. In emergency situations, voice and data services provided by public network providers are likely to be overloaded or damaged and therefore unusable.

In contrast, broadband wireless access systems such as Worldwide Interoperability for Microwave Access (referred to as WiMAX) can provide a low-cost, locally managed, wireless metropolitan area network (MAN) infrastructure with capabilities that can equal or surpass those of 3G/3G+/4G public wireless networks.

WiMAX networks can be deployed for temporary or permanent use and can be much more easily isolated from large-scale failures in the electric power or telephone grids. With additional economic benefits of using low cost commercial-off-the-shelf (COTS) communications gear, there is significant interest from the public safety community in understanding how WiMAX technology might help the industry.

Similar to WiFi, WiMAX is a MAC and physical layer wireless communications technology. Unlike WiFi, WiMAX was designed to provide outdoor broadband wireless access at a municipal, state-wide, or regional level. The set of standards that define WiMAX are developed and maintained by the IEEE 802.16 Working Group [1,2]. Two major variants of WiMAX have emerged and are being deployed: 802.16d standard supports fixed or slowly moving users; 802.16e standard supports mobile users. While both variants of WiMAX are now specified by a single standard [2], we refer to each using the original standard names of 802.16d and 802.16e. A consortium of WiMAX vendors and providers, referred to as the WiMAX Forum, serves to promote the technology by specifying common operating modes and offering test certification services to promote interoperability [5].

802.16d and 802.16e networks operating at licensed 2.5 GHz spectrum are being deployed by broadband wireless Internet Service Providers such as Sprint and Clearwire at specific locations around the country. States and cities are deploying WiMAX for Internet access in licensed 3.65 GHz spectrum. 802.16d is available with no restrictions in unlicensed 5.8 GHz spectrum. Public safety and homeland security agencies can deploy 802.16d in licensed 4.9 GHz spectrum. Outside North America, WiMAX at 3.5 GHz is being deployed. The Federal Communications Commission has allocated a block of 700 MHz spectrum for exclusive use by public safety for broadband access. At least one vendor has WiMAX equipment that can operate in this spectrum. However the spectrum will not be generally available for at least one year<sup>1</sup>.

Despite the large amount of press coverage, WiMAX is a relatively unproven technology. Although the protocol has been under development for almost 10 years

---

<sup>1</sup> Please refer to the FCC website <http://www.fcc.gov/pshs/public-safety-spectrum/700-MHz/> and to Airspan's web site: [http://www.airspan.com/solutions\\_700.aspx](http://www.airspan.com/solutions_700.aspx)

significant deployments did not occur until 2007. Except for several recent measurement studies based on actual deployments [3,4,19], prior research has involved simulation or analytic modeling. The WiMAX standard leaves key areas of the protocol, including packet scheduling, frame packing, and adaptive modulation/coding unspecified. In order to accurately model and analyze WiMAX, realistic assumptions must be used. Because WiMAX systems have not been widely studied, there is a disconnect between theoretical WiMAX systems and real-world deployed systems. This motivates the research presented in this paper.

We have deployed an 802.16d WiMAX testbed at Clemson University using Harris Corporation's Vida WiMAX equipment<sup>2</sup>. The equipment operates in point-to-multipoint mode at 4.9 GHz. The Clemson University Police Department holds the FCC license to operate radio equipment at the 4.9 GHz band on our behalf. Although a WiMAX Forum profile for 4.9 GHz has not yet been defined, a group of WiMAX equipment vendors have agreed on a set of operating parameters allowing interoperability. We refer to this set of operating modes and parameters as the 4.9 GHz profile. In summary, the profile specifies 5 MHz channels, time division duplex (TDD) mode, and 10 millisecond frames. The physical layer is based on 256 fast Fourier transform (FFT) orthogonal frequency division multiplexing (OFDM). Roaming between base stations is achieved via 'hard handoffs'.

