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. 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 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. While the 4.9 GHz spectrum is not expected to be used for Internet access or as a part of an entertainment network, a study of WiMAX at any frequency is of value to both industry and the research community. Over a 5 MHz OFDM channel, we observe TCP application throughput ranging from 5 Mbps to 0.6 Mbps. The link was operational as long as the subscriber station remained in near line-of-sight of the base station and within a distance of 0.5 miles.

Index Terms—WiMAX, 802.16, broadband wireless, performance analysis

I. 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. The 802.16d standard supports fixed or slowly moving users. The 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 [3].

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 (the origins of WiMAX can be traced back to line-of-sight wireless cable distribution systems such as Local Multipoint Distribution Systems introduced in 1997), significant deployments did not occur until 2007. Consequently there are virtually no measurement studies providing insight into how WiMAX operates in actual deployments. With several recent exceptions, academic research has been based on simulation or analytic modeling.

We have deployed an 802.16d WiMAX testbed at Clemson University using M/A-COM’s Vida WiMAX equipment. 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 M/A-COM equipment uses 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’. Our network consists of a single base station and consequently client handoffs between base stations are not considered in the analysis.

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. While the 4.9 GHz spectrum is not expected to be used for Internet access or as a part of an entertainment network, a study of WiMAX at any frequency is of value to both industry and the research community. Aspects of our results can be extrapolated and applied to other deployments. As expected, 4.9 GHz is not conducive to near line-of-sight environments and consequently offers a challenging test case for WiMAX. Nevertheless, two characteristics 4.9 GHz WiMAX make it very useful as a research network. First, the spectrum is licensed and thereby provides a controlled test environment.

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Second, since the equipment is intended to be operated by law enforcement, a 4.9 GHz network is reasonably accessible in terms of cost and obtaining a license to use the spectrum is simple and free.

This paper is organized as follows. After a brief background discussion of WiMAX and related research, we summarize our deployment at Clemson University. In order to interpret the observed results, it is necessary to have a basic understanding of how WiMAX works. Therefore, the next section of the paper describes 802.16 operation primarily by highlighting expected performance of the network. The next section summarizes observed results from our study. We end the paper with a summary of our conclusions and with a list of future work.

II. BACKGROUND

A. 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 or 802.16e operation. The two modes are incompatible and generally require different hardware.

B. Related Work

There is a rapidly growing amount of research related to WiMAX. One method of describing WiMAX related research is by identifying three broad categories of research. First, there are numerous studies that provide performance analysis of WiMAX systems[4 - 9]. These studies are usually based on simulation or analytic methods, although a few recent studies include measurement results based on live networks [10]. Second, there have been a significant number of studies focused on scheduling [11-18]. Third, other studies have focused on OFDM or OFDMA physical layer issues [19,20]. Of particular relevance are the studies that examine cross layer scheduling which combines WiMAX MAC layer service flow management with optimal resource allocation of the OFDM or OFDMA channel [21-23]. The research that we present in this paper falls into the first category. However, because our performance analysis involves measured data from a testbed network under our control, our research is unique.

III. THE CLEMSON NETWORK

The WiMAX network at Clemson University consists of one base station and four subscriber stations. The base station and four of the subscriber stations are from M/A-COM. Of the subscriber stations from M/A-COM, two are high power and transmit with a maximum power of 27 dBm, and two are low 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 omnidirectional antenna with 9 dB of gain is used at the base station site producing a maximum radiated power of 36 EIRP.

One subscriber station is permanently mounted on a light pole in a parking lot on campus. A pan/tilt/zoom H.264 IP surveillance camera, also located at the light pole, is connected to it. Another 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. Although the campus police department does have access to the surveillance camera, the system is presently used only as a research testbed and is not used in an official capacity.

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, but only the camera can be accessed from outside the WiMAX network (through reverse NAT operating at the gateway).

IV. EXPECTED PERFORMANCE

Aside from performance issues caused by network congestion, 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. We develop test case estimates for expected application layer throughput based upon physical layer characteristics and estimates of protocol overhead at the MAC layer.

A. Expected Physical Layer Impacts

We define the ‘effective burst rate’ to be the bit rate that is available to the MAC layer for a transmission burst. The effective burst rate takes into account the modulation and coding method and the ratio of upstream to downstream bandwidth (assuming TDD operation). The measure does not account for MAC level overhead (that is the next step).

