Performance Evaluation of Broadband Fixed Wireless System based on IEEE 802.16

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***Abstract*— Fixed Wireless Access systems operating below 11 GHz have the potential to provide broadband wireless access for non line-of-sight operation. In this paper the performance of a typical broadband fixed wireless system based on the IEEE 802.16-2004 specifications is determined. A scenario for business applications with outdoor customer premises equipment is investigated in the 3.5 GHz frequency band. Different path loss models and terrain types are considered. Coverage and throughput in a sector are determined for this business scenario.**

I. Introduction

The enormous growth of the internet causes a rising demand for high-speed internet access. WiMax (Worldwide Interoperability for Microwave Access) – based on the standards IEEE 802.16 [1] and HiperMAN [2] – for BWA (Broadband Wireless Access) promises high data rates and gains popularity compared to DSL (Digital Subscriber Line) and cable technologies. The advantages of fixed broadband wireless access over wired systems are mainly the lower cost and the flexibility for the deployment of the system compared to the deployment of DSL and cables.

We analyze the 2 - 11 GHz 802.16-2004 system for Non Line-Of-Sight (NLOS) operation because such systems will be deployed in the very near future. In this paper the air interface WirelessMAN-OFDM, a 256 carrier orthogonal frequency division multiplexing (OFDM) scheme, will be considered because this air interface is favored by the vendors (low peak to average ratio, faster FFT calculation and less stringent frequency synchronization requirements than 2048 carrier OFDM). The competitiveness of WiMax will largely depend upon the actual data rates and ranges that can be achieved. Therefore we investigate in this paper the coverage and throughput in a sector for a typical system (in Belgium) based on the WiMax specifications [1] for a 3.5 MHz channel.

The characteristics of the 802.16 based system are described in Section II. In Section III the coverage of the system under consideration is discussed. The throughput is determined in Section IV. Throughput and coverage are combined in Section V. Finally, the conclusions are presented in Section VI.

II. Selection of characteristics of 802.16 based system

A. Frequency band selection

When planning a FWA (Fixed Wireless Access) network, the operator has to make a choice between the available frequency bands. The selection of the frequency band to be used has a major effect on the dimensioning and planning of the FWA network.

Here, the 3.5 GHz FWA band was chosen. The decision was based on the fact that the band is licensed and interference is under control. Also higher transmission powers are allowed and the frequencies of the band are sufficiently low to obtain a better range and coverage than at 5.8 GHz.

B. Selected parameters and scenario

We will investigate a scenario for business applications. The height of the base station (BS) h_{BS} and the height of the receiver (Rx) h_{Rx} are 30 m and 6 m, respectively. The input power P_i to the BS antenna is 35 dBm (3.2 W). Table I summarizes the selected parameters and the scenario under investigation. The gains of BS and Rx correspond to a typical business modem scenario. The channel bandwidth (BW) of WiMax systems can be varied from 1.25 to 28 MHz [1]. In this paper we assume a channel bandwidth of 3.5 MHz (typical at 3500 MHz in Belgium). We consider outdoor CPE (customer premises equipment), which has larger gains than when indoor CPE would be used. Also no penetration loss into the building has to be considered for outdoor CPE. The coverage margin depends upon the standard variation of the path loss model and the coverage requirement. We will investigate a coverage requirement of 90 %. Furthermore, we will consider here a fade margin of 10 dB (see Section III-B).

We consider in this paper the downlink (DL) performance. The uplink (UL) input power will be lower but sub-channeling and diversity techniques will enhance the uplink budget, resulting in a similar performance.

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TABLE I

CHARACTERISTICS OF SELECTED 802.16 SYSTEM.

parameter	value
frequency	3500 MHz
duplexing	TDD
multiple access	TDMA
modulation	adaptive BPSK, QPSK, 16-QAM, 64-QAM
channel bandwidth	3.5 MHz
input power P_i	35 dBm (3.2 W)
h_{BS}[m]	30
h_{Rx}[m]	6
BS antenna gain G_i	17 dBi
BS feeder loss	0.5 dB
receiver antenna gain G_r	18 dBi
Rx feeder loss	0 dB
CPE	outdoor
coverage requirement	90 %
fade margin	10 dB

C. Receiver sensitivity

Table II shows the receiver sensitivity for the subscriber terminal of the business modem system under consideration for a 3.5 MHz channel. Table II shows that the Rx sensitivity depends on the type of modulation. The Rx sensitivity of 64-QAM modulation is less than for BPSK modulation. The coverage range will thus be higher for BPSK than for 64-QAM. The values of Table II are better compared to the required *minimum* receiver sensitivities defined in [1].