In this paper, we present the results from a performance analysis we have conducted of a WiMAX network deployed at Clemson University. The Harris equipment supports the 4.9 GHz profile. Our network consists of a single base station and consequently client hand-offs between base stations are not considered in the analysis. To the best of our knowledge the work reported in this paper is the first academic study of WiMAX operating at 4.9 GHz in an operational network in which controlled experiments could be conducted.

Based on guidance from our equipment vendor, we derive the best-case theoretical application throughput that can be achieved by the implementation. We correlate expected results with empirical results. Unlike other measurement studies of WiMAX, our research provides insight on the real-world impacts of a deployed WiMAX system.

This paper is organized as follows. After a brief background discussion of WiMAX and related research, we summarize our deployment at Clemson University. The next section of the paper highlights expected performance of the network. The next section summarizes observed results from our study. We end the paper with a summary of our conclusions.

## 2. BACKGROUND

### *Overview of WiMAX*

WiMAX is designed to operate in radio frequencies ranging from hundreds of megahertz to 66 GHz. To operate over a wide range of environments and to meet requirements of broadband applications, WiMAX is a versatile and justifiably complex protocol. The WiMAX Forum addresses this complexity by identifying working profiles that define operating modes and configuration settings allowing equipment set to the same profile to interoperate. Operating modes and configuration options that are specified by a profile include:

- Point-to-multipoint (PMP) or mesh operating modes. PMP implies subscriber stations (SSs) must communicate through a central point, the base station. Mesh mode implies subscriber stations can communicate directly with other SSs. To the best of our knowledge, there are no WiMAX implementations that support mesh mode.
- Operational parameters such as center frequency range, channel bandwidth, channel frequency step size, FFT size and duplexing mode (time division duplex and frequency division duplex).
- 802.16d (fixed, portable) or 802.16e (mobile) operation.

### *Related Work*

There is a rapidly growing amount of research related to WiMAX. Related WiMAX research falls into one of three broad categories. First, there are studies that provide performance analysis of WiMAX systems [5 - 8]. These studies are primarily based on simulation or analytic methods, although a few recent studies include measurement results based on live networks [3,4,9,19]. Second, there are studies that focus on scheduling [10-15]. Third, there are studies that focus on OFDM or OFDMA physical layer issues and methods to deal with cross layer optimization [16-17]. The research that we present in this paper falls into the first category. The analysis presented in [9] focuses on the sensitivity of TCP variants in a WiMAX network. Similarly, the work in [4] documents measured application performance over a public WiMAX network. Our study involves measured data from a testbed network under our control allowing us to add deeper insight in observed performance.

## 3. THE CLEMSON NETWORK

WiMAX network at Clemson University consists of one base station and six subscriber stations. The base station and four of the subscriber stations are from Harris. Of the subscriber stations from Harris, two transmit with a maximum power of 27 dBm, and two are lower power units that transmit at 20 dBm. The other two subscriber stations are EasyST subscriber stations from Airspan which transmit at 20 dBm.

The base station is located on the rooftop of the tallest dormitory on campus. It is 110 feet above the street at an elevation of 820 feet above sea level. Transmit power is

<sup>2</sup> Harris recently acquired the broadband division of M/A-COM and now owns the Vida WiMAX broadband wireless equipment brand. Information regarding the equipment can be found at : <http://www.pspc.harris.com/>

limited to 27 dBm as required by the FCC. An omnidirectional antenna with 9 dB of gain is used at the base station site producing a maximum radiated power of 36 EIRP.

A subscriber station is installed in a vehicle and is used for field and coverage testing. The other units are installed in offices on campus and are used for testing. The WiMAX network is a private IP network connected to the main campus network through a Linux host serving as a gateway. The gateway uses Network Address Translation (NAT) to provide Internet access to all hosts on the WiMAX network.

#### 4. EXPECTED PERFORMANCE

The performance of a WiMAX network is determined largely by physical layer characteristics such as the channel bandwidth, OFDM settings, modulation/coding, and channel conditions.

