An Evaluation of the Effects of Propagation Channels on the Performance of WiMAX (IEEE 802.16-2004)

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***Abstract*— The purpose of this paper is to evaluate the performance of fixed-WiMAX (IEEE 802.16-2004) operating in seven propagation channel models, by implementing a WirelessMAN-OFDM physical layer simulator. Through comparative analysis of BER and throughput, the performance of the specified modulation and coding schemes and adaptive control actions were evaluated. Furthermore, the behavior of fixed-WiMAX subjected to a multipath propagation environment and utilization conditions characterized by both stationary and partially mobile applications was also exploited. Thus, this article provides a complementary vision of the standard, which has enabled the determination of customized values for the SNR levels employed for adaptive control, as well as the determination of the capacity obtainable under conditions of partial mobility.**

Keywords- WiMAX, IEEE 802.16-2004, simulation, fading, performance, ITU-R M.1225, mobility

I. INTRODUCTION

WiMAX (*Worldwide Interoperability for Microwave Access*) is a Wireless Metropolitan Area Network (WMAN) technology that enables broadband connectivity for fixed and mobile users. Its specifications are systematized by the 802.16 standard, created by the IEEE with the aim of establishing standards for metropolitan networks, in order to attain interoperability, flexibility and high data rates.

Currently, there are several lines of research on the WiMAX standard underway in technical literature, and data and information from this research have greatly enhanced the existing knowledge base. However, there are still many operational characteristics and peculiarities of this standard that require deeper and more focused analysis.

As means of going some way to bridge this gap, this article presents the results of a study about a fixed-WiMAX (IEEE 802.16-2004) [1] simulation with different propagation channel configurations, which extended the scope of the original specification by considering propagation losses, as well as the implications of its use under conditions of partial mobility.

Accordingly, section II features a brief description of the main aspects related to the fixed-WiMAX physical layer. Section III covers the modeling and implementation processes of the simulator. In section IV, the characteristics of propagation channels and their effects on communication systems, as well as the configurations of the modeled channels, are analyzed. Section V presents the results of simulations in the proposed test scenarios, including graphical representations and corresponding analyses. Finally, section VI contains the article conclusions and final considerations.

II. THE WIMAX 802.16-2004 STANDARD

WiMAX is a family of standards that defines high speed hertzian data transmission through broadband connections. This nomenclature was assigned by a consortium formed on the initiative of several enterprises in the WiMAX Forum (e.g., Alvarion, Intel), with the purpose of attaining convergence and interoperability between two standards theretofore independent: 802.16 [1] and HiperMAN [2].

This unification took place in 2004 with the publication of the 802.16-2004 [1] standard, instituted as a basis for the WiMAX standard. It supports point-to-multipoint and mesh topologies, thus providing LOS (*Line Of Sight*) and NLOS (*Non-Line Of Sight*) coverage in licensed and non-licensed frequency bands, encompassing the 2 to 11 GHz range [3].

WiMAX standardizes the air interface through the specification of the medium access control (MAC) layer and the physical (PHY) layer. The PHY layer establishes a connection between the transmitting station and the receiver, and it also defines some parameters such as the type of signal and the methods of modulation and demodulation [3], [4].

With the 802.16-2004 [1] standard as its focus, the most relevant PHY layer is the *WirelessMAN-OFDM*. It is based on OFDM (*Orthogonal Frequency-Division Multiplexing*) modulation, with 256-point FFT (*Fast Fourier Transform*), operating under NLOS conditions in the 2 to 11 GHz range. This layer has been extensively applied to fixed operations, and, accordingly, it is also known as fixed-WiMAX [5].

III. MODELING AND IMPLEMENTATION OF THE SIMULATOR

The simulator was created in order to evaluate the performance of fixed-WiMAX under a variety of operating conditions. Accordingly, a comparative analysis of input and output data was carried out, considering the Bit Error Rate (BER) and the throughput as a function of the Signal to Noise Ratio (SNR) of the channel.

Thus, a simulator based on the *WirelessMAN-OFDM* PHY layer was created and it was implemented using MATLAB® and SIMULINK® applications [6]. This simulator was based on an application model [7] that was customized and improved to enable the execution of specific verifications, in order to:

- Correlate the levels of sensitivity (BER_{TARGET}) with the SNR limits used by adaptive control (AMC - *Adaptive Modulation and Coding*) to select the codification and modulation schemes (*RateID* parameter).
- Correct the propagation effects with the AMC using new customized values (i.e., not covered in the original specification) for the SNR limits.