III. COVERAGE PLANNING AND LINK BUDGET

To determine the coverage of the system we first consider different path loss models. Then the shadowing and fade margins will be discussed. Finally the range of the system will be determined for the scenario discussed in Section II.

TABLE II

RX SENSITIVITY FOR THE SUBSCRIBER TERMINAL OF THE WIMAX SYSTEM FOR 3.5 MHZ CHANNEL WIDTH (BER = 10^{-6}).

modulation	coding rate	Rx sensitivity [dBm]
BPSK	1/2	-98.0
QPSK	1/2	-95.0
QPSK	3/4	-93.3
16-QAM	1/2	-88.0
16-QAM	3/4	-86.3
64-QAM	2/3	-81.8
64-QAM	3/4	-80.0

A. Path loss models

Path loss (PL), is defined as the transmit power times the antenna gains divided by the mean received power. Different models have been defined [3] and some of them will be discussed in this paper.

1) Cost 231 Hata-model: The most widely used path loss model is the Hata-Okumura model [4], [5]. This model is valid for the 500-1500 MHz frequency range. There exists an elaboration on the Hata-Okumura model that extends the frequency range. This model is not suitable for lower base station antenna heights, and hilly or moderate-to-heavy wooded terrain. More information about this model can be found in [3]–[5].

2) Erceg model: The limitations of the Hata-model [4], [5] are corrected in the Erceg model [6]. The model covers three most common terrain categories found across the United States. The maximum path loss category is hilly terrain with moderate-to-heavy tree densities (terrain type A). The minimum path loss category is mostly flat terrain with light tree densities (terrain type C). Intermediate path loss condition is captured in terrain type B. The extensive experimental data were collected by AT&T Wireless Services across the United States in 95 existing macrocells at 1.9 GHz. These models are recommended by the IEEE 802.16 Broadband Wireless Access Working Group [1]. The median path loss (PL in dB) is calculated as follows (for a given distance d_0):

$$PL = A + 10\gamma \log(d/d_0) + \Delta PL_f + \Delta PL_h + s \quad \text{for } d > d_0 \quad (1)$$

where

$A = 20\log10(4\pi d_0/\lambda)$ and λ is the wavelength in m
γ is the path-loss exponent with $\gamma = (a - b \cdot h_{BS} + c/h_{BS})$, h_{BS} is the height of the base station) and a, b, and c are constants representing a certain terrain type
d is the distance between base station (BS) and receive antenna (Rx) in m
$d_0 = 100$ m
ΔPL_f is the frequency correction term
ΔPL_h is the receive antenna height correction term
s is the shadow fading component

The shadowing effect is represented by s, which follows a lognormal distribution. The typical value of the standard deviation for s is between 8.2 and 10.6 dB, depending on the terrain and tree density type [6].

3) Cost 231 Walfish-Ikegami (W-I) model: It is shown that the Cost 231 Walfish-Ikegami (W-I) model [7] matches extensive experimental data for flat suburban and urban areas with uniform building height. The COST 231 W-I model gives more precise path loss than e.g., the Hata model. This is due to additional data

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parameters, which describe the characteristics of the environment: building heights, street width, building separation and street orientation with respect to the direct radio path. The model distinguishes line-of-sight (LOS) and NLOS situations. It has also been found that the W-I model for suburban areas is in a good agreement with the Erceg model, providing continuity between the two proposed models. More information about this model can be found in [3] and [7]. In the following we perform simulations with a street width of 25 m, a building height of 12 m, a building to building distance of 50 m and a street orientation of 30 degrees [8].

4) Model for rural areas: For rural areas, the free space path loss model [3] can be used, extended with a term representing excess attenuation in vegetation. The International Telecommunications Union (ITU) deals with attenuation in vegetation in ITU-R Recommendation P.833 [9]. Vegetation can play a significant role for outdoor radio propagation and has to be taken into consideration. The wide range of types of foliage and conditions makes it difficult to develop a generalized prediction.