##### *OFDM Characteristics*

The 802.16d OFDM physical layer has the following characteristics:

- 256 total subchannels
- 8 "pilot" channels used to establish/maintain physical layer synchronization
- 55 channels used as guard bands
- A null carrier is transmitted on the center frequency channel

192 of the 256 total subchannels are available for data transfer. Each subchannel has a bandwidth of 19.531 KHz (i.e., 5 Mhz bandwidth / 256 subchannels). For channels having a bandwidth that is a multiple of 1.24 MHz the standard specifies an oversampling factor of 144/125 yielding a carrier spacing of 22.5 KHz. The FFT symbol time is the inverse of the carrier spacing or 44.44 microsecond/symbol. To counter intersymbol interference, WiMAX defines possible cyclic prefix intervals of 1/4, 1/8, 1/16 and 1/32 of the FFT symbol duration. Our equipment employs a guard interval of 1/8. Therefore the OFDM symbol time is 50.0 microseconds (i.e., the FFT symbol duration plus the guard time of 44.44/8).

##### *Framing Impacts*

Based on the OFDM characteristics defined in the previous section, the number of symbols in a 10 ms frame is 200 (i.e., a 10 ms frame time divided by a symbol time of 50.0 microseconds). In every frame 8 symbols are consumed by the transmit/receive transition gap (TTG) and the receive/transmit transition gap (RTG) leaving 192 symbols per frame available to carry data. Assuming a 50/50 split of bandwidth allocated to upstream and downstream, there are 96 symbols in each subframe for either downstream or upstream operation.

A downstream transmission begins with a long preamble (2 symbols) followed by 1 symbol containing a frame control header (FCH). The FCH describes up to 4 bursts immediately following the FCH symbol. The next burst is referred to as the broadcast burst. It contains up to

4 messages: the downlink allocation message (DL-MAP); the uplink allocation message (UL-MAP); the downstream channel descriptor (DCD); the uplink channel descriptor (UCD). Only the UL-MAP is required to be in every frame.

The DL-MAP consumes 8 bytes plus 4 additional bytes for each burst description. An UL-MAP consumes 8 bytes plus 8 additional bytes for each allocation. The DCD consumes 3 bytes plus a variable amount of information describing the channel and downstream burst profiles. The UCD consumes 8 bytes plus a variable amount of information describing the upstream channel and upstream burst profiles. Following these messages, the frame can contain one or more bursts. Bursts can optionally be preceded by a short preamble that consumes one symbol. In our analysis we assume one short preamble for each downstream burst. Based on information obtained from Harris Corporation, MAPs are sent each frame and 20 symbols-large DCD/UCD messages and are sent every other frame. With these assumptions we estimate that 17 symbols are consumed by overhead in the downstream direction.

For upstream operation, the first 6 symbols are allocated for initial ranging purposes. By default, the base station allocates ranging opportunities once every five frames. Therefore, on average, 1.2 symbols are consumed per frame for ranging. The next 2 symbols are allocated for a bandwidth request contention opportunity. The WiMAX services that require quality of service guarantees such as Unspecified Grant Service (UGS) and Real-time Polling Service (rtPS) would further reduce the number of available symbols. For the analysis reported in this paper, one rtPS flow is provisioned A unicast request opportunity consuming 3 symbols is allocated every frame. We estimate that a total of 7.2 symbols are consumed by overhead. When the TTG and RTG are added to the MAC layer overhead, there are 79 symbols available for downstream PDU bursts and 88.8 symbols available for upstream bursts.

Our analysis of expected results suggested that 79 symbols are available for PDU bursts. We found this not to be true and Harris has advised us that an unplanned issue in the scheduling software unnecessarily consumed 10 symbols. By taking this situation into account, the number of symbols available for downstream is 69.