The operation in the 3.5 GHz licensed frequency range was decided upon, and a 3.5 MHz nominal band width (BW) was selected, which is analogous to a typical application described in the standard [1]. It was also assumed the use of just an antenna at transmitter and receiver - SISO (*Single-Input Single-Output*) system [6].

The Monte Carlo Method was employed to execute the computational tests, with a confidence interval of 95% having been adopted. Thus, dozens of megabits information (100.000 frames) were transmitted, enabling a sensibility to estimate the performance of the model, given by the BER, in order of 10^{-5}.

Despite the 802.16-2004 [1] standard being specified for fixed applications, the use of the system with a certain degree of mobility was also considered (maximum speed of 3 km/h or approximately 1 m/s)

IV. The Propagation Channel

Three basic channels were modeled (without fading, frequency-flat fading and frequency-selective fading), which, when added to the mobility configurations (without mobility or with partial mobility) and the propagation environment (external or internal), resulted in the simulation of seven operational modes, as detailed in Table I.

With the intention of enabling comparison with other wireless communications systems whilst at the same time obtaining a suitable representation of urban macro-cellular environments [4], the modeling of multipath propagation made use of ITU specifications, which feature in the ITU-R M.1225 recommendation [8]. This study took into consideration internal and external (pedestrian) environments for ITU channels with the B-type profile (i.e., urban environment), with signal reception originating from six different paths.

For fixed applications, a maximum frequency of 0.25 Hz (within the specified range of 0.1 to 2 Hz [9]) for *Doppler* spread was arbitrarily assumed, with the *Doppler* spectrum approximated for a rounded wave shape [9]. In order to simulate an operation with movement, the *Doppler* spread was calculated as a function of the relative velocity between Tx and Rx, the signal frequency and the speed of light [10], obtaining 9.7 Hz.

The classical *Doppler* spectrum *(Jakes)* was selected for mobile frequency-flat fading channels [8]. On the other hand, for frequency-selective fading channel and mobile applications, this parameter followed ITU specifications: flat for internal environment and classical (*Jakes*) for external (pedestrian) environment [8].

TABLE I. Configuration of Simulated Propagation Channels

Channel	Fading	Environment	Mobility
AWGN	N/A	N/A	N/A
FLAT-I	frequency-flat fading	N/A	no
FLAT-II	frequency-flat fading	N/A	partial
ITU-B-I	frequency-selective fading	internal	no
ITU-B-II	frequency-selective fading	internal	partial
ITU-B-III	frequency-selective fading	external	no
ITU-B-IV	frequency-selective fading	external	partial

TABLE II. Codification and Modulation Schemes –*RateID* [1]

RateID	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Code_ Rate	½	½	¾	½	¾	⅔	¾
Modu_ lation	BP SK	QP SK	QP SK	16-QAM	16-QAM	64-QAM	64-QAM

V. Simulation Results

This section details the simulation results and provides an overview of the operation and performance of the model. The effects on the adaptive codification and modulation schemes, as well as the fading phenomena and the impact of partial user movement are all discussed.

Tests were carried out in the downlink direction, with a ⅛ Cyclic Prefix. Duration of the frame was specified at 7199.9 ms, with the transmission of one OFDM symbol per frame [6]. The sensitivity level considered the BER_{TARGET} equal 10^{-5}, since lower values would require a computational effort that would have made the execution of tests unfeasible.

A. Evaluation of AMC and codification/modulation schemes

Adaptive control of codification and modulation schemes is carried out through a comparative analysis between instant values of the estimated SNR of the channel and the SNR standard limits, thus enabling the automatic selection of a suitable configuration for *RateID* [1] (Table II). The standard vector that contains these SNR limits was obtained from the response to the AWGN channel, as indicated in Fig. 1. This vector is presented in Table III, and was validated with the standard [1] and technical literature [6], [11].