The 802.16d OFDM physical layer has the following
characters:
- 256 Total subchannels
- 8 "Pilot" channels used to establish/maintain physical layer synchronization
- 192 Data channels
- 55 Channels used as guard bands
- A null carrier is transmitted on the center frequency channel

Each subchannel has a bandwidth of 5 MHz / 256 channels = 19.531 KHz. 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 usec/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.

The OFDM symbol time is: \( 44.44 + (44.44/8) = 50.0 \text{ usec} \). Therefore the aggregate OFDM symbol rate is 20,000 symbols per second. Assuming that 50% of channel capacity is allocated to both upstream and downstream flows, using 64 QAM 2/3 modulation mode as an example, the effective burst rate is:

\[
(6 \times \frac{2}{3}) \times 1.92 \text{Msymbols/second} = 7.68 \text{Mbps}
\]

The second column of Table 1 indicates the maximum possible effective burst rate for each modulation method specified by the WiMAX standard. The results apply to both downstream and upstream.

B. Expected Link Rate

The 802.16 MAC layer operates over a physical layer that offers an effective burst rate as described in the previous section. The available bandwidth over the channel offered to higher layer protocols (we refer to this as the ‘effective link rate’) is lower than the effective burst rate because of PHY and MAC layer overhead. We continue developing the example from the previous section. The number of symbols in a 10 ms frame is:

\[
Ts = 0.01 / 0.000050 = 200
\]

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. Assuming a 50/50 split of bandwidth allocated to upstream and downstream, there are 96 symbols in each subframe.

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. We assume the MAPs are sent each frame, that DCD/UCD messages consume 20 symbols 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. We have configured the base station to allocate a ranging opportunity once per 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 subscriber station on the network has an rtPS flow. A unicast request opportunity consuming 3 symbols is allocated every frame. We estimate that a total of 7.2 symbols are used by overhead.

Based on these assumptions, 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. Using 64 QAM 2/3 as an example, the maximum data rate available to carry protocol data units would be:

\[
\text{downstream: } (192 \times 6 \times 2/3 \times 79) / 0.01 = 6.07 \text{Mbps}
\]

\[
\text{upstream: } (192 \times 6 \times 2/3 \times 88.8) / 0.01 = 6.82 \text{Mbps}
\]

<table>
<thead>
<tr>
<th>Modulation / coding</th>
<th>Effective burst rate (Mbps)</th>
<th>Max US data rate (Mbps)</th>
<th>Max DS data rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-QAM ½</td>
<td>0.64</td>
<td>0.85</td>
<td>0.76</td>
</tr>
<tr>
<td>16-QAM ½</td>
<td>1.64</td>
<td>1.92</td>
<td>1.85</td>
</tr>
<tr>
<td>16-QAM ¾</td>
<td>2.68</td>
<td>3.76</td>
<td>3.44</td>
</tr>
<tr>
<td>64-QAM ½</td>
<td>3.84</td>
<td>4.55</td>
<td>3.92</td>
</tr>
<tr>
<td>64-QAM ¾</td>
<td>5.76</td>
<td>7.00</td>
<td>6.83</td>
</tr>
<tr>
<td>QPSK ½</td>
<td>1.92</td>
<td>2.29</td>
<td>2.04</td>
</tr>
<tr>
<td>QPSK ¾</td>
<td>2.38</td>
<td>2.62</td>
<td>2.30</td>
</tr>
<tr>
<td>BPSK ½</td>
<td>0.96</td>
<td>1.06</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table 1. Best case link rates accounting for framing and overhead

The third and fourth columns of Table 1 identify the maximum data rate available to carry application data in the downstream and upstream directions for all modulation/coding levels.

C. Expected Application Throughput

The scheduling software operating at the base station allocates bandwidth to subscriber flows by assigning transmission bursts in a TDMA manner. Transmission 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.

Fig. 1. WiMAX Transmission Burst Formats

We develop the best case TCP throughput in both the downstream and upstream directions. Our analysis relies on the following assumptions.

- The base station or the subscriber station always has IP packets (of MTU 1448 bytes) waiting to send.
- IP packets are concatenated and sent as a single burst (as depicted in Figure 1).
- The overhead associated with a burst is illustrated in Figure 1.
- An IP packet that will not fit in the space available in a subframe is fragmented so that no symbols are wasted.
- A single TCP flow is active in the network.
- An ideal channel (i.e., no bit errors or fading effects).

