WiMAX Performance at 4.9 GHz

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Abstract—Worldwide Interoperability for Microwave Access (referred to as WiMAX) is a MAC and physical layer wireless communications technology for outdoor broadband wireless coverage. In collaboration with the Clemson University Police Department, we have deployed an 802.16d WiMAX network that operates at 4.9 GHz at Clemson University. In this paper, we present the results from a performance analysis we have conducted of the WiMAX network. To the best of our knowledge the work reported in this paper is the first academic study of an operational 4.9 GHz WiMAX in which controlled experiments could be conducted. While neither the 4.9 GHz spectrum nor the current WiMAX profiles settings might be optimal for space or lunar communications, a study of WiMAX at any frequency is of value to both the aerospace industry and the research community. 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 disconnection 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. We also summarize results from a coverage analysis of the system. The combined results lead to an important point: 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.[1][2]

Keywords- WiMAX, 802.16, broadband wireless, performance analysis

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1. INTRODUCTION

Similar to WiFi, Worldwide Interoperability for Microwave Access (referred to as 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 multi-state 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.

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

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[2] IEEEAC paper #1271, Version 1, Updated November 1, 2009

WiMAX equipment[3]. 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. While the 4.9 GHz spectrum is not expected to be used for space communications, a study of WiMAX at any frequency is of value to the aerospace research community.

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 the community with 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 limited to 27 dBm as required by the FCC. An omni-directional 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 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

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[3] 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/

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 MAP (DL-MAP); the uplink MAP (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. UGS and rtPS provisioned flows 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 used 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 (ie., a fragment), or multiple SDUs concatenated into one PDU burst. Fig. 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:

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

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

As we mentioned earlier, each frame takes 10ms. If we assume all available symbols are allocated to a single PDU burst, and if we factor in an overhead caused by TCP/IP of 1448/1500, we get a maximum TCP application throughput of:

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

$$\text{Upstream:}\quad (681{,}98.4 / 0.01) * 0.965 = 6.58 \text{ Mbps}$$

For UDP, we adjust the TCP/IP overhead to 1472/1500 which leads to a maximum application throughput of:

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

$$\text{Upstream:}\quad (681{,}984 / 0.01) * 0.981 = 6.69 \text{ Mbps}$$

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

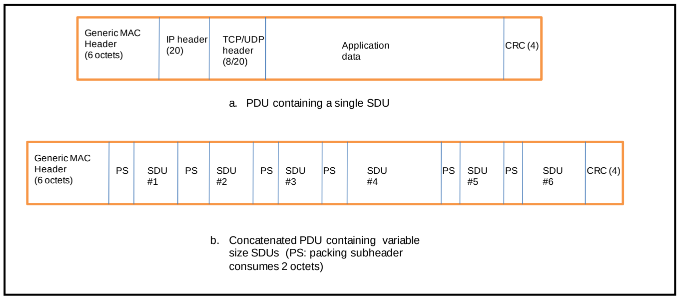

Figure 1. WiMAX Transmission Burst Formats

Table I Expected TCP Application Throughput

Modulaiton/ 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

Table II Expected UDP Application Throughput

Modulaiton/ 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

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.

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 ¾. Table III identifies the observed results. 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.

Table III Measured TCP Application Throughput

Modulation/ 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%)

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 0.67% (10/1488) overhead is accounted for, the discrepancy is about 1%.

UDP Application Throughput Results

We also used the *iperf* 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. We configured iperf to transfer UDP data 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 and summarize the average results as presented in

Similar to the situation of TCP throughput experiments, we were not able to find a location on campus with the upstream link using 64 QAM or the downstream connecting at 64 QAM ¾. The WiMAX base station profile was configured to the same for both TCP and UDP throughput experiments.

The UDP throughput experiments 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 which accounts for 0.68% (i.e, 10/1472) of the error.

Table IV Measured UDP Application Throughput

Modulation/ Coding	**Average DS Application Throughput (Mbps) (% of error)**	**Average US Application Throughput (Mbps) (% of error)**
64-QAM ¾		
64-QAM $^{2}/_{3}$	5.18(-0.38%)	
16-QAM ¾	3.88(-0.51%)	4.91(-2.00%)
16-QAM ½	2.59(-0.38%)	3.29(-1.79%)
QPSK ¾	1.94(-0.51%)	2.46(-1.99%)
QPSK ½	1.29(-0.77%)	1.63(-2.40%)
BPSK ½	0.64(-1.54%)	0.81(-2.41%)

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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, IP Ping.

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.

Fig. 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 Fig 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 increment 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 ½. 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

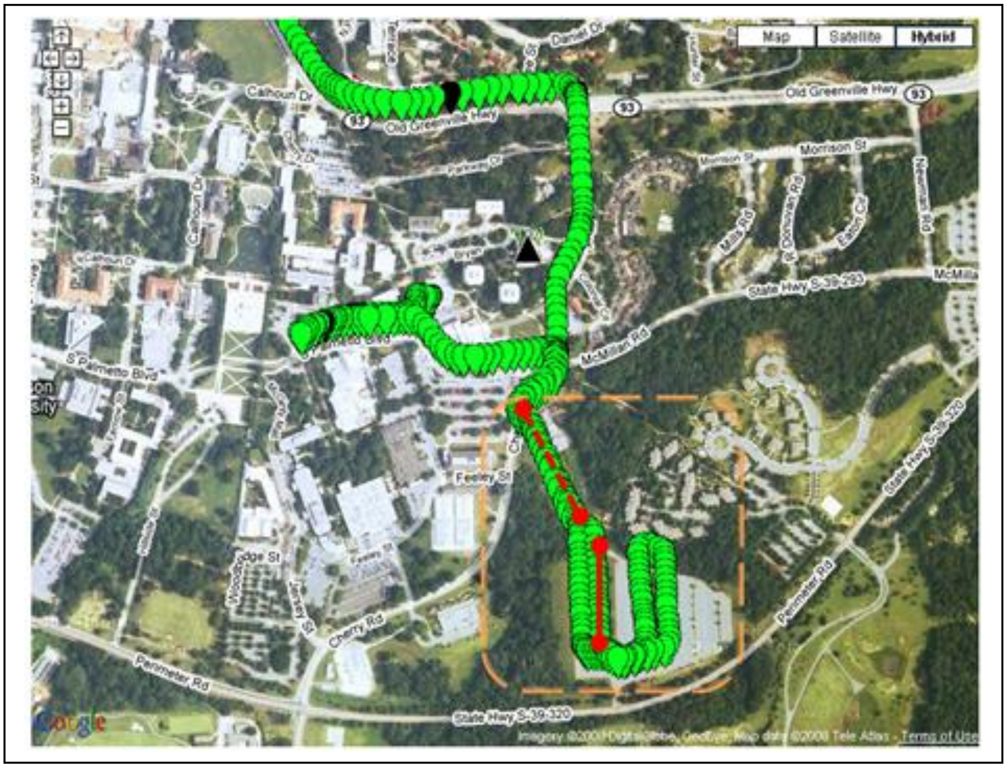

Figure 2. Coverage Data from 2/15/2009 (Basestation Identified by the Black Triangle)

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 application throughput was about 1.0% (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. The combined results from the coverage analysis and from the throughput analysis reinforce 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.

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