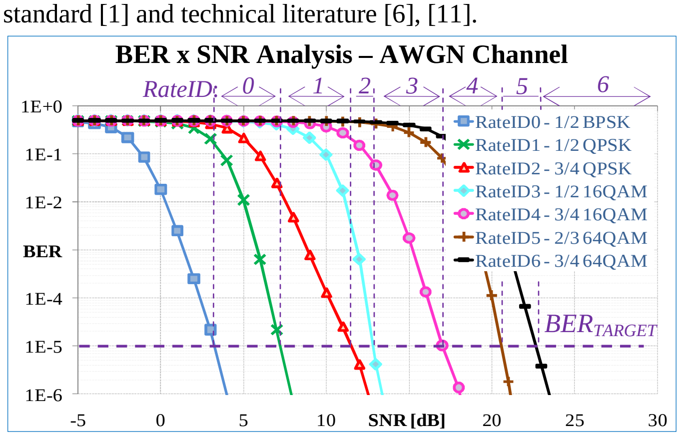

Figure 1. BER x SNR Analysis – AWGN Channel.

Thus, the graphs in Fig. 1 enable the determination of the SNR variation range limits linked to the BER_{TARGET} to be maintained by the AMC (10^{-5}), therefore resulting in the decision of a new value for *RateID* that will be used in the next frame transmission. As the SNR increases, larger *RateID* values are employed, reconciling BER_{TARGET} and more sophisticated codification/modulation schemes.

However, for channels with fading characterized by Rayleigh distribution, subject to conditions of mobility and propagation environment in Table I, the evaluation of the AMC response brings to light relevant information on its performance, as presented in the BER *x* SNR graphs for the channels FLAT-I and FLAT-II (Fig. 2), ITU-B-I and ITU-B-II (Fig. 3), and ITU-B-III and ITU-B-IV (Fig. 4).

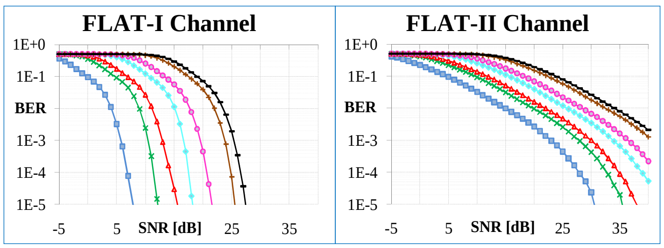

Figure 2. BER x SNR analysis, FLAT-I and FLAT-II channels.

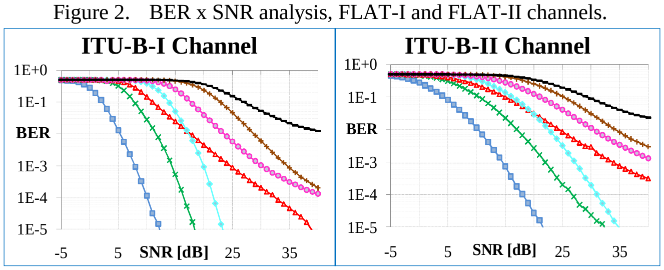

Figure 3. BER x SNR analysis, ITU-B-I and ITU-B-II channels.

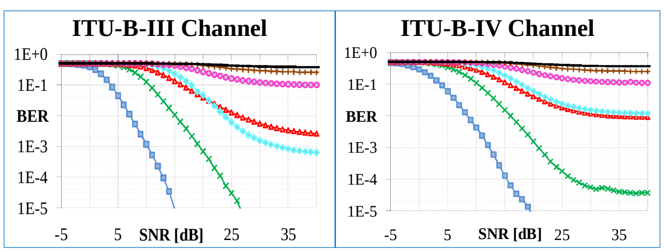

Figure 4. BER x SNR analysis, ITU-B-III and ITU-B-IV channels.

RateID0 - 1/2 BPSK
RateID1 - 1/2 QPSK
RateID2 - 3/4 QPSK
RateID3 - 1/2 16QAM
RateID4 - 3/4 16QAM
RateID5 - 2/3 64QAM
RateID6 - 3/4 64QAM

When comparing these curves with the response to the AWGN channel (Fig. 1), the pernicious effects of multipath propagation, regarding reception errors, are observed, especially for less robust codification/modulation schemes. For example, in an AWGN channel, a 23 dB SNR provided $BER=10^{-5}$ with *RateID6* (Fig. 1), but in ITU-B-III (Fig. 4) the more sophisticated codification/modulation scheme (i.e., higher rate) that ensures such BER is *RateID1*, with 27 dB.

