Field Performance Study of a Regional WiMAX Network for Intelligent Transportation System Applications

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Of the various advanced wireless communication technologies used for intelligent transportation systems (ITS), WiMAX has recently received much attention because of its potential to provide broadband network connectivity, large coverage areas, quality assurance, and mobile access. However, few studies have focused on the deployment, operational, and performance issues of using WiMAX networks for ITS applications in a real roadway environment. This study performed a field performance evaluation of a regional WiMAX network in West Virginia by using important network metrics, including uplink and downlink throughput, signal strength, and connectivity level. On the basis of performance analysis, this paper discusses the feasibility and suitability of a regional WiMAX network deployment for a wireless sensor-based traffic surveillance system in terms of frequency, power, and client side radio requirements. This study provides an insight into the feasibility of using WiMAX to address ITS applications. It will benefit transportation agencies and other stakeholders to support decision making in the deployment and operation of a WiMAX-based ITS network in the future.

The demands of faster, more efficient, and more reliable communication systems for intelligent transportation system (ITS) applications increase the requirements for high-speed broadband communication technologies. Off-the-shelf wireless technologies are being widely deployed for ITS across the country. ITS has adopted mostly cellular-based wireless communications to connect its subsystems: wireless fidelity (WiFi) to provide hot-spot wireless access in public areas and dedicated short-range communication to support vehicle-to-vehicle and vehicle-to-infrastructure short-range communications for applications such as automated toll collection and vehicle-infrastructure integration.

WiMAX, known as the IEEE 802.16 Worldwide Interoperability for Microwave Access standard, is a globally rising wireless communication technology that offers high-speed broadband access, easy extension to suburban and rural areas, and broad coverage. WiMAX is more similar to the cell-phone network than to the WiFi hot-spot type of coverage (1). To support either fixed location or mobile communication, a typical WiMAX network consists of two types of components: base stations (BS) and client devices known as customer premises equipment (CPE) (1). A WiMAX station can have different types and numbers of antennas depending on the required coverage range, direction, and throughput. The CPEs are often engineered differently for indoor and outdoor uses and line-of-sight (LOS) and non-line-of-sight (NLOS) conditions.

ITS applications rely on a huge amount of real-time traffic information, which needs a fast, reliable, and easily accessible communication network. WiMAX holds much promise of meeting these requirements. First, known as the “last mile” connectivity for delivering broadband access to customers, WiMAX can support a LOS communication range up to 50 km and NLOS range between 6 and 10 km (1). Second, WiMAX supports a large frequency range from 2 to 66 GHz and flexible channel bandwidth in both licensed and unlicensed spectra, which simplifies the spectrum selection and acquisition process. Third, theoretically WiMAX can provide a data rate up to 75 megabits/s (Mbps) (with each 20-MHz channel), which can support all levels of real-time traffic surveillance or video conferencing needs between different traffic agencies. For instance, the emergency management service is able to have real-time images of an accident location or the victims who need immediate care. Furthermore, the WiMAX network configuration provides a possibility of integrating different traffic agencies working in the same region. For example, traffic management centers, emergency management service, police, and other agencies will be able to collaborate with each other by using the same communication network to save time and increase efficiency. Last, mobile WiMAX technologies can be used in emergency situations when wired or other wireless technologies are not available to support the required communication for traffic monitoring and management as well as backhaul service from one site to another.

Wireless sensor technology, using spatially distributed sensors connected by a wireless network, is a promising solution for data collection in a large-scale traffic surveillance system. The general idea of using a wireless sensor network for ITS is to deploy a wireless sensor along the roadside to detect traffic information and then send the information to traffic management centers to support further traffic control operations. Within a WiMAX network, each sensor is equipped with a CPE to receive a wireless signal and transmit messages. No extensive and expensive wired communication infrastructure is needed, thus allowing economical system expansion and easier access to remote and rural areas. The large amount of online traffic information from roadside and traffic management centers over the WiMAX network can provide traffic agencies with high-bandwidth streaming to transmit traffic conditions, such as rapid incident and emergency detection.