For a terrestrial radio path, the excess attenuation $\mathrm{A_{ev}}$ due to the presence of vegetation is characterized according to [9]:

$$\mathrm{A_{ev}} = \mathrm{A_m}\left(1 - e^{-\mathrm{d}\gamma/\mathrm{A_m}}\right) \tag{2}$$

where d is the length of the path within woodland (m), γ is the specific attenuation for short vegetative paths (dB(1/m)) and $\mathrm{A_m}$ is the maximum attenuation for one terminal within a specific type and depth of vegetation (dB). The frequency dependent equation of $\mathrm{A_m}$ (dB) is the following:

$$\mathrm{A_m} = \mathrm{A_1}\mathrm{f}^{\alpha} \tag{3}$$

where $\mathrm{A_1}$ and α are coefficients derived from various experiments and f is the frequency in MHz. Values for the parameters of this rural model are given in [9].

We will use in this report an excessive loss of 15.7 dB i.e., approximately 30 m of the path within woodland.

5) Results: Fig. 1 shows the path loss at 3500 MHz for the different models. The height of the BS ($\mathrm{h_{BS}}$) is 30 m and the height of the receiving antenna ($\mathrm{h_{Rx}}$) is 6 m. Also the free space PL is shown in this figure. Due to the multipath environment the PL is much higher than in free space. Fig. 1 shows that terrain C (flat / low tree density) delivers the most optimistic estimation of the path loss. The Hata and W-I model correspond reasonably well with the moderate terrain B model. Mountainous and hilly terrain deliver the highest path losses.

Fig. 2 shows the PL (for the Erceg model and different types of terrain) as a function of the height of the base station from 10 to 80 m. The distance between BS and Rx is 1 km and $\mathrm{h_{Rx}} = 6$ m. It is obvious that placing the base stations higher, results in a

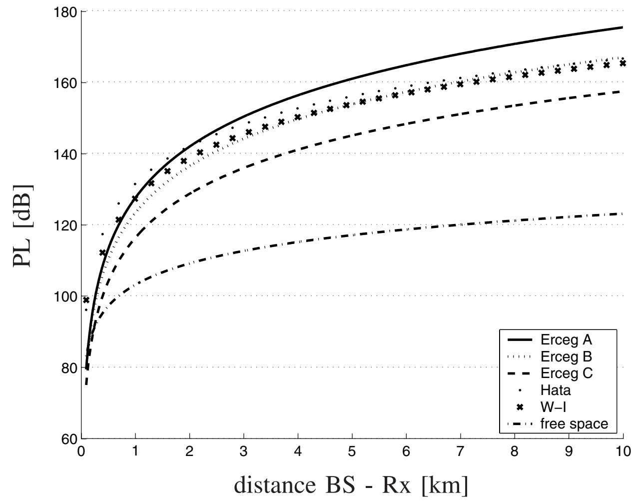

Fig. 1. Path loss at 3500 MHz as function of the distance from the BS for different models ($\mathrm{h_{BS}} = 30$ m and $\mathrm{h_{Rx}} = 6$ m).

lower PL and thus a larger coverage. Changing the height of the BS has a large influence on the PL: e.g., at $\mathrm{h_{BS}} = 10$ m the PL is 130 dB, while at $\mathrm{h_{BS}} = 80$ m the PL is only 110 dB (terrain C).

Fig. 3 shows the PL as a function of the height of the Rx from 2 to 10 m. The distance between BS and Rx is 1 km and $\mathrm{h_{BS}} = 30$ m. For e.g., terrain C the PL varies from 126 to 112 dB. Placing the Rx higher, will again result in lower PL.

These figures clarify the relative large heights of BS and Rx in the business scenario to obtain higher coverage. The models discussed in this section will be used to obtain the ranges of the system under consideration.

B. Shadowing and fade margins

The shadowing margin and fade margin have an important role in the link budget. They depend on the coverage and reliability requirements of the operator for the system. A service could have to be provided at 90 % of all locations within a cell with 99 % reliability. For the Erceg path loss model [6], the shadowing effect, which follows a lognormal distribution, has values for the standard deviation of 10.6 dB for terrain A, 9.6 dB for terrain B and 8.2 dB for terrain C. For a coverage requirement of 90 % we obtain then a *shadowing margin* of 13.6 dB (A), 12.3 dB (B), and 10.5 dB (C) [3]. The coverage requirement described here is for locations at the *edge* of the cell. For the Hata model, W-I model, and the rural scenario we use shadowing margins of 10 dB for 90 % coverage.