Based on these graphs and upon execution of the same analysis carried out for the AWGN channel, new values (i.e., not specified) can be determined that are more suitable to the new conditions of the channel and, thus, customized vectors can be created that contain these SNR variation range limits

TABLE III. VECTORS WITH SNR LIMITS LINKED TO *RATEID*

Table Head	Vector Type	*RateID x* SNR Limits [dB]						
		0	*1*	*2*	*3*	*4*	*5*	*6*
AWGN	standard	[04	08	12	13	18	21	23]
FLAT-I	customized	[08	13	16	19	22	26	28]
FLAT-II	customized	[31	36	38	–	–	–	–]
ITU-B-I	customized	[13	19	–	24	–	–	–]
ITU-B-II	customized	[22	33	–	35	–	–	–]
ITU-B-III	customized	[15	27	–	–	–	–	–]
ITU-B-IV	customized	[20	–	–	–	–	–	–]

linked to *RateID*, pertaining to the mobility, environmental and propagation conditions under evaluation.

Knowledge of this data enables the correction of the propagation effects to be implemented, thus maximizing AMC efficiency with the purpose of ensuring adequate levels of quality for the received signal. Table III features the new customized vectors for the channels under study (BER_{TARGET} of 10^{-5}), linking the SNR limits to *RateID*.

Continuing with the BER *x* SNR curves, it is possible to compare the simulated results with the standard curves available in technical literature. Considering the transmission of non-codified signals in an AWGN channel, the probability of bit error (P_b) for the BPSK modulation is calculated by the Q-Gaussian function, according to (1) [12]–[14].

$$P_{b\ \ BPSK} = Q\left(\sqrt{2 \cdot E_b / N_0}\right). \qquad (1)$$

It is important to emphasize that the curves with the simulations results previously presented refer to a codified signal and, for the sake of comparison, theoretical signal curves also codified must be taken into consideration.

With this premise in mind, Fig. 5 features a comparative performance analysis of the system with propagation in an AWGN channel, operating with a codification/modulation scheme parameterized by *RateID*0; in other words, with a native code rate of ½ and constraint length equal to 7. Non-codified theoretical BER was obtained by (1), and a theoretical codified value was calculated by (2) [14].

$$P_{b\ \ BPSK} < \sum_{d=d_{free}}^{\infty} \left(a_d \cdot f_{(d)} \cdot Q\left(2 \cdot R_{cr} \cdot d \cdot E_b / N_0\right)\right). \qquad (2)$$

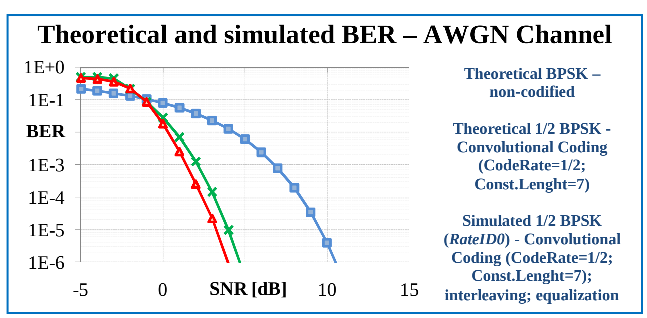

Figure 5. Analysis of theoretical and simulated BPSK signals [13].

According to the graph, the BER *x* SNR response to non-codified signals is less efficient than that to codified signals, both for simulated and theoretical values, given the 7 dB difference to obtain a BER = 10^{-6}. This occurs because in the non-codified signals, a bit of information is equal to a bit of code, making the codified bit error probability (P_{bc}) and the bit error probability (P_b) equal. However, in codified signals, there are two bits of code for every bit of information [13].

The codified BER curves prove that the simulated values are a little better than the theoretical values [13]. This small difference is due to the fact that, for *RateID0*, WiMAX employs a Convolutional encoder in conjunction with a process of interleaving (in order to reduce the concentration of errors) and, furthermore, there the received signal is equalized. Thus, these transformations in the signal executed by the WiMAX structured redundancy scheme make the simulator marginally more efficient when compared to a Convolutional encoder, resulting in a gain of 0.7 dB in the SNR, which is necessary to obtain a BER of 10^{-6}.