##### *Expected Application Throughput*

The scheduling software operating at the base station allocates bandwidth to subscriber flows by assigning transmission bursts in a TDMA manner. Transmissions bursts have a start and stop time and are characterized with a set of burst parameters that include modulation and coding, power levels. The data in a burst is packaged in a protocol data unit (PDU). The scheduler decides if a PDU consists of a single service data unit (SDU), a partial SDU (i.e., a fragment), or multiple SDUs concatenated into one PDU burst. Figure 1 illustrates two possible scenarios.

We develop the average TCP and UDP application throughput in both the downstream and upstream

directions. Our analysis relies on the following assumptions.

- A single unidirectional service flow is active in the network which is mapped to a best effort service flow.
- For downstream transfers, the base station always has IP packets waiting to send. For upstream transfers the subscriber station always has packets waiting to send.
- IP packets (TCP/UDP data segments or TCP acknowledgement packets) are concatenated and sent as a single burst.
- An IP packet that will not fit in the space available in a subframe is fragmented so that no symbols are wasted.
- The channel is ideal (i.e., there are no bit errors or dropped packets caused by propagation or fading effects).

The maximum number of bits that can be sent per frame (*bpf*) can be expressed as:

$$bpf = c * m * CR * n$$

The factor  $c$  is the number of data channels. Component  $m$  is the modulation factor (transmission rate per symbol) which is the modulation's power of 2. For example in 64QAM modulation,  $64=2^6$ , so the modulation factor is 6.  $CR$  is the code rate of forward error correction (FEC) and  $n$  is the number of symbols that can be sent in one direction each frame.

Using 64 QAM 2/3 as the example, we derive the maximum downstream and upstream throughput. The maximum number of bits that can be sent downstream or upstream in a single frame time is:

$$\text{Downstream: } 192 * 6 * 2/3 * 69 = 52,992 \text{ bits}$$

$$\text{Upstream: } 192 * 6 * 2/3 * 88.8 = 68,198.4 \text{ bits}$$

As we mentioned earlier, each frame takes 10ms. If we assume all available symbols are allocated to a single PDU burst, and if we compensate for the overhead caused by TCP/IP (the ratio of user data per IP datagram or 1448/1500), we get a maximum TCP application throughput of:

$$\text{Downstream: } (52,992 / 0.01) * 0.965 = 5.11 \text{ Mbps}$$

$$\text{Upstream: } (68,198.4 / 0.01) * 0.965 = 6.58 \text{ Mbps}$$

For UDP, we compensate for TCP/IP overhead by multiplying by the ratio 1472/1500. This leads to a maximum application throughput of:

$$\text{Downstream: } (52,992 / 0.01) * 0.981 = 5.20 \text{ Mbps}$$

$$\text{Upstream: } (68,198.4 / 0.01) * 0.981 = 6.69 \text{ Mbps}$$

Table I shows the expected maximum downstream and

upstream TCP application throughput for all modulation/coding combinations. Table II shows the expected maximum downstream and upstream UDP application throughput for all modulation/coding combinations.

## 5. OBSERVED RESULTS

We have conducted a measurement study of the WiMAX network deployed at Clemson University. The network provides coverage in areas that have near line-of-sight and that are within roughly 0.5 miles of the base station. Only locations with clear line-of-sight to the base station have coverage beyond 0.5 mile. The farthest distance we observed an operational link was 1.2 miles.

We present three types of measured results. First, we summarize the results of experiments that show the average TCP application throughput over a range of modulation and coding settings. Second, we summarize the experiments that show the average UDP application throughput over the same range of modulation schemes. Third, we present the results of coverage tests that were designed to ground the best-case results with the impacts of realistic deployment issues.

For all results reported in this paper we used the higher power Harris subscriber station in a vehicle. Two types of antenna were used for our study. For the application throughput results, a MAXRAD directional antenna with 18 gain dB was used to ensure stable link connections. For the coverage test, an external 6 gain dB antenna was used. We used a Linux host located in a car as the client-side platform for all measurement experiments reported in this paper. The server was located on the Linux gateway machine on the wired network.