Not many studies have reported the performance of WiMAX networks with respect to requirements for advanced traffic management.
or the feasibility of using a regional WiMAX network to support ITS applications. From the wide WiMax spectrum range, the spectrum that is appropriate for ITS must be chosen, and, more specifically, the WiMax system profiles must be selected for traffic management applications. Moreover, the performance of a typical WiMAX CPE on real roadway environments needs to be evaluated to determine whether it can support the required data bandwidth for transmission of effective and reliable traffic data. This paper aims to discuss the feasibility of deploying a regional WiMAX network for traffic surveillance in terms of performance, coverage, and variation of client radio capabilities and power supply requirements.

The paper is organized as follows. The next section provides a variation of client radio capacity overview of WiMax technology specification. The third section summarizes related work in performance evaluation of WiMAX for non-ITS and ITS applications. The fourth section describes the field test tools and experimental methodology. The fifth section analyzes the results and discusses deployment and operational issues of WiMAX in ITS. Conclusions are presented in the final section.

**WiMAX Overview**

WiMAX is based on an IEEE 802.16 family of standards and designed to deliver high-speed wireless broadband access to fixed, nomadic, and mobile users. In a fixed WiMAX environment, a BS connects to fixed or slowly moving client devices. In a mobile WiMAX environment, a BS connects to potentially fast-moving clients and ensures seamless handoffs as a client moves into the range of a different BS. For example, the client is a vehicle that is moving at high speed on the highway. Nomadic application falls between fixed and mobile environments, where clients may change locations and connect to different BSs through the relatively disruptive hard handoff process. WiMAX has been an attractive consideration as it supports high bit rates with an extended coverage suitable for rural and suburban areas. Wired connections are not required, as needed with other high-speed broadband services for a larger coverage area.

WiMAX supports connectivity between BS and client devices for LOS or NLOS, making it an attractive option for urban application where LOS is unlikely due to buildings and trees. However, an NLOS WiMAX application may require increased power to support the same throughput as a LOS application, which can make mobile WiMAX more costly. Furthermore, WiMAX also supports dynamic modulations where optimal modulation is selected based on environmental signal propagation conditions. On the basis of knowledge of bandwidth requirements and range coverage, different modulations will be selected by the WiMAX base station. Modulation robustness ranges from 64 quadrature amplitude modulation (64QAM) down to quaternary binary phase shift keying (QPSK) or even binary phase shift keying (BPSK). QAM is a modulation scheme that conveys data by changing the amplitude of two carrier waves. QPSK is a two-bit digital modulation that conveys data by changing the phase of the carrier wave. BPSK is a one-bit modulation. Lower modulation normally needs more complex coding. The further the client subscriber is from the BS, the greater is the possibility of a lower form of modulation and thus lower bit rate, as shown in Figure 1.

**Related Work**

Although WiMAX is a new technology, it has been used worldwide to provide broadband wireless service. The tsunami in Aceh, Indonesia, in December 2004 destroyed all communication infrastructures in the area, other than radio services, making the survivors unable to communicate with people outside the disaster area and vice versa. WiMAX provided broadband access that helped regenerate communication to and from Aceh to assist with disaster recovery. Similarly, after Hurricane Katrina in Mississippi in 2005, WiMAX was used by Intel to assist the Federal Emergency Management Administration in communication efforts in areas affected by flooding. In 2007, the Michigan Department of Transportation established a wide area vehicle-infrastructure integration test bed on I-96 and I-696 in Oakland, Michigan, that integrates several communication technologies, dedicated short-range communication, cellular, and WiMAX service. In California, Caltrain commuters traveling between San Francisco and San Jose enjoy WiMAX wireless service. A broadband wireless system was deployed over 16 mi of track to connect commuters traveling at speeds up to 120 km/h. Besides exploring web pages and receiving e-mail, commuters also enjoy voice over Internet protocol and high-quality media service. The Berkeley Highway Lab in California installed a WiMAX base station on a 100-m-tall building to support a traffic surveillance system that consists of eight cameras and 168 loop detectors on a 2.7-mi section of I-80. This test study found out that WiMAX networking can support large-scale traffic monitoring and enhance video processing and recording.