The *fade margin* takes the yearly availability of the system

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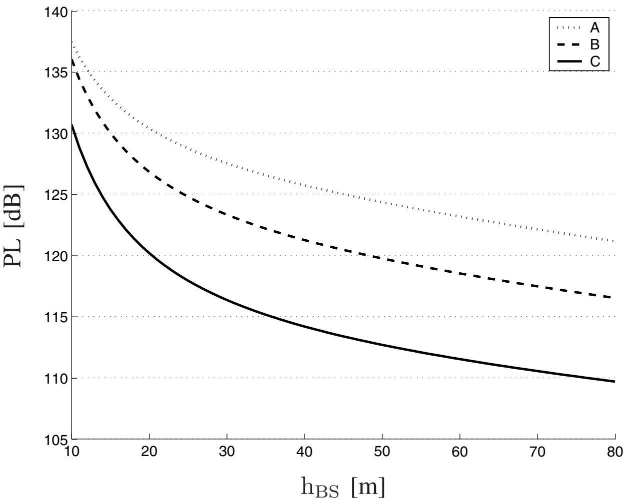

Fig. 2. Path loss at 3500 MHz as function of the height of the BS for different types of terrain (distance BS - Rx = 1 km, $h_{Rx} = 6$ m).

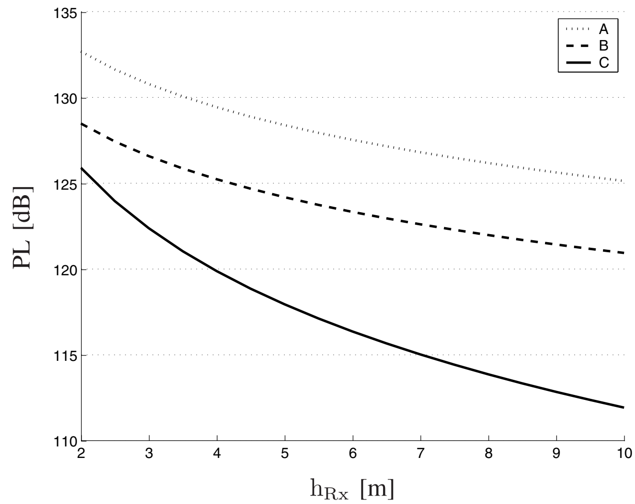

Fig. 3. Path loss at 3500 MHz as function of the height of the Rx for different types of terrain (distance BS - Rx = 1 km, $h_{BS} = 30$ m).

into account. The link availability will be affected by clear-air multipath. We use the ITU-R P.530 model [10] described in ECC report 33 [11] for the fade margin. We will use a fade margin of 10 dB resulting in a yearly availability of 99.995 % for a cell radius of 10 km.

C. Range of selected system

The calculation and tabulation of signal powers, gains, losses and SNR for a complete communication link is called a link budget, which is a useful approach for the basic design of a communication system. To determine the link budget and the coverage range of the WiMax system we use the parameters of Tables I and II and the path loss of Fig. 1. The range of the system for a coverage of 90 % and a fade margin of 10 dB (availability of 99.995 %) for the business modem scenario is shown in Table III. The range that can be obtained depends on the type of modulation. BPSK 1/2 results in ranges up to 5.5 km for suburban regions (terrain C) while 64-QAM 3/4 is only possible up to 2.0 km (terrain C). Terrain C is the most optimistic model for suburban regions. This table shows that for QPSK 1/2 this scenario delivers a range of 1.9 km for hilly terrain of type A, 2.7 km for moderate terrain B, and 4.7 km for flat terrain of type C. The W-I model corresponds reasonably well with the moderate terrain B of the Erceg model. The Hata model delivers higher PL values than the W-I model and the Erceg model (for terrain B and C) and results thus in somewhat lower ranges. For rural terrain and the W-I LOS model larger ranges are possible, e.g., 18.7 to 24.2 km for QPSK 1/2. Because the Hata model was initially intended for a frequency range of 500-1500 MHz we should mainly focus on the Erceg and W-I models for the determination of the coverage.

TABLE III

RANGES [KM] FOR THE SCENARIO UNDER STUDY.

	models						
modulation	Erceg A	Erceg B	Erceg C	Hata	W-I	W-I (LOS)	rural
BPSK 1/2	2.2	3.2	5.5	2.8	3.4	31.6	26.4
QPSK 1/2	1.9	2.7	4.7	2.3	2.8	24.2	18.7
QPSK 3/4	1.7	2.5	4.3	2.1	2.5	20.8	15.4
16-QAM 1/2	1.4	1.9	3.2	1.5	1.8	13.0	8.4
16-QAM 3/4	1.2	1.7	2.9	1.3	1.7	11.2	6.9
64-QAM 2/3	1.0	1.3	2.2	1.0	1.3	7.5	4.1
64-QAM 3/4	0.9	1.2	2.0	0.9	1.1	6.4	3.3

IV. Estimation of Throughput

A. Estimation of delay spread

The phenomenon of delay spread is due to multipath scattering. In order to avoid inter-symbol interference (ISI), a cyclic prefix (CP) is introduced in front of every data part of an OFDM symbol. It is therefore necessary to choose a CP larger than the maximum delay spread.

