On the impact of hybrid errors on mobile WiMAX networks

Rafael Kunst *, Cristiano Bonato Both, Lisandro Zambenedetti Granville, Juergen Rochol

Institute of Informatics, Federal University of Rio Grande do Sul, Av. Bento Goncalves, 9500 Porto Alegre, RS, Brazil

**Abstract**

Burst and AWGN errors affect mobile WiMAX networks because of propagation conditions generally resulting from the mobility characteristics. Mobile WiMAX networks are inherently vulnerable to transmission errors due to propagation conditions such as multipath fading, shadowing, and Doppler spectrum. To ensure reliable communications, even in adverse physical conditions, errors must be detected and corrected by the receiver device. The traditional approach to deal with this problem is the employment of forward error correction techniques along with bit interleaving during the phase called channel encoding. In this article we propose an hybrid errors model where both burst and AWGN errors are considered. Moreover, we present an error sequence generator, used to simulate and evaluate the use of forward error correction techniques and bit interleaving applied to nomadic (fixed) and mobile WiMAX systems affected by hybrid errors. Simulation results show that using a hybrid error model better reflects the realistic behavior of RF channels, than models which consider only AWGN.

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1. Introduction

Network infrastructures based on the IEEE 802.16 standard are today one of the most important solutions for Broadband Wireless Access (BWA) in large geographical areas, mainly because of their high throughput and wide coverage at low cost [1]. The importance of IEEE 802.16 – also referred to as WiMAX (Worldwide Interoperability for Microwave Access) – can be observed in industry’s high level of investments in developing IEEE 802.16 compatible devices, and in academia through the current extensive research efforts in this area. Especially important is the development of the IEEE 802.16 amendment to the original standard that covers communications of mobile devices in environments with varying conditions of signal propagation. Mobile WiMAX enables, for example, long distance communications in rural areas where Line-Of-Sight (LOS) propagation is common, as well as in urban areas where Non-Line-Of-Sight (NLOS) is more frequent because of buildings and other obstacles [2]. Mobile WiMAX networks are inherently susceptible to errors resulting from the propagation conditions of the environment where the wireless infrastructures are deployed (e.g., presence of multipath fading, shadowing, and Doppler spectrum) [3]. Such susceptibility, if ignored, can lead to performance degradation and low availability of the mobile WiMAX communication services. It is thus not surprising that treating the damages caused by errors on mobile WiMAX networks is an intensive area of computer network research [4].

In general, the recent literature on error control in digital wireless communications [4,5] classifies errors, depending on the distribution of erroneous bits inside a transmission block, as burst errors or random errors. Burst errors are characterized by two erroneous bits separated from each other by a known number of correct bits. When modeling burst errors, the number of correct bits between two erroneous bits is defined by the particular model adopted, which must consider time variant characteristics of the Radio Frequency (RF) channel under observation. By contrast, random errors consist of erroneous bits randomly

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*Corresponding author.

E-mail addresses: rkunst@inf.ufrgs.br (R. Kunst), cboth@inf.ufrgs.br (C. Both), granville@inf.ufrgs.br (L.Z. Granville), juergen@inf.ufrgs.br (J. Rochol).

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distributed in the transmission block, and being the result of uncorrelated events. In terms of modeling communication channels, Additive White Gaussian Noise (AWGN) is an important example that considers random errors [6].

Mobile WiMAX networks implement error control employing Forward Error Correction (FEC), whereby redundant bits are sent to the receiver device, triggering a repair capability in this device. In addition to FEC, WiMAX also implements bit interleaving [7] to reduce the impact of possible errors. In order to investigate the effectiveness of both FEC and bit interleaving for mobile WiMAX networks, one must consider the presence in the channel of both burst and random errors. However, most of the current research considers only random errors [5,8,9], usually modeled according to AWGN, then partially or completely neglecting the existence of burst errors. Burst errors, however, are indeed investigated in research efforts not related to WiMAX. For example, Wang and Xu [4] proposed a deterministic process used to derive a new class of hard and soft generative models for simulation of digital wireless channels. Using the approximate Fourier series technique, Sandeep et al. [10] obtained expressions for the probability of error for bandlimited Binary Phase Shift Keying (BPSK) signaling in the presence of timing errors and fading.