To understand the characteristics and performance of the WiMAX network, studies were conducted to assess WiMAX communication performance under different applications. WiMAX Forum (11) combined many efforts and evaluated the performance of a minimal configuration-based WiMAX with WiMAX Forum Release 1 system profiles. It was reported that WiMAX can meet stringent requirements to deliver broadband service in a mobile environment. It also demonstrated the advantages of mobile WiMAX compared with other mobile wireless alternatives in terms of superior throughput and spectral efficiency. Chen analyzed the capacity and overhead of using WiMAX as backhaul and found that it can provide adequate backhaul transport at a certain modulation compared with traditional licensed band microwave backhaul (12).

**FIGURE 1 WiMAX modulation with respect to distance.**
versity, South Carolina (13). This study observed application level throughput ranges from 0.64 to 5.1 Mbps over a 5-MHz channel.

With the motivation trend of deploying a WiMAX network for ITS, some researches have identified the operational feasibility in different applications (12, 14–16). Niyato and Hossain introduced an integrated WiMAX and WiFi network architecture for ITS by providing optimally priced mobile hot-spot services (14). Chen described a WiMAX and WiFi integrated emergency management system that can spread the wireless communication coverage area and guarantee efficient emergency operation (12). Bulitude et al. studied a mobile WiMAX server housed in an emergency vehicle for public safety applications (15). Wang et al. evaluated the performance of two non-stationary vehicle-to-vehicle channels and found that WiMAX system performance in the nonstationary channel is more volatile than that in stationary channels (16).

In summary, few studies actually discussed the deployment feasibility of a regional WiMAX network for ITS applications in terms of performance and coverage. The relationship of distance between WiMAX BS and signal loss pattern, as presented in this paper, provides tools to investigate the potential of a WiMAX-based highway traffic sensor network.

EXPERIMENT METHODOLOGY

This section describes the test network, experimental setup, and methodologies used to collect field data in a real highway environment.

WiMAX Test Bed

This field study was conducted in Fairmount, West Virginia, where the WiMax network consists of three BS and each station has two or three 120° antennas. One station is located on the rooftop of the Research Center of the West Virginia High Technology Consortium Foundation building with an altitude of 1,341.7 ft (BS1 in Figure 2). The other two, Verizon tower (BS2) and Fairmont tower (BS3), are located on the top of hills within the city limits. The altitude of the Verizon tower is 1,341.7 ft; however, information on the altitude of Fairmont tower was not available. The research center had two antennas, the Verizon tower had two antennas, and the Fairmont tower had three. Antenna heights for all three towers are about 160 ft. Figure 2 shows the sectors supported by the directional antennas and the extent (in miles) of approximate coverage associated with each BS. All three BS are high powered and produce a maximum effective isotropic radiated power (EIRP) of 40 dBm (where dBm is decibels referenced to milliwatts). EIRP is a measure of the effective power emitted by a transmitter or a measure of the signal strength received. The major technical characteristics of the experimental test bed are shown in Table 1.

Experimental Setup

Field tests were conducted from June through July 2008. The project objectives were to measure and assess the performance of the West Virginia High Technology Consortium Foundation WiMAX network. Two types of tests were conducted: fixed and nomadic. In fixed operation, a client radio, Airspan EasyST, was located in a stationary car. In nomadic operation, performance was measured when the car was moving. The client radio is a higher-power M/A-COM subscriber (with an external gain of 6 dB) antenna attached to the roof of the test car while the measurement tool was operated in the car. The equipment operated in the 4.9-GHz band reserved for public safety operations. All measurements were taken on or near the highway. Because of the geographic and environment characteristics of the city of Fairmont, some test locations or segments of the road did not have a clear LOS with the base station due to a large amount of vegetation and the presence of hills in the area. During the nomadic test, the client antenna did not always have a LOS to the associated BS. Client radios were fixed to one channel during all testing to avoid handoffs. Future work will focus specifically on the impacts of handoffs. Figure 2 shows the experimental set up.

