Measurements and Evaluation of the Network Performance of a Fixed WiMAX System in a Suburban Environment

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Abstract—Fixed WiMAX can be a solution for delivering broadband wireless access, because of its low deployment costs and its offered bandwidth. But it is of great importance that this technology can offer the same network performance as its competitors. We therefore propose in this paper the results of extensive measurements of the network performance (i.e., throughput, latency, and jitter) of an 802.16-based system during a field trial, and investigate the influence of different base station and WiMAX modem heights. We also analyze the correlation of these network performance characteristics with distance and carrier-to-interference-noise ratio (CINR). It is shown that the latter can be used for developing reliable and accurate semi-empirical models of these network performance characteristics. These models can then be used to estimate throughput, latency, and jitter by means of CINR measurements.

I. INTRODUCTION

The last decade there is an increasing demand for broadband network access. Most of these broadband services have been delivered by cable and DSL (Digital Subscriber Line) operators. Because the demand for high-speed services is still increasing, there is a great interest in alternative wireless low-cost solutions to provide broadband network access. This paper focuses on WiMAX (Worldwide Interoperability for Microwave Access), a wireless broadband technology based on the standards IEEE 802.16-2004 [1], and ETSI TS102177 [2], promising high data rates for large ranges.

Research about the performance of WiMAX has already been done, in particular about the propagation models applicable for WiMAX rollouts [3], [4]. [3] compares different propagation models with each other and provides a theoretical performance analysis for a 802.16 system. In [4] measurements of the carrier-to-interference-noise ratio (CINR) in an urban environment have been performed, but actual measurements of typical network performance characteristics such as throughput, latency, and jitter have not been determined. In [5], limited measurements of throughput for one specific modulation are presented. Thus, only few data of actual WiMAX network performance measurements are available. Therefore, measurements of the actual performance of a real WiMAX system are necessary and provided in this paper.

In this paper, we analyze the experimental results of the network performance for different configurations of the system such as different base station (BS) and modem heights for a fixed WiMAX system in a suburban environment at Ghent (Belgium). Extensive measurements at many different outdoor locations for the different configurations are performed and analyzed, and relationships between CINR and different network performance characteristics (i.e., throughput, latency, and jitter) are determined. These models can then be used by WiMAX network operators for future WiMAX network planning.

The paper is organized as follows. Section II describes the configuration of the WiMAX system, and the parameters of the setup for the investigated configurations. Section III presents the results of the measurements for the different configurations. Section IV shows the relationships between the observed CINR and the different network performance characteristics. Finally, conclusions are presented in Section V.

II. MEASUREMENT METHODOLOGY

A. WiMAX system

The WiMAX system includes the base station (BS), the CPEs (customer premises equipment, also called WiMAX modems) for residential and business users and is part of an end-to-end network solution that provides an evolution path for fixed, and nomadic services according to WiMAX Forum recommendations [1], [2].

For the considered configurations described in Section II-B, the BS is located on the roof of a modern office building in Ghent (height $h_{BS} = 15$ m or $h_{BS} = 45$ m). The BS antenna is an 120° sector antenna with vertical polarization. The electrical beam tilt is -2° (or 2° below the horizontal plane). The input power to the BS antenna is 35 dBm.

The channel bandwidth (BW) of WiMAX systems can be varied from 1.25 to 28 MHz [1]. A channel BW of 3.5 MHz is analyzed in this paper because this BW is typical for the 3500 MHz band in Europe. The downlink (DL) frequency is 3520 MHz, the uplink (UL) frequency is 3420 MHz.

The WiMAX system supports BPSK, QPSK, 16-QAM, and
64-QAM modulations and provides a per-allocation adaptive modulation and coding scheme, which means that the WiMAX system should ensure the most robust link conditions with the highest data rate by optimally selecting the best physical mode in DL and UL.

The CPE is a half duplex unit, so the DL and UL are tested consecutively and not simultaneously. The CPEs are positioned in a mini-van with the antennas mounted outside the car on a telescopic mast at a height \( h_{\text{CPE}} = 2.5 \text{ m} \) or \( h_{\text{CPE}} = 6 \text{ m} \).

### B. Investigated configurations

The measurements are performed at different outdoor Line-Of-Sight (LOS) or non-Line-Of-Sight (nLOS) locations. At each location, the CPE antennas are oriented in the direction where the RSSI (Received Signal Strength Indication) reaches a maximum. The sector link performance is investigated. The following configurations are used for the measurements in the suburban environment. For configuration 1, the BS and CPE are placed at heights of \( h_{\text{BS}} = 15 \text{ m} \) and \( h_{\text{CPE}} = 2.5 \text{ m} \), respectively. Configuration 2 uses heights of \( h_{\text{BS}} = 15 \text{ m} \) and \( h_{\text{CPE}} = 6 \text{ m} \). Finally, the heights for configuration 3 are \( h_{\text{BS}} = 45 \text{ m} \) and \( h_{\text{CPE}} = 2.5 \text{ m} \). The measurements for the configurations 1, 2, and 3 have been performed at 79, 23, and 50 locations, respectively (thus 152 locations in total).