We believe that a more adequate observation of the FEC and interleaving techniques in mobile WiMAX networks must consider, at the same time, both random and burst errors. However, the current WiMAX researches treat random errors only, while burst errors are addressed in investigations not related to WiMAX. Considering this situation, in this article we propose a model, called hybrid error model, where random and burst errors are jointly observed in WiMAX networks by comparing the impact of hybrid errors with random errors modeled using AWGN.

The remainder of this article is organized as follows. Section 2 reviews important background issues related to mobile WiMAX channel encoding. In Section 3 we model the behavior of the RF channel using our error sequence generator and present a simulation scenario. In Section 4 we give our results and discuss their implications for error control in mobile WiMAX networks. Section 5 closes the article with concluding remarks and directions for future investigations.

2. Mobile WiMAX channel encoding

This section describes the channel encoding mechanism that aims to provide reliable data transmission over noisy RF channels in mobile WiMAX networks. This mechanism can be viewed as a sequential process in which bits to be sent are scrambled, FEC encoded, interleaved, modulated, and finally multiplexed by an Orthogonal Frequency Division Multiple Access (OFDMA) system. Understanding this mechanism is important for understanding the relationship among the processes defined by the IEEE 802.16e standard in order to enable mobile communications. Fig. 1, presents a compilation of the standard components of the channel encoding mechanism. In Fig. 1 we highlight the phases of FEC encoding, bit interleaving and RF channel multiplexing. These phases of channel encoding/decoding and transmission/reception that are crucial for data transmission and error control and thus will be especially relevant for our discussions later in the article.

2.1. Scrambler

Channel encoding begins in the scrambler, also known as randomizer. Scrambling homogeneously distributes the bits to be sent in the frequency domain. This reduces power peaks, thereby reducing the possibility of interference between adjacent subcarriers [11].

Scrambling is carried out on the serialized bit stream of each transmission block. If the amount of data to be transmitted does not fit exactly the amount of data allocated, padding (bits with value equal to 1) is added to the end.

Fig. 1. Mobile WiMAX channel encoding process.
of the transmission block. This process begins with the generation of a Pseudo Random Binary Sequence (PRBS), which is obtained using the polynomial $x^{15} + x^{14} + 1$. The vector used in PRBS is initialized with the sequence 0110110010010101, as shown in Fig. 2 [12].

The process of homogeneously distributing the bits in the frequency domain involves two XOR operations. The first operation combines the bits 14 and 15 of the PRBS vector. The result of this operation feeds back to the vector, becoming the first position of the updated PRBS vector and causing a shift in the bits that compose the PRBS vector. In other words, the value of position 15 of the PRBS vector is discarded and the value of the remaining positions of the vector are moved one position to the right. The result of the first XOR operation is then input to the second XOR operation, where it is combined with the first bit of the input bit stream in order to generate the output of the scrambler.

2.2. FEC encoding

After scrambling, bits are FEC encoded. In this step, redundant information is added to the transmitted data in order to allow error detection and correction by the receiver device. FEC capabilities (i.e., error detection and error correction) in WiMAX networks are obtained through the application of Reed-Solomon (RS), Convolutional Codes (CC), Convolutional Turbo Codes (CTC), or Low-Density Parity Check Codes (LDPC) [13]. In nomadic WiMAX networks, FEC is deployed through the concatenation of an inner RS code with an outer CC of compatible rate [14]. However, the implementation of concatenated codes demands high processing power, which generally is not available in the context of mobile network devices.

Due to the processing and power consumption problems that result from the hardware limitations of mobile network devices, FEC encoding in mobile WiMAX networks is based only on the implementation of a standalone code. According to the mobile WiMAX standard, CC implementation is mandatory for device interoperability, while the deployment of other codes is optional.

The use of coding techniques alone is generally not sufficient for efficient recovery after some kinds of errors, e.g., when the RF channel is affected by burst errors. Therefore, FEC encoding is accompanied by the introduction of interleaving techniques, which consist of re-sequencing a block of bits before signal transmission. Thus, originally adjacent bits are separated by a distance that may vary over time. This distance enables more efficient error correction on the decoder side. The implementation of interleaving is important because it allows longer link distance with resistance to difficult propagation conditions [7].