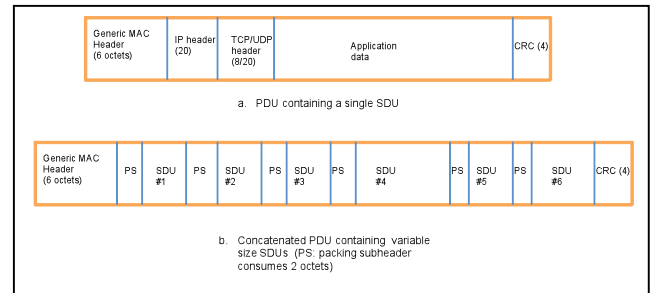


Figure 1. WiMAX Transmission Burst Formats

Table I Expected TCP Application Throughput

Modulation and Coding	Max DS Application Throughput (Mbps)	Max US Application Throughput (Mbps)
64-QAM $3/4$	5.75	7.41
64-QAM $2/3$	5.11	6.58
16-QAM $3/4$	3.84	4.94
16-QAM $1/2$	2.56	3.29
QPSK $3/4$	1.92	2.47
QPSK $1/2$	1.28	1.65
BPSK $1/2$	0.64	0.82

### TCP Application Throughput Results

We used the *iperf* performance tool to obtain TCP throughput measurements. We positioned the measurement laptop at a location that resulted in the desired combination of upstream and downstream modulation settings. We used *iperf* to transfer as much TCP data as possible for 10 seconds first in the upstream direction and then in the downstream direction. We configured *iperf* to display the observed TCP throughput every second. The TCP throughput reported for each measurement is the average TCP throughput of these ten seconds. We ensured that the modulation did not change during the course of the transfer. The socket buffer size was optimized to ensure that the pipe was always full but that buffer overflow at any queue over the path did not occur. Ten measurements were performed for each possible modulation scheme. The average results are summarized in Table III.

Table II Expected UDP Application Throughput

Modulation and Coding	Max DS Application Throughput (Mbps)	Max US Application Throughput (Mbps)
64-QAM $3/4$	5.85	7.53
64-QAM $2/3$	5.20	6.69
16-QAM $3/4$	3.90	5.01
16-QAM $1/2$	2.60	3.35
QPSK $3/4$	1.95	2.51
QPSK $1/2$	1.30	1.67
BPSK $1/2$	0.65	0.83

Table III identifies the observed results. We were not able to find a location on campus where the upstream link connected using 64 QAM or where the downstream link connected at 64 QAM  $3/4$ . The results table entry are blank for these measurements. The value in parenthesis indicates the error between the observed throughput and the expected throughput shown in Table I. The WiMAX base station profile was configured using the 4.9 GHz profile settings described earlier.

The downstream error was quite consistent, ranging from -0.40% to -1.44% and averaging -0.80%. As we ensured the link was stable, the average throughput statistics were within 0.2% of the true mean with 99% confidence.

The upstream measured results were consistent with expectations. The error ranged from -1.62% to -2.44% and averaged -1.99%. Our measured throughput did not include the 6 byte generic MAC header and 4 byte CRC required for each PDU burst. When this extra overhead is accounted for, the discrepancy is about 1%.

Table III Measured TCP Application Throughput

Modulation and Coding	Average DS Application Throughput (Mbps) (% of error)	Average US Application Throughput (Mbps) (% of error)
64-QAM $3/4$		
64-QAM $2/3$	5.05(-1.25%)	
16-QAM $3/4$	3.82(-0.40%)	4.83(-2.23%)
16-QAM $1/2$	2.54(-0.66%)	3.23(-1.82%)
QPSK $3/4$	1.91(-0.40%)	2.43(-1.62%)
QPSK $1/2$	1.27(-0.66%)	1.62(-1.82%)
BPSK $1/2$	0.63(-1.44%)	0.80(-2.44%)