The delay profile is characterized by $\tau_{\rm rms}$ (rms delay spread of the entire delay profile). It was found that the rms delay spread for omnidirectional antennas [12] follows a lognormal distribution and that the median of this distribution grows as some power of

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distance. The model is the following:

$$\tau_{\rm rms} = \rm T_1 \ d^{\epsilon} y \quad (4)$$

where $\tau_{\rm rms}$ is the rms delay spread, d is the distance in km, T_1 is the median value of $\tau_{\rm rms}$ at d = 1 km, ϵ is an exponent that lies between 0.5 - 1.0 and y is a lognormal variate with standard deviation between 2 - 6 dB. The parameters $\rm T_1$ and ϵ are shown in Table IV [12]. The delay spread remains unchanged for frequencies above 30 MHz, since the wavelengths become much smaller than human-made architectural structures [13], [14]. Because cell ranges (in suburban regions) will certainly be smaller than 10 km we investigate here the delay spread for ranges up to 10 km.

Fig. 4 shows the cumulative distribution function (CDF) of the rms delay spread at 10 km simulated using the model of (4). Table IV lists also the median delay spread values in different types of environment for a cell range of 10 km (range, see Section III-C) and the maximum rms delay spread for 90 % of the delay spread values at 10 km. Fig. 4 and Table IV show thus that 90 % of the delay spreads is smaller than 3 μs for suburban regions. The delay spread is the smallest for rural areas and has the largest values for mountainous areas.

For directive antennas, the delay profile can be represented by a spike-plus-exponential shape [15]. It was shown that 32° and 10° directive antennas reduce the median $\tau_{\rm rms}$ values for omnidirectional antennas by factors of 2.3 and 2.6, respectively. Because in Belgium the terrain is mostly flat and suburban and because directional antennas will be used, a maximum delay spread of 3 μs is a suitable assumption. In [13] a majority (95 %) of the measured delay spreads is less than 1.75 μs.

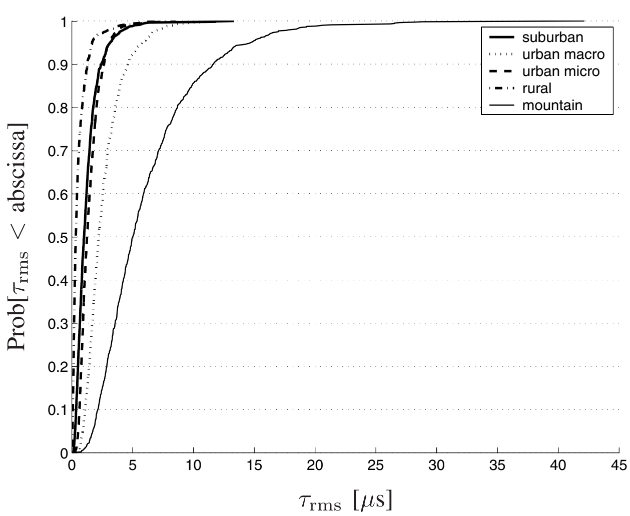

Fig. 4. CDFs of simulated rms delay spread at 10 km for different environments.

TABLE IV

RMS DELAY SPREAD FOR A RANGE UP TO 10 KM USING THE MODEL OF [12].

environment	$\rm T_1$ [μs]	ϵ	median $\tau_{\rm rms}$ [μs] spread at 10 km	maximum $\tau_{\rm rms}$ [μs] in 90 % at 10 km
rural	0.1	0.5	0.3	1.3
suburban	0.3	0.5	1.0	2.4
urban micro	0.4	0.5	1.3	2.6
urban macro	0.7	0.5	2.2	4.6
mountain	0.5	1.0	5.0	11.6

TABLE V

CHOICE OF OFDM PARAMETERS FOR CHANNEL BANDWIDTH (BW) OF 3.5 MHZ.