2.3. QAM mapper

After FEC encoding, the data bits to be transmitted must be mapped into a modulation constellation. A modulation constellation is formed by symbols that define the quantity of data that can be transmitted. The mobile WiMAX standard permits the use of many Quadrature Amplitude Modulation (QAM) constellations. Therefore, it is possible to vary the quantity of bits transmitted per modulation symbol, which is also called transmission capacity. The combination of a modulation constellation and a FEC encoding rate yields an Adaptive Modulation and Code (AMC) configuration. AMC configurations change dynamically to adapt the transmission reliability to the time variant propagation conditions typically found in the context of RF channels.

The transmission capacity of an RF channel varies according to the number of symbols that form a modulation constellation, as well as with the quantity of bits transmitted within a modulation symbol. The number of symbols that comprise a modulation constellation has a relationship with the amount of data that can be sent within each modulation symbol. This amount of data per symbol ($b_{sym}$) is typically represented in unit of bits and can be calculated through Eq. (1), where $n$ is the number of symbols inside a QAM constellation.

$$b_{sym} = \log_2(n).$$

The modulation constellations defined in the mobile WiMAX standard are BPSK, QPSK, 16-QAM, and 64-QAM. The standard mandates the use of BPSK 1/2 AMC configuration to encode control information exchanged among Base Station (BS) and Mobile Stations (MSs), due to its robustness for ensuring successful transmissions to all MSs within a network. To meet interoperability criteria, the WiMAX forum mandated that all devices must support both QPSK and 16-QAM, while the implementation of 64-QAM is optional. In total, seven AMC configurations are defined in addition to BPSK 1/2, depending on the modulation constellation and FEC encoding rates used. These AMC configurations, as well as the quantity of bits per symbol for each configuration, are shown in Table 1.

The main impact of dynamic AMC configuration changes in production networks is to reduce the number of retransmissions, with the goal of improving the overall

![PRBS for scrambler process for OFDMA-based transmissions.](image-url)
Quality of Service (QoS) of the network. The reduction on the number of retransmissions can be obtained through the correct choice of AMC configuration, considering the propagation condition of the RF channel in a given moment. For example, considering a situation in which parts of a transmitted frame are discarded because of the presence of uncorrectable errors, the entire frame may be retransmitted. In this situation, QoS requirements, such as delay and jitter, will be compromised, reducing the overall QoS of the network. Therefore, to reduce the probability of occurrence of the mentioned situation, when a station (BS or MS) recognizes that the RF channel is facing adverse propagation conditions, a more robust AMC configuration (i.e. one that transmits less data and increases the error correcting capability of FEC mechanism) is used. Therefore, even if the frame is lost, a small quantity of data needs to be retransmitted, compromising additional network resources.

2.4. RF channel multiplexing

The IEEE 802.16 standard specifies multiple physical layers, designed for different scenarios. The initial Single Carrier (SC) physical layer was introduced. SC is designed to operate in the range of frequencies between 10 and 60 GHz. This frequencies range is susceptible to channel impairments such as attenuation and multipath delay spread which affect overall transmission reliability. Therefore, SC requires LOS for correct operation. SC is based on time division of the RF channel to implement RF channel sharing [15].

In 2004 the IEEE 802.16d [16] standard made possible the operation in NLOS scenarios by proposing the implementation of OFDM in frequencies below 11 GHz. Designed for nomadic users, the technique divides the RF channel into multiple subcarriers. During transmission, a given user receives complete control of all subcarriers. Since the user transmits using all available frequencies, RF channel sharing in OFDM is essentially based on time division. In other words, a station is scheduled by the BS to transmit using all subcarriers during a predetermined portion of time, called a time slot.

The IEEE 802.16e standard, published in 2005, was designed to permit operations in both nomadic and mobile scenarios. Toward this goal, it mandated the implementation of the OFDMA physical interface. OFDMA is a multiplexing technique that combines time division and frequency division techniques to provide RF channel sharing. As depicted in Fig. 3, the main advantage of OFDMA over techniques such as SC and OFDM, is the support given to multiple users to transmit within the same symbol. This advantage is obtained through the division of the RF channel into subchannels. In OFDMA, each subchannel is composed of a set of subcarriers in a process called subchannelization. The IEEE 802.16 standard specifies seven subchannelization methods, out of which only Partial Usage of Subchannels (PUSC) is mandatory in order to guarantee devices interoperability [15].