The network testing tool Iperf was used to obtain application throughput measurements. Originally created by researchers at the University of Illinois, Iperf is a network testing tool commonly used to measure transmission control protocol (TCP) or user datagram protocol application throughput (17). TCP is a commonly used protocol...
on the Internet, which offers error correction and flow control to guarantee reliable delivery. A laptop was used for collecting the data through Iperf and was positioned in the test car for each test; then the Iperf program transferred as much TCP data as possible for 10 s—first in the upstream direction and then in the downstream direction. Iperf is configured to display the observed TCP throughput every second, and the modulation was assumed to keep constant during the transfer process.

**ANALYSIS OF RESULTS**

The results presented in this section describe the performance observed for fixed and nomadic modes of operation.

**Fixed Operation Tests**

Seven locations were selected to measure the upstream and downstream throughput. Upstream is data transmission from the client side to the BS and downstream is from the BS to the client. Table 2 summarizes the throughput measurement and modulation of each test location. The throughput results represent the average of 10 1-s samples as observed by Iperf.

As shown in Table 2, the observed average upstream throughputs of all seven test locations range from 714 kilobits/s (kbps) to 6.3 Mbps depending on the distance and environment. In these experiments, substantial losses were observed at multiple occasions. The link errors will likely lead to end-to-end retransmissions, which consumes usable bandwidth and leads to throughput degradation. The disparities in throughput, while using a common modulation scheme (e.g., the downstream TCP throughput for Locations 4, 5, and 6 were quite different even though the same modulation was used), reflect relative packet loss.

Today’s standard definition video surveillance format can consume large amounts of bandwidth (up to 2 Mbps for high-quality H.264 content). The purpose of the fixed operational test was to provide rough data points demonstrating that WiMAX can support current standard definition video traffic devices. With a typical data rate requirement ranging from 64 to 384 kbps for each traffic camera, the test network is clearly capable of supporting useful camera-based surveillance systems (18).

**Nomadic Operation Tests**

Nomadic operation tests use a coverage measurement tool developed by the School of Computing at Clemson University to assess coverage of the WiMAX network (13). This tool is a program that collects information such as time and date, Global Positioning System (GPS) location, vehicle speed, and various measures that represent the link connectivity quality, including the received power signal strength and the signal-to-noise ratio. During a data collection run, data samples were obtained periodically (every 1 s) and recorded by the laptop. The program runs on a Linux host, which is connected to the WiMAX network through a client radio. A website, using Google map service, was used to visualize the data sets. The data at each point are represented by a color-coded ice cream cone. The top part of the symbol represents the most recent downstream received signal strength indicator statistic observed by the radio, and the bottom cone represents the most recent downstream signal-to-noise ratio. The received signal strength indicator is a value representing the received signal strength in dBm (AnaCom Inc.). Green, yellow, orange, and red stand for the level of excellent, good, fair, and poor, respectively. Black means no signal was detected; thus, there is no connection at all. Figure 3 shows the legend used in the visualization results.

Figures 4 through 7 illustrate the connection status while the test vehicle was driving along several paths on the highway. The vehicle speed (obtained from the client GPS device) was generally slower

### Table 1: Technical Characteristics of Experimental Test Bed

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Stations—CPE</td>
<td></td>
</tr>
<tr>
<td>Standard compliance</td>
<td>IEEE 802.16d</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Duplex method</td>
<td>Time division duplex</td>
</tr>
<tr>
<td>Modulation supported</td>
<td>BPSK, QPSK, 16QAM, 64QAM</td>
</tr>
<tr>
<td>Maximum Tx power</td>
<td>Up to +40 dBm per antenna element</td>
</tr>
<tr>
<td>Maximum radiated power</td>
<td>EIRP 40</td>
</tr>
<tr>
<td>Rx sensitivity</td>
<td>−115 dBm(1/16), −103 dBm(1/1)</td>
</tr>
<tr>
<td>Frequency</td>
<td>4.9 GHz</td>
</tr>
</tbody>
</table>

| Antenna System                |               |
| Degree                        | 120           |
| Gain                          | 12 dBi        |