OFDM parameters	value	choice BW = 3.5 MHz
sampling frequency $\rm F_s$	7/6 or 8/7 ·BW	4 MHz
carriers $\rm N_{FFT}$	256	256
data carriers $\rm N_{used}$	192	192
useful time $\rm T_b$	$\rm N_{FFT}/F_s$	64 μs
subcarrier spacing Δf	$\rm F_s/N_{FFT}$	15.625 kHz
$\tau_{\rm rms}$	3 μs	3 μs
$\rm T_g/T_b$	1/32, 1/16, 1/8, 1/4	1/16
CP time $\rm T_g$	$\rm T_b/16$	4 μs
symbol time $\rm T_s$	$\rm T_b + T_g$	68 μs
bandwidth efficiency	$\frac{\rm F_s}{\rm BW} \cdot \frac{\rm N_{used}+1}{\rm N_{FFT}}$	86 %

B. OFDM parameters

We choose the CP time equal to 4 μs and thus larger than $\tau_{\rm rms} = 3$ μs. The chosen IEEE 802.16 OFDM parameters [1] are shown in Table V [1].

C. Physical layer (PHY) bit rates

Using the OFDM parameters of Table V for a BW of 3.5 MHz the physical layer (PHY) bit rates can be calculated for the different modulations and coding rates [1]. Table VI shows these raw bit rates on the PHY level. The throughput varies from 1.4 to 12.7 Mbps. Approximately 90 % of this bit rate on the PHY level is available to higher layers [14]. Thus the MAC overhead will reduce the bit rate with 10 %.

V. THROUGHPUT AND COVERAGE

Fig. 5 shows the PHY throughput in a sector for the scenario under consideration for a 3.5 MHz channel as a function of the distance. For this figure we combine the coverage distances obtained from Section III-C with the throughput of Table VI. The theoretical PHY throughput for the three types of terrain of the

TABLE VI
PHY MODES AND BIT RATES FOR BW = 3.5 MHZ.

modulation	coding rate	PHY bit rate [Mbps]	spectral efficiency [bit/s/Hz]
BPSK	1/2	1.41	0.40
QPSK	1/2	2.82	0.81
QPSK	3/4	4.24	1.21
16-QAM	1/2	5.65	1.61
16-QAM	3/4	8.47	2.42
64-QAM	2/3	11.29	3.23
64-QAM	3/4	12.71	3.63

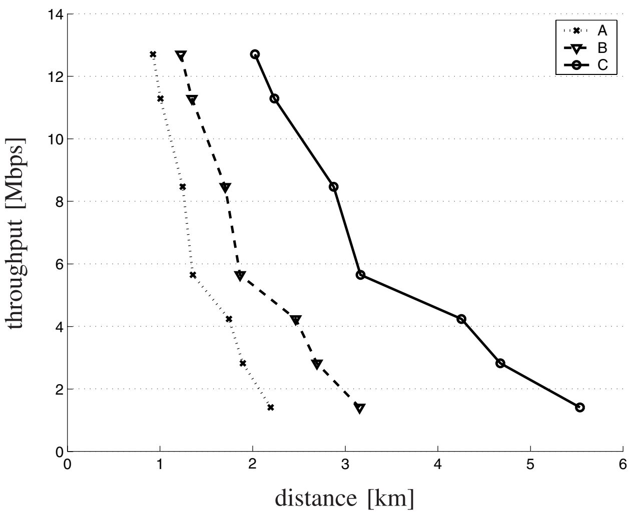

Fig. 5. Throughput for 3.5 MHz channel as function of the distance (P_i = 35 dBm, h_{BS} = 30 m, and h_{Rx} = 6 m).

Erceg model are shown. Each marker on the the curve of a terrain type corresponds with a modulation. BPSK 1/2 corresponds with the highest ranges while 64-QAM 3/4 will reach the shortest distances. E.g., at a range of 2 km a throughput of 5.3 Mbps can be obtained for terrain type B.

VI. CONCLUSIONS

In this paper the coverage and the throughput for fixed wireless systems operating at 3.5 GHz with a BW of 3.5 MHz are analyzed. We have investigated a scenario with input power, BS height and Rx height chosen for business applications. The ranges obtained for QPSK 1/2 are 4.7 km for flat terrain and 2.7 km for an intermediate path loss model. Also the throughput for the different modulation schemes, depending on typical delay spreads, is calculated. The throughput varies from 1.4 Mbps to 12.7 Mbps for a 3.5 MHz channel. For intermediate terrain, a PHY throughput of about 5.3 Mbps for a 3.5 MHz channel can be obtained at 2 km.

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