OFDMA channel multiplexing technique involves three steps, as shown in Fig. 1. First, the OFDMA system adds pilot subcarriers to provide synchronization. Next, QAM symbols, represented in frequency-domain, are submitted to an Inverse Fast Fourier Transform (IFFT) that brings the signal into the time-domain in the form of OFDM symbols. In the last step a guard interval, called a Cyclic Prefix (CP) is inserted at the beginning of each OFDM symbol, consisting of redundant information obtained through a replica of the symbol’s final portion. This guard interval is used to reduce the probability of occurrence of inter-symbol interference, since the redundant portion is discarded by the destination station.

After the channel encoding, the digital information is passed through a Digital to Analog Converter (DAC), resulting in an analog signal that is transmitted using the RF channel. However, in our approach, the behavior of the RF channel is simulated through the use of an error sequence generator, which will be explained in next section.

3. Simulating the mobile WiMAX channel

The goal of this study is to propose and evaluate a novel channel model that accounts for hybrid error during data transmission in mobile WiMAX networks. In this section we present details on the design of a tool\(^1\) that is able to simulate data transmissions in such networks. The tool both simulates the channel encoding mechanism of mobile WiMAX networks, and generates error sequences in order to simulate the behavior of the RF channel through which data is transmitted. The design of the tool’s channel encoding mechanism incorporates all the processes previously discussed in Section 2. The design of the error sequence generator, as well as the considerations that led to its design, are presented below. We end the section by proposing a simulation scenario to evaluate the proposed hybrid error model.

3.1. Considerations behind our error sequence generator design

Models which describe the physical impairments that affect an RF channel, fall into two categories: physical channel models, and digital time-discrete channel models. In the context of physical channel, one important example typically found in the literature is Rayleigh small-scale fading model that describes the dramatic changes in signal amplitude and phase that can occur as a result of small changes in the spatial separation between a receiver and transmitter [17]. Physical channel models are normally used to help in the design, testing, and optimization of realistic wireless communication systems.

Among models of digital channel behavior, one of the most important is proposed by Gilbert [18]. Gilbert models the behavior of errors on an RF channel through a Markov chain composed of two states, named Good and Bad. In Good state no errors occur, while in the Bad state the RF channel is affected by errors. As we explain later, the concept of a two-state Markov chain is one we harness in our own modeling approach.

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\(^1\) The simulation tool is available for download at [http://www.in-f.ufg.br/~rkunst/tool.zip](http://www.in-f.ufg.br/~rkunst/tool.zip).
Compared to physical channel models, digital time-discrete channel models, also called error models, are less accurate in terms of modeling the RF channel behavior. This characteristic makes digital channel models suitable for simulations purpose, because they demand less computational power, and consequently provide faster results [4].

Models for simulating errors can be classified as descriptive or generative. Descriptive models use experimental data in order to obtain statistics about the error sequence. Generative models are mathematical models that generate error sequences statistically similar to the sequence produced by a physical channel. Since our goal is to simulate the behavior of a RF channel, the model proposed in this article can be classified as a generative error model that describes a time-discrete digital RF channel.

We believe that any model of RF channel behavior in mobile WiMAX networks must account for both AWGN errors as well as burst errors. Thus, in Section 3.1.1 we describe the details of our AWGN error sequence generator. The model for generation of burst errors is depicted in Section 3.1.2. These error generators are based on the work originally proposed by Kunst et al. [6].

3.1.1. AWGN error sequence generation

The AWGN model generates uniformly distributed random error sequences composed of \( n_e \) erroneous bits. The probability of occurrence of one bit error \( n_{be} \) in a block of bits with length of \( L_{bl} \) can be approximated by Eq. (2):

\[
n_{be} = \frac{n_e}{L_{bl}}.
\]

Considering \( L_{bl} \gg n_e \), the total number of correct bits per error is given by \( n_{bc} = L_{bl}/n_e \). Therefore, we can define the bit error probability \( (p_{be}) \) as in Eq. (3).

\[
n_{be} = \frac{n_e}{L_{bl}} = \frac{1}{n_{bc}} \equiv p_{be}.
\]