Continuing to use 64 QAM 2/3 as the example, we derive the best case downstream and upstream throughput. The maximum amount of data that can be sent in a single frame:

- **Downstream:** \( 192 \times 6 \times \frac{2}{3} \times 79 \times \frac{1}{8} = 7,584 \text{ bytes} \)
- **Upstream:** \( 192 \times 6 \times \frac{2}{3} \times 88.8 \times \frac{1}{8} = 8,524.8 \text{ bytes} \)

If we assume all available symbols are allocated to a single PDU burst, and if we factor in an overhead of 1500, we get a maximum application throughput of:

- **Downstream:** \( (7,584 \times 8 / 0.01) \times 0.965 = 5.86 \text{ Mbps} \)
- **Upstream:** \( (8,524.8 \times 8 / 0.01) \times 0.965 = 6.58 \text{ Mbps} \)

<table>
<thead>
<tr>
<th>Modulation / coding</th>
<th>Max US Application Throughput (Mbps)</th>
<th>Max DS Application Throughput (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64-QAM ½</td>
<td>6.59</td>
<td>7.41</td>
</tr>
<tr>
<td>64-QAM 2/3</td>
<td>5.86</td>
<td>6.58</td>
</tr>
<tr>
<td>16-QAM ½</td>
<td>4.93</td>
<td>4.54</td>
</tr>
<tr>
<td>16-QAM ¾</td>
<td>2.93</td>
<td>3.28</td>
</tr>
<tr>
<td>QPSK ½</td>
<td>2.20</td>
<td>2.47</td>
</tr>
<tr>
<td>QPSK ¾</td>
<td>1.46</td>
<td>1.65</td>
</tr>
<tr>
<td>BPSK ½</td>
<td>0.73</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Table 2. Expected application throughput

Table 2 shows the best case downstream and upstream TCP throughput for all modulation/coding combinations.

V. 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 that have clear line-of-sight have coverage beyond 0.5 mile. The farthest distance we observed an operational link was 1.2 miles.

We present two types of measured results. First, we summarize the results of TCP throughput experiments that show the best case throughput over a range of modulation and coding settings. Second, we present the results of coverage tests that provide an assessment of the impact that channel impairments have on the network.

For all results reported in this paper we used the higher power M-A/COM subscriber station in a vehicle with an external 6 gain dB antenna attached to the roof. 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.

A. Application Throughput Results

We used the *iperf* performance tool to obtain application 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. 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.

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 3 identifies the observed results. The value in parenthesis indicates the error between the observed throughput and the expected throughput shown in Table 2. The WiMAX base station profile was configured using the settings described in Section 2.

<table>
<thead>
<tr>
<th>Modulation Method</th>
<th>Downstream Application Throughput (Mbps) (Δ of error)</th>
<th>Upstream Application Throughput (Mbps) (Δ of error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64-QAM ½</td>
<td>5.90 (-12.52%)</td>
<td>4.87 (-13.39%)</td>
</tr>
<tr>
<td>64-QAM 2/3</td>
<td>5.38 (-15.58%)</td>
<td>4.34 (-14.35%)</td>
</tr>
<tr>
<td>16-QAM ½</td>
<td>1.59 (-12.95%)</td>
<td>1.59 (-12.95%)</td>
</tr>
<tr>
<td>16-QAM ¾</td>
<td>1.31 (-13.76%)</td>
<td>1.31 (-13.76%)</td>
</tr>
<tr>
<td>QPSK ½</td>
<td>0.64 (-12.71%)</td>
<td>0.92 (-10.55%)</td>
</tr>
<tr>
<td>QPSK ¾</td>
<td>0.73 (-12.94%)</td>
<td>0.92 (-10.55%)</td>
</tr>
</tbody>
</table>

Table 3. Measured downstream and upstream application throughput
The downstream error was quite consistent, ranging from -12.75% to -13.5% and averaging -13%. Where our earlier analysis of expected results suggested that 79 symbols are available for PDU bursts, the data indicates that only 69 symbols are actually available. Without a MAC layer trace it is not possible to provide a definitive explanation for the discrepancy. However, since the discrepancy is a fixed number of symbols per subframe, the most plausible explanation is that there is additional overhead such as provisioning data being carried in the broadcast burst which is always transmitted using BPSK ½ on our system.