B. *Evaluation of fixed WiMAX in conditions of mobility*

This section establishes an analysis of the performance of fixed-WiMAX when users undergo partial movement. This displacement is linked to the delay spread (coherence bandwidth), the *Doppler* spread (coherence time) and the *Doppler* spectrum [4], [9]. Thus, fixed applications have an elevated coherence time (T_c), because f_d = 0.25 Hz, and for mobile applications, the value of T_c is lower (f_d = 9.7 Hz), causing a greater dispersion in frequency.

In the throughput *x* SNR curves, the beginning of the operation occurs when the value of the BER supplied is less or equal to the configured sensitivity ($BER_{TARGET} = 10^{-5}$). The throughput levels were obtained as a function of *RateID*, totally adherent to the standardized values [1].

The simulations were executed in two distinct manners: the first one considers the operation with specified SNR limits, where the AMC is based on standard SNR vectors (line 1 in Table III, channel AWGN). The other form considers the operation with customized SNR limits. In this case, the correction resource for propagation effects is activated, which minimizes damaging interference from multipath fading and optimizes the systems through the use of new values for the SNR limits by the AMC (lines 2 to 7 in Table III).

1) *FLAT-I and FLAT-II channels*

Fig. 6 (a) shows the results of the simulations with the specified SNR limits, and Fig. 6 (b) shows the results of the customized SNR limits (i.e., correction of propagation effects). As expected, the FLAT-I channel presented a better response than the FLAT-II channel, in terms of both the SNR level for the beginning of the operation and the throughput.

According to Fig. 6 (a), for the FLAT-II channel, the configured BER_{TARGET} was ensured only with an SNR of 29 dB, which occurred at 8 dB in the FLAT-I, characterizing a relative degradation of 21 dB. The throughput were also lower, and an additional 10 dB SNR was necessary in order to obtain the maximum rate (12 Mbps), supplied with 40 dB in the FLAT-II channel and with 30 dB in the FLAT-I.

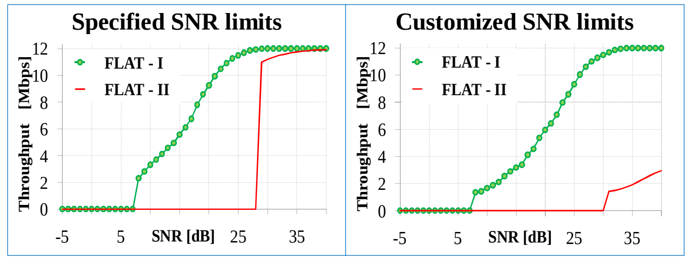

Figure 6. Throughput x SNR, FLAT-I and II channels. Specified (a) and customized (b) limits.

Even after correction of the propagation effects, the prevalence of the fixed channel was maintained in detriment of propagation with mobility. In this condition, the FLAT-II channel presented a minimum operational SNR of 32 dB (Fig. 6-b), leading to a loss of 23 dB with regards to the FLAT-I channel (starting with 8 dB). The throughput was much lower for the FLAT-II channel due to the inefficiency of the correction of propagation effects for this type of channel.

Although the frequency-flat fading channel has a significant correlation of its spectral components ($BW < B_c$) [10], the increase in *Doppler* spread to 9.7 Hz and the resulting reduction of coherence time, as well as the use of a classical *Doppler* spectrum (*Jakes*) in the FLAT-II channel, resulted in a greater dispersion in frequency. This phenomenon had a negative effect on the simulator operation, which started to experience greater difficulty in predicting the propagation channel coefficients and, therefore, in AMC actions.

However, in spite of the degradation observed, simulations proved that fixed-WiMAX can supply high transmission data rates in a frequency-flat fading channel with partial mobility, as long as specific SNR levels were ensured (e.g., 32 dB).

2) *ITU-B-I and ITU-B-II channels*

In the these new propagation conditions, the ITU-B-I and II channels were not successful in the delivery of data for the operational condition with the specified SNR limits, within the SNR range under study, since the resulting error rate did not fulfill the precision required ($BER_{TARGET} = 10^{-5}$).

An important point to be considered in the analysis of the influence of mobility over a frequency-flat fading channel is its inherent characteristic to have a greater delay spread than the period of the transmitted symbol ($BW > B_c$) [13], [15], which naturally impairs the response of the model. Thus, this undesirable condition is leveraged by the effects of a greater *Doppler* spread and a lower coherence time, associated with the condition of mobility. Therefore, the sum of these factors intervened negatively in the instantaneous prediction of the SNR of the channel and AMC actions, causing the mobile channel not to fulfill the BER_{TARGET}.