We can approximate the error rate \( (n_{re}) \) to the error probability \( (p_{be}) \) if we consider a large block of bits \( (L_{bl}) \). To generate an error sequence of length \( L_{bl} \) composed of \( n_e \) erroneous bits we randomly choose \( k \) bits and invert their values. This approach allows one bit to be chosen more than once. If this situation occurs, the affected bit will be correct as a result of two inversions of its value. In order to cover this situation, we calculate the effective number of erroneous bits \( (n_e) \) using Eq. (4).

\[
n_e = k(1 - \rho_{be}).
\]

where \( \rho_{be} \) is the probability of a bit being inverted twice. This probability can be expressed as in Eq. (5). It is important to note that there is a small probability of a bit being chosen more than twice. Since we guarantee a confidence interval of 95% in our simulations, this probability is considered to be irrelevant.

\[
\rho_{be} = \exp \left[ \frac{-k(k-1)}{L_{bl}} \right].
\]

Therefore, the injected error rate \( (R_{ie}) \) can be expressed as (6):

\[
R_{ie} = \frac{n_e}{L_{bl}} = \frac{k(1 - \rho_{be})}{L_{bl}}.
\]

Considering the injected error rate \( (R_{ie}) \) we calculate the number of errors that must be generated, that is \( n_{re} \). After the generation of \( n_{re} \) errors, we apply the error control techniques discussed in Section 2. Therefore, the residual error rate \( (R_{re}) \), i.e. the number of errors not corrected by application of error control techniques, is then calculated using Eq. (7):

\[
R_{re} = \frac{n_{re}}{L_{bl}}.
\]

A performance analysis of the mobile WiMAX networks channel encoder considers the injected error rate and the consequent residual error rate, obtained through Eqs. (6) and (7), respectively. In AWGN errors generation mode, the variables are set to provide a homogeneous distribution of errors throughout the transmission. In other words, the probability of errors is considered to be constant for each transmission block.

3.1.2. Burst error sequence generation

The second operation mode of the proposed error sequence generator is burst errors generation. In this mode, the block length \( (L_{bl}) \) must be an integer multiple of \( m \) blocks of length \( L \), so that: \( L_{bl} = mL \). The value \( L \) defines the normalized duration of the burst of errors, in terms of a determined quantity of bits. Thus, \( L \) depends on the network throughput \( (R) \) and on the typical duration of a burst of errors \( (L_{b}) \), as can be seen in Eq. (8).

\[
L = \frac{L_{b}}{R}.
\]

To generate a burst error sequence of \( k \) bits in a block of \( L \) bits, we choose \( k \) random bits in the interval \([1..L]\) and invert their values. As in AWGN mode, a bit can be chosen twice, so the number of errors inserted into the block can be smaller than \( k \). Therefore, we can calculate the effective number of errors \( (K) \) as in Eq. (9):

\[
K = k(1 - \rho_{be}).
\]
\[ K = k(1 - \rho_{k,1}). \]  

(9)

In this equation, \( \rho_{k,1} \) represents the probability of a bit being chosen twice. As in AWGN mode, the probability of a bit being chosen more than twice is not considered, because due to the assumption of a confidence interval of 95\%, which renders this value irrelevant to obtain results. The value of this probability, adapted to a block of length \( L \), can be calculated using Eq. (10).

\[ \rho_{k,1} = \exp \left( -\frac{k(k - 1)}{2L} \right). \]  

(10)

For a large number of blocks (\( n_{bl} \)), we can obtain the injected error rate (\( R_{bl} \)) and the consequent error probability (\( p_e \)) for burst errors as in Eq. (11):

\[ R_{bl} = \frac{n_{bl}}{n_{bl}L} = \frac{1}{n_{bl}} \Xi p_e, \]  

(11)

where \( n_{bl} \) is the number of correct blocks per erroneous blocks, \( n_{bl} \) is the total number of blocks with burst errors, and \( n_{bl}L \) is the total number of blocks of length \( L \). We insert \( K \) errors to the blocks affected by burst errors. Therefore, we can redefine Eq. (11) as a function of the total number of bits (\( n_{bl}L \) and the \( K \) injected errors. Thus, the injected error rate can be expressed as in Eq. (12):

\[ R_{bl} = \frac{K}{n_{bl}L} = \frac{(1 - \rho_{k,1})}{n_{bl}L}. \]  