### UDP Application Throughput Results

We also used the open source *iperf* throughput performance tool to obtain UDP throughput measurements. Similar to what we did for the TCP throughput measurements, the measurement laptop and radio is placed at a location to obtain the desired combination of upstream and downstream modulation settings. The WiMAX base station profile was identical for for both the TCP and UDP throughput experiments. We configured *iperf* to transfer 1472 bytes of data per UDP datagram at the theoretical bandwidth for 10 seconds first in the upstream direction and then in the downstream direction. The UDP throughput reported for each measurement is the average UDP throughput of these ten seconds. We ensured that the modulation scheme kept stable during the course of the data transfer. For each possible modulation scheme, we performed ten measurements. Table IV summarizes the average results. As with the TCP throughput experiments, we were not able to find a location on campus where the client's upstream link connected using 64 QAM or where the downstream connected at 64 QAM  $3/4$ .

The UDP throughput experimental results are consistent with the TCP throughput experiments. The downstream error ranges from -0.38% to -1.54% and averaging -0.68%. The upstream measured results were consistent with expectations. The error ranged from -1.79% to -2.41% and averaged -2.12%. The error rate is around 1% after correcting the 10 bytes consumed by generic MAC head and CRC.

Table IV Measured UDP Application Throughput

Modulation and Coding	Average DS Application Throughput (Mbps) (% of error)	Average US Application Throughput (Mbps) (% of error)
64-QAM $3/4$		
64-QAM $2/3$	5.18(-0.38%)	
16-QAM $3/4$	3.88(-0.51%)	4.91(-2.00%)
16-QAM $1/2$	2.59(-0.38%)	3.29(-1.79%)
QPSK $3/4$	1.94(-0.51%)	2.46(-1.99%)
QPSK $1/2$	1.29(-0.77%)	1.63(-2.40%)
BPSK $1/2$	0.64(-1.54%)	0.81(-2.41%)

### Campus Wide Coverage Results

We developed a coverage tool to assess the coverage of the WiMAX network. A complete description of the tool and the results are available at [18]. In brief, the tool is a program that runs on a Linux host that is connected to the WiMAX network through a subscriber station. The tool periodically collects a data sample that includes the time/date of the sample, the GPS location, the speed of the client, RF information from the layer, and IP Ping round-trip time samples.

From June 2008 through February 2009 we collected 12 sets of data. A data set is a set of samples obtained from a 30 minute drive around campus. We had a standard driving path within the coverage area that facilitated comparing different data sets obtained at different times of year. The vehicle speed never exceeded 10 mph.

We developed a web site that provides both data archival and analysis capabilities. For brevity, we present results that are based on link connectivity. A green symbol implies network connectivity; a black symbol implies there is no connectivity. The criteria that determines network connectivity is if the SNR is greater than a value of 5. This is roughly the point where the link loses synchronization and where any IP packets that do get transmitted will not be successfully received.

Figure 2 illustrates the data collected on 2/15/2009. The black triangle located in the center of the map represents the location of the base station. All data points (600 in all) are from locations that fall within a circle of coverage extending 0.5 miles in radius around the base station. The subscriber's link never dropped in this data set. Data sets obtained later in the year, when leaves were on trees, suffer frequent link drops.

We focus on the data in the dashed rectangle shown in Figure 2 and on data from another data set (not pictured) obtained on 2/15/2009. We look at two portions of the path identified by a dashed and a solid line segment (segments A and B respectively). The starting point of the dashed segment is 974 feet from the base station. The starting point of the solid segment is 1790 feet from the base station. Table V identifies the average signal to noise

ratio (SNR) in db and the received signal strength (RSS) in dBm for the measurement samples associated with each path segment from both the February and June data sets. The average RSS level observed along the dashed segment increased by 10.4 dBm and the SNR increased by 54% between June and February. The increase along the other segment was also significant (7.7 dBm and 35.2% respectively) for measurements taken over the solid segment. In February, the locations over the dashed segment were partially obscured by tree branches with no leaves but heavily obscured by foliage in June. The locations associated with the solid segment had clear line-of-sight all the time both dataset were collected. Table V also indicates the percentage of samples (for each path) that the downstream modulation method was BPSK  $1/2$ . For path A, this statistic dropped from 87.5% to 50%.