### C. Measurement equipment

ByteBlower is a powerful measurement tool designed by Excentis [6] and is able to measure the most important network performance characteristics introduced by broadband networks: packet loss, latency, and jitter. To obtain information of the several Radio Frequency (RF) characteristics such as modulation, CINR, and received signal power, the webinterface of the CPE is used. Using a simple webbrowser tool, these parameters are measured each second. For this study, the CINR is only monitored for the DL; the webinterface does not provide information about the CINR in the UL. This characteristic is measured by the BS (for reliable processing of the adaptive modulation and coding scheme in the UL), but not available in the BS used for this research. In this paper, we assume that the CINR measured in the DL is a good estimation of the CINR in the UL.

The measurement positions are acquired with a GPS device. Using a vehicle, the CPEs are moved in the environment from location to location. Car batteries are used as power supply for the equipment.

### D. Overview of analyzed parameters

The different parameters necessary for the performance analysis are the following: packet loss (PL), latency (L), jitter (J), and CINR. UDP (Uniform Data Protocol) traffic, with a packet size of 1500 bytes, is analyzed (UDP traffic eliminates the influence of congestion control used in Transmission Control Protocol (TCP) traffic, resulting in more reliable estimations of the effective throughput of the WiMAX link). The throughput is measured by transmitting data through the WiMAX link at 12 Mbps (this is the maximum available data rate for the WiMAX system with a BW of 3.5 MHz). Because ByteBlower measures only the packet loss, the throughput (TP) is then derived using the following equation:

\[
TP = S \cdot (1 - PL)
\]

with

- \( TP \) = throughput [Mbps]
- \( S \) = transmission rate [Mbps] = 12 Mbps
- \( PL \) = packet loss

The latency and jitter are measured by transmitting data through the WiMAX link at 0.5 Mbps, because this data rate is guaranteed with the lowest modulation scheme BPSK. By using this rate, the measured latency will not include the buffer latency. In this paper, we are only interested in the latency caused by other factors such as the access, and transmission latencies (see Section IV-B).

### III. MEASUREMENT RESULTS AS A FUNCTION OF DISTANCE BS-CPE

The range of the considered system and the percentage of locations with connection are discussed for the different configurations in Section III-A. We also discuss the high correlation of the network performance characteristics with the CINR in Section III-B.

#### A. Range of the system

Fig. 1 shows the relationship between CINR and distance (BS-CPE) for the three configurations. Only a moderate correlation between CINR and distance can be observed (a correlation coefficient of about -0.5 has been found for the three configurations). CINR is shown in Fig. 1, because of the high correlation between the CINR and the network performance characteristics (see Sections III-B and IV). Linear regression models, which are obtained by applying an MMSE (Minimum Mean Square Error) curve-fitting algorithm to the measurements, are also added in Fig. 1. Note that only the results of the locations where the CPE could connect to the BS are shown in Fig. 1 (95 of the 152 locations).

Configuration 1 shows a maximum range of 1.3 km, of which there is always connection in a range of only the first 300 m. By raising the CPE antenna from 2.5 m to 6 m (configuration 2), only marginal improvement is noticed: the CINR increases somewhat compared to configuration 1, but the maximum range remains 1.3 km. A significant improvement is noticed for configuration 3: increasing the height of the BS from 15 m to 45 m enlarges the range from 1.3 km to 2.2 km, and there is almost everywhere connection in a range of 1 km.

#### B. Network performance characteristics

The throughput has also a moderate correlation with distance (similar as CINR to distance: \( p_{\text{distance}} \) about -0.4 for DL), but a much higher correlation with CINR (i.e., \( p_{\text{CINR}} \) of about 0.97 for DL), indicating that environmental conditions play a more important role to predict the throughput. Because
of this high correlation, a model will be proposed and discussed in Section IV-A.
In DL and UL, maximum throughputs of 8.9 Mbps and 11.95 Mbps are obtained, respectively. The difference between the maximum throughputs in DL and in UL is due to the implementation of this WiMAX system under test. DL packets carry relatively a lot more control signaling and dummy bytes than UL packets. These dummy bytes are provided for future enhancements.

The latency and jitter have also low correlations with distance (similar as CINR to distance: $\rho_{distance} \approx 0.3$ and 0.2 for latency and jitter, respectively), but much higher correlations with CINR (i.e., $\rho_{CINR}$ of about -0.73 and -0.6 for latency and jitter, respectively), again indicating that environmental conditions play a more important role to predict latency and jitter. Because of these high correlations, models will be proposed and discussed in Section IV-B.