With the activation of the correction of propagation effects, the simulator started to supply excellent results for the fixed channel (ITU-B-I), despite the lower rates, whose maximum value was 2.7 Mbps. For ITU-B-II channel, the results remained inferior. Fig. 7 shows that with this channel, the simulator fulfilled the BER_{TARGET} with an SNR = 22 dB.

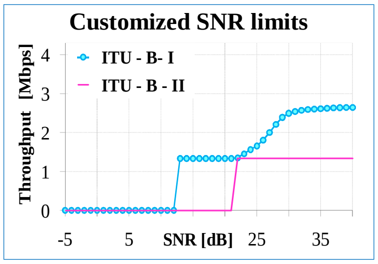

Figure 7. Throughput x SNR, ITU-B-I and II channels. Customized limits.

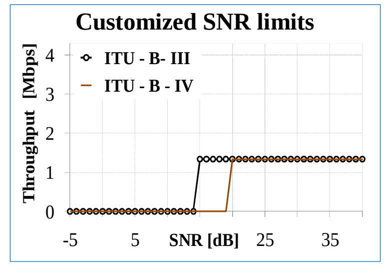

Figure 8. Throughput x SNR, ITU-B-III - IV channels.Customized limits.

As the ITU-B-I channel fulfills BER_{TARGET} with a SNR of 13 dB, there was a relative loss of 9 dB. But the throughput of FLAT-II channel did not surpass the minimum value (1.33 Mbps), equivalent to half rate of FLAT-I channel.

However, these simulator responses for the ITU-B-II channel can be considered acceptable, because the use of customized values of SNR limits through AMC has made the operation of fixed-WiMAX possible, even with the existence of fading and under conditions of partial mobility.

3) ITU-B-III and ITU-B-IV channels

In this situation, the operation with the specified SNR limits was not possible in the fixed (ITU-B-III) and mobile (ITU-B-IV) channels, because in the configurations studied, the maximum value of BER_{TARGET} (10^{-5}) was not attained. Even with a high coherence time for the ITU-B-III channel (small *Doppler* spread and rounded *Doppler* spectrum [9]), the incidence of an elevated delay spread ($BW > B_c$) meant that signals presented significant inter-symbolic distortions and interferences due to attenuation and lag caused by the multipath fading [13], [15], which in turn made the AMC and the prediction of the channel coefficients unfeasible.

Thus, starting from the premise that the simulator cannot operate suitably in a fixed propagation channel (ITU-B-III), proper for this communication system, the equally insufficient performance for propagation in a channel with partial mobility (ITU-B-IV) is justified. However, this situation is totally reversed when a correction of the propagation effects is undertaken, as shown in the graphs in Fig. 8. The activation of this resource enables the simulator to begin responding in a suitable manner, in both the fixed and mobile channels.

Therefore, in this new scenario, it is possible to establish a comparative analysis about the conditions of mobility of the propagation channel. As expected, the graphs present a less efficient response for the ITU-B-IV channel in relation to the minimum operational SNR, despite the transmission rate having been equal to the ITU-B-III channel (1.33 Mbps).

The ITU-B-IV channel caused the simulator to fulfill the BER_{TARGET} only with an SNR of 20 dB, characterizing a relative degradation of 5dB in the ITU-B-III channel (e.g., an SNR of 15 dB for the operation). This took place due to a lower coherence time caused by greater *Doppler* spread and, furthermore, the use of a classical *Doppler* spectrum (*Jakes*) specified for external environments [8].

Also in this case, the results of channels with mobility may be considered effective, because the use of customized values of SNR limits by AMC has enabled the operation of fixed-WiMAX, even with a partial-mobile fading channel.

VI. Conclusions

This article presented an analysis about the performance of fixed-WiMAX, by evaluating adaptive control actions with the determination of new customized values for the SNR levels used in the *RateID* calculation, the effects caused by the characteristics of the channel with the operation based on specified (standard vectors) and customized (correction of propagation effects) SNR limits, as well as the behavior of the model with regards to partial user mobility.

The results of the simulations in the seven channel configurations supplied complementary data on the operation of fixed-WiMAX, thus contributing to existing technical literature with information on more extreme operational conditions than the specification was designed to support.

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