Table V RF Path Analysis for January and June Data

Path segment	6-15-2008			2-15-2009		
	SNR	RSS	% BPSK	SNR	RSS	% BPSK
A (dashed)	7.75	-93.2	87.5	17.0	-82.8	50.0
B (solid)	10.9	-90.6	81.0	16.8	-82.9	53.7

## 6. CONCLUSIONS

In this study we have analyzed the performance of a 4.9 GHz WiMAX network at Clemson University. We observed TCP throughput in range from 5.2 Mbps to 0.65 Mbps and UDP throughput in range from 5.31 Mbps to 0.66 Mbps. We showed that the measured average TCP and UDP application throughput was within 1.0% of expected values (after adjusting for the anomaly in the scheduling implementation).

Using a coverage tool, we monitored the achieved coverage over a specific path around campus for a period of 6 months. We found that an operational link required near line-of-sight between the subscriber station and the base station and was highly sensitive to the level of foliage present at the time of data collection. We found the SNR increased over two different path segments by 54% and 35% between the months of February (with minimal foliage impeding line-of-site) and June (with maximal interference from foliage). The combined results from the coverage analysis and from the throughput analysis suggest an obvious but important observation: although equipment implementation choices contribute to the achieved performance of WiMAX, the physics surrounding 4.9 GHz RF propagation will likely have the most significant impact on system performance.

In spite of the spectrum difficulties, we have demonstrated that a WiMAX network can support applications that can help law enforcement. Our Clemson Police Department collaborators suggest that video streamed to or from police cars or to mobile devices would have significant impact on their ability to serve the public. They also told us that police officers frequently drive to locations on campus where indoor 802.11 signals bleed



outside allowing officers Internet connectivity from their vehicle. While achieving 100% coverage across campus is simply not feasible with 4.9 GHz, a much more practical solution is to deploy equipment providing ‘corridors’ of support within a region. A corridor might be a 1 mile long stretch of a highway. Within an urban area, hot spots would support Internet access or streaming video applications. Although we did not specifically compare WiMAX to WiFi at 4.9 GHz, we do conjecture that in

uncongested scenarios the choice of MAC layer protocol (WiMAX or WiFi) has an insignificant impact on performance when devices are limited to a single omnidirectional antenna operating at 4.9 GHz. In future work, we plan to explore the impact of MIMO and adaptive antennas and the subsequent cross layer support required by the MAC layer protocol. We are also planning to expand the testbed at Clemson to possibly include WiMAX equipment operating at 2.5 GHz and at 700 MHz.



Figure 2. Coverage Data from 2/15/2009 (Basestation Identified by the Black Triangle)

## ACKNOWLEDGEMENT

This work was supported in part by the U.S. Department of Justice Grant 2006-IJ-CX-K035. We acknowledge Mike Gaudette of Harris Corporation for providing helpful implementation details of the base station. We also acknowledge the Clemson University Police Department for their support throughout this project.