IV. EMPIRICAL MODELS FOR NETWORK PERFORMANCE CHARACTERISTICS VS. CINR

The lower correlation of the network performance characteristics to distance than to CINR indicate that CINR is a more relevant parameter to predict the link quality. In this section empirical models will be proposed for throughput, latency, and jitter versus CINR, for both DL and UL.

A. Throughput

Fig. 2 shows the relationship between throughput and CINR for all configurations. High correlation can be observed for all configurations (correlation coefficients $\rho_{CINR}$ of 0.96 and 0.68 have been found for DL and UL, respectively) throughput almost increases exponentially with CINR, until a maximum throughput is reached.

[7], [8], [9] proposed empirical throughput models for WLAN 802.11b/g networks: piecewise and exponential models enable reliable predictions of WLAN throughput based on the measured Signal-to-Noise Ratio (SNR). Because of the high correlation between CINR and throughput, a similar empirical throughput model can be developed for WiMAX. An exponential piecewise model is proposed for DL and UL (Fig. 2):

$$TP = TP_{max}$$
if $CINR > CINR_c$

$$= A_b \cdot \left( e^{A_c(CINR-CINR_0)} - 1 \right)$$
if $CINR < CINR_c$

(2)

The two lines of (2) intersect at $CINR_0$, which can be obtained using (3).

$$CINR_c = \frac{ln(TP_{max} + 1)}{A_c} + CINR_0$$

(3)

$TP_{max}$, $CINR_0$, $CINR_c$, $A_b$, and $A_c$ are constants that are scenario specific: they are dependent on vendor [9], application (UDP packets show lower SNR requirements than TCP ones to obtain equal throughputs [8]), measurement environment and location [8]. $TP_{max}$ is the throughput saturation level resulting from the CINR exceeding the critical threshold $CINR_c$. $CINR_0$ is the CINR where the throughput is zero. $A_b$ and $A_c$ determine the rate at which the throughput reaches saturation for the considered WiMAX system. Table 1 summarizes the values for these different parameters of the fits in Fig. 2 for DL and UL.

The parameters of the model (Table I) are determined by applying an MMSE curve-fitting algorithm on the measurements of all configurations together. The method to obtain these parameters is explained as follows (based on [9]). A wireless link with high CINR should be reliable. Fig. 2 indicates already that from a certain CINR a high throughput is obtained with only little fluctuation. Thus, the highest 5% of throughput values are averaged to determine the saturation level $TP_{max}$. The other 95% of the measurements are used together with the MMSE algorithm to determine the other parameters $A_0$, $A_c$, and $CINR_0$. Finally, $CINR_c$ can be obtained using (3). Table I shows the values for the parameters. The intersection $CINR_c$ results in a threshold CINR value of about 30 dB (for both DL and UL).

The model can be evaluated by the mean error $\mu$, standard
deviation $\sigma$, and the correlation coefficient $R$ between measured throughput and modelled throughput. The results (Table I) show that the model produces a curve with a very low mean error (only 0.03 Mbps), low standard deviation (about 0.5 Mbps) and a high correlation coefficient $R$ (about 98%) for DL, which indicates the high reliability of the proposed model for DL. The model for UL delivers higher deviations (e.g., a standard deviation of about 2 Mbps): this can be explained by the fact that we assumed that the UL CINR is equal to the DL CINR. Nevertheless, there is still a good agreement for UL between model and measurements (as shown in Fig. 2).

**B. Latency and jitter**

Fig. 3 shows the results of the measurements of latency in DL and UL for all configurations, respectively. A high correlation is also observed between latency and CINR: high CINR values correspond with low latencies (e.g., $\rho_{\text{CINR}} = -0.73$ for DL). Latency decreases for higher CINR values (negative correlation coefficient) up to about 28 dB, from which on the latency saturates at a level of about 17 ms and 37 ms in DL and UL, respectively. This negative correlation is of course due to the adaptive modulation: the higher the CINR, the higher the modulation scheme, the higher the transmission rate, thus the lower the latency. This adaptive modulation causes thus a transmission latency, which can be calculated as the ratio between packet size and transmission rate.