**NOTE:** Tx = transmit, Rx = receiver, dBi = decibel power relative to an isotropic source.

### Table 2: Performance Measurement Results

<table>
<thead>
<tr>
<th>Location No.</th>
<th>Avg. US TCP Throughput (Mbps)</th>
<th>Avg. DS TCP Throughput (Mbps)</th>
<th>US Modulation</th>
<th>DS Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>714 kbps</td>
<td>900 kbps</td>
<td>BPSK1/2</td>
<td>64QAM3/4</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>1.8</td>
<td>QPSK1/2</td>
<td>64QAM2/3</td>
</tr>
<tr>
<td>3</td>
<td>2.2</td>
<td>2.7</td>
<td>QPSK3/4</td>
<td>64QAM2/3</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>3.6</td>
<td>16QAM1/2</td>
<td>64QAM3/4</td>
</tr>
<tr>
<td>5</td>
<td>4.4</td>
<td>5.4</td>
<td>16QAM3/4</td>
<td>64QAM3/4</td>
</tr>
<tr>
<td>6</td>
<td>5.8</td>
<td>6.2</td>
<td>64QAM1/2</td>
<td>64QAM3/4</td>
</tr>
<tr>
<td>7</td>
<td>NA</td>
<td>6.3</td>
<td>64QAM3/4</td>
<td>64QAM3/4</td>
</tr>
</tbody>
</table>

**NOTE:** US = upstream, DS = downstream, NA = data not available.
In this case, the client always has a very good LOS, which ensures an operational link.

Performance of the network depended primarily on whether the client was in LOS of the BS. When in LOS, coverage extended for 1 to 2 mi. Another factor is the specific client devices—in particular, the quality of the antenna system.

Figure 7 compares the connectivity performance of the same driving path but with different client devices. The left one used an M/A-COM radio and the right one used an Airspan EasyST radio. The test location was in a parking lot in front of a mall. While driving slowly around the parking lot, the client maintained LOS with the BS most of the time. The Airspan EasyST clearly achieved better connectivity in this scenario. With one data point located furthest from the BS (roughly 2,595 ft away), the Airspan radio receives a signal strength 30 dB higher than that received by the M/A-COM radio.

As revealed by the field test, several issues must be considered to deploy a WiMAX network for ITS applications. First, the location of the WiMAX tower is crucial. Second, client devices need to be tested beforehand to ensure the performance can meet the minimum communication requirements for different ITS applications.

**Discussion of Power Requirements**

Supporting a large-scale wireless network with a wired power supply may negate the advantage of using wireless over wired applications. Additionally, a wired power supply may not be available or may be expensive to build in rural areas where wireless communication is needed. Therefore, power supply must be considered as part of the system’s planning and design when using WiMAX to support ITS applications. Using traffic surveillance application as an example, this study proposes a solar power configuration to support
FIGURE 5 Connectivity level when associated with BS2.

FIGURE 6 Connectivity level when associated with BS3.
both the traffic camera and the required client radio along the highway. Solar power is a clean and renewable energy that uses solar panels to collect sunlight and convert it into electricity for power supply (19). Each solar panel is composed of many solar cells and absorbs the photons to initiate an electric current. Currently, solar panel arrays can be sized to support most electrical load requirements and have been widely applied to home and commercial use, such as remote traffic controllers, telecommunication equipment, and facility monitoring.

The size of solar panel needed for traffic camera and client device depends on power loads. For stakeholders to design and build their own solar supply traffic surveillance system, the first step is to calculate the current and voltage of the client WiMAX radio and traffic camera and then calculate the wattage needed. Table 3 shows the proposed solar power size based on regional sun rate, solar module, solar rating, and power needs of client radios and traffic cameras. Sun rate indicates the amount of sunlight exposure throughout the year in different regions, normally measured in kWh/m². Using the southeastern area as an example, the average sun rate is 4.5 (19).