The upstream measured results were consistent with expectations. The error ranged from -0.53% to -1.43% and averaged -0.99%. Our measured throughput did not include the 6 byte generic MAC header and 4 byte CRC that frames each burst. When this extra 0.67% overhead is accounted for, the discrepancy is less than 1%.

B. 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 [24]. In brief, the tool is a program that runs on a Linux host that is connected to the WiMAX network through a subscriber station. While accumulating data, the coverage tool periodically collects the following information:

- Time/date of the sample
- The GPS location of the vehicle which was obtained from the GPS Daemon software (gpsd version 2.37 [25] and a USB PHAROS GPS-500 sirf III gps device
- The speed of the vehicle (obtained from gpsd)
- RF information obtained from the WiMAX client radio. The information included the most recent downstream received signal strength and SNR measures calculated by the radio.
- WiMAX PHY layer information including the upstream and downstream modulation/coding method
- Link status determined by the WiMAX radio (the M/A-COM radio defines the link to be either operational, syncing, or ranging)

From January 2008 through June 2008 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. We developed a web site that provides both data archival and analysis capabilities. The web site allows a user to select (and to upload) a data set which is then visualized using a Google Map service. The visualization has two modes: one that shows the RF properties observed with each data sample; a second that shows link connectivity. For brevity, we present results 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.

Figures 2 and 3 show data collected on 1/4/2007 and 6/15/2008 respectively. The black triangle located in the center of the map represents the location of the base station. All data points are from locations that fall within a circle of coverage extending 0.5 miles in radius around the base station. Figure 2 shows that the subscriber station did not have network connectivity roughly 4 times. Further study of the data shows that the subscriber station never lost synchronization rather the SNR dropped below the threshold of 5. Figure 3 shows a significantly larger number of network disconnect events. The gaps in the data occur when the subscriber station did lose synchronization and had to reacquire the channel. While in this state, the subscriber station would not respond to the coverage tool’s request for status information.

We focus on the data in the dashed rectangle shown in Figures 2 and 3. In particular, we look at two portions of the path identified by a dashed and a solid line segment. 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 4 shows the average SNR and received signal strength (in dB) for the measurement samples associated with each path segment from both the January and June data sets. The average receive signal level observed along the dashed segment dropped by 7.2 dB and the SNR dropped by 58% between January and June. The drop was less significant (1.4 dB and 22.1% respectively) for measurements taken over the solid segment. In January, 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 in both January and June.

<table>
<thead>
<tr>
<th>Path segment</th>
<th>1-4-2008 SNR</th>
<th>1-4-2008 RSS</th>
<th>6-15-2008 SNR</th>
<th>6-15-2008 RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dashed</td>
<td>18.6</td>
<td>-86.0</td>
<td>7.79</td>
<td>-93.2</td>
</tr>
<tr>
<td>Solid</td>
<td>14</td>
<td>-89.2</td>
<td>10.9</td>
<td>-90.6</td>
</tr>
</tbody>
</table>

Table 4. RF path analysis for January and June data
VI. CONCLUSIONS

In this study we have analyzed the performance of a 4.9 GHz WiMAX network at Clemson University. We observed application level throughput in range from 5.1 Mbps to 0.64 Mbps. We showed that the measured best case TCP application throughput was about 13% lower than expected values for downstream and within 1.0% for upstream. A detailed frame level trace is required to explain the discrepancy however we conjecture that there is additional overhead such as provisioning data being carried in the broadcast burst which is always transmitted. 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. The coverage was sensitive to the level of foliage present at the time of data collection. During the Winter months, it was possible to maintain network connectivity over the path visualized in Figure 2. However, during the Spring and Summer, the subscriber station suffered frequent link disconnects.

We conclude by noting the limitations of our study. First, our results are based on a deployment involving a single base station. Second, the results provided in this report were from one type of client radio. Additional tests (not reported in this paper) with an Airspan client radio exhibited higher receive signal levels (up to 20 dB in some cases). Finally, we acknowledge that improvements can be made to our deployment. The location of the base station antenna can be tweaked. A higher gain antenna or directional antennas at the base station would presumably improve coverage.

REFERENCES