We can also see that DL latencies are generally smaller than UL latencies (UL latency is often twice the DL latency, see Fig. 3). This difference is due to the MAC mechanism of the WiMAX system, which causes an access latency. The DL traffic is directly forwarded from BS to the CPEs, causing a low access latency. The UL traffic, on the contrary, has to follow the MAC (Media Access Control) protocol. This protocol forces CPEs to request bandwidth from the BS before the CPEs are granted to send data in the UL. UL traffic has thus a higher access latency than DL traffic due to the ‘request-grant’ principle in the UL. Thus we can conclude that the total latency consists of two main parts: the transmission latency caused by the available transmission rate of a modulation scheme and the access latency caused by the MAC mechanism of the WiMAX system. Note that also other factors such as serialization and channel coding contribute to the total latency. The following empirical model is proposed for latency:

$$L = L_{\text{max}} - (L_{\text{max}} - L_{\text{min}}) \cdot (1 - e^{-A_d(CINR-CINR_0)})$$

(4)

$L_{\text{max}}$, $L_{\text{min}}$, $\text{CINR}_0$, and $A_d$ are also constants that are scenario specific. $L_{\text{min}}$ is the saturation level. $\text{CINR}_0$ is the minimum CINR for which connection can be obtained. $A_d$ determines the rate at which the latency reaches saturation. Table I summarizes the values for these different parameters and shows very good agreement between model and measurements.

Fig. 4 shows the results of the measurements of the jitter in DL and UL for all configurations. A moderate to high correlation is observed for the jitter (e.g., $\rho_{\text{CINR}} = -0.57$ for DL). Jitter decreases with increasing CINR values up to about 28 dB, from which on the jitter reaches a constant level of about 3 ms and 18 ms in DL and UL, respectively (but with higher variation at saturation level than for throughput and latency, see Fig. 4).

Also DL jitters are generally much smaller than UL jitters. Again, the difference can be explained by the MAC mechanism. Several time slots in the UL are reserved, in which CPEs may send their bandwidth requests. These time slots are also called ‘contention slots’ because these requests can cause a collision. For example, two CPEs sending at the same time a request, will conflict with each other. Because of this, the two CPEs will wait an arbitrarily time period to send the request again. Obviously, this will result in a higher jitter (and latency) for UL packets.

For the jitter the following empirical model (similar as for WLAN [10]) is proposed:

$$J = A \cdot e^{(-B(CINR-C))}.$$  

(5)

A, B, and C are constants that are also scenario specific. A and B determine the rate at which the jitter reaches ‘saturation’ (parameter values are shown in Table I).

The parameters of the models (Table I) are again determined by applying an MMSE curve-fitting algorithm for the measurements of all configurations together. The models can be evaluated by the mean error $\mu$, standard deviation $\sigma$, and the correlation coefficient $R$ between measured latency/jitter and modelled latency/jitter. The results show that the model for DL latency produces a curve with a very low mean error (0 ms), low standard deviation (about 3 ms) and a high correlation coefficient $R$ (about 80%), indicating the very high reliability of the proposed model. DL jitter shows also a low mean error (about 0 ms) and low standard deviation (about 1 ms), but with a lower correlation coefficient $R$ (about 60%) than the models for throughput and latency.
### Table I

<table>
<thead>
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<th>Model</th>
<th>Coefficients</th>
<th>Statistics</th>
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<td>$T_{max}$ [Mbps]</td>
<td>$A_0$</td>
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<td>DL</td>
<td>8.8552</td>
<td>2.9207</td>
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<tr>
<td>UL</td>
<td>11.8496</td>
<td>0.0502</td>
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<td></td>
<td>$L_{max}$ [ms]</td>
<td>$L_{min}$ [ms]</td>
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<tr>
<td>DL</td>
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<tr>
<td>UL</td>
<td>100.1936</td>
<td>0</td>
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<tr>
<td></td>
<td>$C$ [dB]</td>
<td>$E$</td>
</tr>
<tr>
<td>DL</td>
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<td>0.0495</td>
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<tr>
<td>UL</td>
<td>16.0807</td>
<td>0.1085</td>
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</table>

The deviations for UL latency and jitter are higher than for DL, again because of the assumption that the UL CINR is equal to the DL CINR.

### V. Conclusions

In this paper the experimental results and evaluation of the link performance for a 802.16 based (WiMAX) system for a 3.5 MHz channel in the 3.5 GHz band have been presented for different configuration setups, such as different base station heights, and WiMAX modem heights. This study shows that increasing the modem height from 2.5 m to 6 m barely improves the network performance and the maximum possible range. Increasing the base station height from 15 m to 45 m significantly improves the maximum range from 1.30 km to 2.21 km.

All investigated configurations indicate a moderate correlation between network performance and distance, and a high correlation between network performance and CINR. Therefore, models are developed for the different network performance characteristics as a function of the CINR, and excellent agreement is obtained between the measurement and model values. WiMAX network operators can apply these models for accurate estimations of throughput, latency, and jitter for future WiMAX network planning.

### Acknowledgment

This work was supported by the IBBT-CiCk project, cofunded by the IBBT (Interdisciplinary institute for BroadBand Technology), a research institute founded by the Flemish Government in 2004, and the involved companies and institutions. W. Joseph is a Post-Doctoral Fellow of the FWO-V (Research Foundation at Flanders).

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