Power specification, such as direct current voltage and watts, for the traffic camera and client radio have been estimated according to vendor advertisements and are summarized in Table 3 assuming the traffic camera is working 8 h/day to support continued traffic monitoring (20, 21). Solar module means that several solar cells were combined into a module with the purpose of harvesting solar energy. Among several available solar modules, this study chose SX-40 and SX-50 as examples, which are general purpose modules suitable for single-module 12-V applications with downstream system voltage (22). Theoretically, the maximum power values, $P_{\text{MAX}}$, of these two models are 40 and 50 W. The warranted minimum $P_{\text{MAX}}$ values of these two are 36 and 45 W, respectively. Battery rating is a term used to measure cumulative energy going into or out of the batteries, which provides an estimate of state of charge (23). Solar array is a group of solar panels designed to support an application.

As shown in Table 3, four SX-series solar modules are needed for each WiMAX wireless network-supported traffic camera, four modules in series and one in parallel. The proposed solar array is 52.7% larger than the required energy amounts when more SX-50 modules

<table>
<thead>
<tr>
<th>Sun Rate</th>
<th>Traffic Camera Watts</th>
<th>Traffic Camera Hours</th>
<th>Client Radio Watts</th>
<th>Client Radio Hours</th>
<th>Base Direct Current Voltage (V)</th>
<th>Total Load (W)</th>
<th>Solar Module</th>
<th>Battery Rating</th>
<th>Solar Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>20</td>
<td>8</td>
<td>22</td>
<td>8</td>
<td>48</td>
<td>420</td>
<td>SX-50</td>
<td>100 amp hours, 12 V</td>
<td>4 modules in series 1 module in parallel 4 SX50 modules needed 52.7% larger than the required amount</td>
</tr>
<tr>
<td>4.5</td>
<td>20</td>
<td>8</td>
<td>22</td>
<td>8</td>
<td>48</td>
<td>420</td>
<td>SX-40</td>
<td>100 amp hours, 12 V</td>
<td>4 modules in series 1 module in parallel 4 SX40 modules needed 21.9% larger than the required amount</td>
</tr>
</tbody>
</table>

TABLE 3 Solar Power Configuration for Traffic Camera

![Figure 7](image-url) Connectivity comparisons of different client devices (RSSI = received signal strength indicator, SNR = signal-to-noise ratio, US = upstream, DS = downstream).
are used; the value decreases to 21.9% when SX-40 is used. The number of modules needed also changes when other solar modules are used. The more devices required, the larger is the size of solar array that is needed. Therefore, stakeholders need to consider power requirements, operation hours, and available installation to save energy consumption, installation space, and cost. Detailed size and cost information were not the focus of this study.

The cost of building a WiMAX network, which includes BS, client radios, and other related fees, is an important issue that needs to be considered for any deployment decision. The typical cost for a client station is about $2,200 and a BS is about $10,000. However, these numbers can be deceiving, as most vendors require clients to purchase other necessary tools, such as network management software, which adds to deployment costs.

CONCLUSIONS

WiMAX has received the attention of many public agencies because it provides a high bandwidth and a large frequency range. Moreover, WiMAX can support a large number of users because of its broad channel range. This paper evaluates performance of a regional WiMAX network in terms of performance and coverage for potential applications in ITS.

Two types of field experiments—fixed and nomadic applications—were conducted in West Virginia on a road network covered by three WiMAX towers. Collected data of fixed applications revealed that achievable throughput ranged from 1.414 to 5.489 Mbps, which satisfies typical traffic sensor data requirements of 64 and 384 kbps. The nomadic experiments related to coverage suggested that LOS greatly affects the connectivity level. Moreover, as an emerging technology, the capabilities and the performance of WiMAX networks sometimes are affected by the characteristics of the client radio. Traffic agencies have to test the performance of different radio products before implementation to ensure the minimum communication requirements per unit can be satisfied.

This study also presented an example of solar power configuration for a WiMAX wireless-supported traffic surveillance system. Given the power requirements of traffic cameras and client radios, engineers can estimate the solar battery array requirements. The solar module, battery rating, regional sun rate, and even the available installation space for each unit affect the configuration design.

Future field experiments should include large highway networks with more sensor nodes or client radios and increased WiMAX coverage. As WiMAX can support communication needs of other public agencies, such as law enforcement and emergency management service, in addition to the needs of transportation agencies, a regional WiMAX deployment will provide multiagency benefits, which would likely optimize the available communication resources.

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