## REFERENCES

- [1] IEEE 802.16-2004, IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems, 7/2004.
- [2] 802.16E-2005&802.16/COR1 IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, 2/2006.
- [3] Dongmyoung Kim; Hua Cai; Minsoo Na; Sunghyun Choi, "Performance measurement over Mobile WiMAX/IEEE 802.16e network," World of Wireless, Mobile and Multimedia Networks, 2008. WoWMoM 2008. 2008 International Symposium on a , vol., no., pp.1-8, 23-26 June 2008
- [4] Joe, J.; Hazra, S.K.; Toh, S.H.; Tan, W.M.; Shankar, J., "5.8 GHz Fixed WiMAX Performance in a Sea Port Environment," Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th , vol., no., pp.879-883, Sept. 30 2007-Oct. 3 2007
- [5] C. Eklund, R. Marks, K. Stanwood, S. Wang, "IEEE Standard 802.16: A Technical Overview of the WirelessMAN Air Interface for Broadband Wireless Access", IEEE Coms Magazine, vol. 40, no. 6, Jun 2002.
- [6] A. Goch, D. Wolter, J. Andrews, R. Chen, "Broadband Wireless Access with WiMAX/802.16: Current Performance Benchmarks and Future Potential", IEEE Communications Magazine, vol. 43, no. 2., 2005
- [7] M. Kuran, T.Tugcu, "A Survey on Emerging Broadband Wireless Access Technologies", Computer Networks, vol.51, no.11, 2007.
- [8] C.Cicconetti, L. Lenzi, E. Mingozzi, C. Eklund, "Quality of service Support in IEEE 802.16 Networks, IEEE Network, vol. 20, no. 2, 2006.
- [9] E. Halepovic, Q. Wu, C. Williamson, M. Ghaderi, "TCP Over WiMAX: A Measurement Study", Proceedings of MASCOTS 2008.
- [10] K. Wongthavarawat, A. Ganz, "Packet Scheduling for QoS Support in IEEE 802.16 Broadband Wireless Access Systems", International Journal of Communications Systems, 2003.
- [11] A. Sayenko, O. Alanen, J. Harhula, T. Hamalainen, "Ensuring the QoS Requirements in 802.16 Scheduling", Proceedings of the 9th ACM international symposium on Modeling analysis and simulation of wireless and mobile systems, 2006.
- [12] A. Baccioccola, C. Cicconetti, A. Erta, L. lenzini, E. Mingozzi, "Bandwidth Allocation with Half-duplex Stations in 802.16 Wireless Networks", IEEE Transactions on Mobile Computing, 2006.
- [13] D. Niyato, E. Hossain, "Queue-Aware Uplink Bandwidth Allocation and Rate Control for Polling Service in IEEE 802.16 Broadband Wireless Networks", IEEE Transactions on Mobile Computing, 2006.
- [14] J. Lin, C. Chou, C. Liu, "Performance Evaluation for Scheduling Algorithms in WiMAX Networks", Advanced Information and Networking Applications - Workshop 2008", March 2008.
- [15] C. Wong, R. Cheng, K. Lataief, R. Murch, "Multiuser OFDM with Adaptive Subcarrier, bit, and Power Allocation", IEEE Journal of Selected Areas of Communication, vol 17, no. 10, Oct 1999.
- [16] J. Jang, K. Lee, "Transmit Power Adaptation for Multiuser OFDM Systems", IEEE Journal of Selected Areas of Communications, vol. 21, Feb 2003.
- [17] I. Wong, B. Evans, "Optimal Resource Allocation in OFDMA Systems with Imperfect Channel Knowledge", IEEE Transactions on Communications, 2007.
- [18] J. Martin, W. Pressly, M. Westall, "WiMAX Performance at 4.9 GHz- Extended Paper", available at <http://www.cs.clemson.edu/~jmarty/projects/PublicSafety/wimaxPerformance.pdf>
- [19] V. Abhayawardhana, I. Wassell, D. Crosby, M. Sellars, M. Brown, "Comparison of Empirical Propagation Path Loss Models for Fixed Wireless Access Systems", IEEE Vehicular Technology Conference, VTC05, 2005.

## BIOGRAPHY



*Dr. Jim Martin is an Associate Professor in the School of Computing at Clemson University. His research interests include broadband access, wireless systems, autonomic computing, Internet protocols and network performance analysis. He has received funding from NSF, NASA, the Department of Justice, BMW, IBM, and Cisco. Dr Martin received his Ph.D. from North Carolina State University. Prior to joining Clemson, Dr Martin was a consultant for Gartner, and prior to that, a software engineer for IBM.*