(12)

A performance analysis of the mobile WiMAX networks channel encoder considers the injected error rate, calculated using Eq. (12). The injected error rate is then used to calculate the number of errors that must be generated. Finally, the residual error rate (\( R_{bl} \)) is obtained through Eq. (13).

\[ R_{bl} = \frac{n_{be}}{n_{bl}L}. \]  

(13)

Using our AWGN and burst errors generators, in the following subsection we present the details of our proposed hybrid errors model. The proposed model considers the occurrence of both AWGN and burst errors in the same transmission frame.

3.2. Hybrid errors model

In this subsection, we describe the proposed hybrid error model. First, we present a mathematical description of the model. Then we describe the implementation of the model in order to simulate the behavior of a mobile WiMAX RF channel.

3.2.1. Model description

The hybrid error model generates errors within a block of bits with length \( L_{bl} = |M| \cdot L \) bits, where \( M \) is a set of blocks of bits. Each element in \( M \) has length \( L \) bits. The number of elements in the set \( M \) that are affected by burst errors (\( m_B \)) is defined using Eq. (14).

\[ m_B = \floor{L_M |M|}. \]  

(14)

where \( L_M \) is the normalized length of the burst of errors. \( L_M \) is related to a block \( m \in M \) of length \( L \) according to Eq. (15).

\[ L_M = \frac{n_{be}}{L}, \]  

(15)

where \( n_{be} \leq L \) is the number of bit errors in a given transmission block \( m \in M \) affected by burst errors. \( n_{be} \) is obtained considering the relationship between the duration of the burst \( T_B \) with the overall network throughput \( (R) \), as shown in Eq. (16).

\[ n_{be} = \frac{T_B}{R}. \]  

(16)

An important assumption in our model is that every block has a related error model based either on burst errors or AWGN. In addition, the number of blocks affected by AWGN (\( m_A \)) is related to the number of blocks that follow the burst error model as follows: \( m_A = |M| - m_B \). In Eq. (17) we expand \( m_B \) in order to calculate the number of blocks affected by AWGN.

\[ m_A = |M| - \floor{L_M |M|}. \]  

(17)

Following the computation of \( m_B \) and \( m_A \), we define the blocks to be affected by burst errors or AWGN. Towards this definition, we need to guarantee that a given block is not chosen more than one time. Guaranteeing that a block \( m \in M \) is chosen only once is important to generate the desired error rate. For example, if a block is selected twice, the error generation will be applied two times to the same block of bits. On the other hand, one element of \( M \) is not going to be chosen, and as a result will not be affected by errors. Therefore, the desired injected error rate is not going to be attained. Thus, we model this problem as a permutation without repetition of the elements of the set \( M \), as defined in Eq. (18).

\[ |M| P_{m_B} = \frac{|M|!}{(|M| - m_B)!}. \]  

(18)

Then, we randomly choose a group of \( m_B \) blocks in the range \([1, |M| - m_B] \), resulting from the permutation of the elements in the set \( M \). These chosen blocks are going to be affected by burst errors. The error generation within this group of blocks is calculated using Eq. (12), which defines the injected bit error rate for the burst error model, defined in Section 3.1.2. The remaining blocks will be affected by AWGN errors therefore, we apply Eq. (6) in order to calculate the AWGN bit error rate, as explained in Section 3.1.1.

3.2.2. Model implementation

The goal of the model implementation is to evaluate how well our hybrid error model performs compared to an error model that considers only AWGN. To do this, we present two approaches. The first approach combines the generation of burst errors with AWGN, specifically, burst errors with background AWGN. This approach permits us to simulate both the natural loss that is related to the RF channels, and the unpredictable noises and interferences that affect transmission [6]. The injection of background noise is possible due to the division of the bit stream into blocks. Thus, in each block, errors can be generated with different distributions (i.e. as AWGN or burst errors), as shown in Fig. 4(a). In the figure, we have divided the bit stream in seven blocks. In block number 4a burst of errors
is injected, while in the remaining blocks, AWGN is injected as background noise.

The second approach consists of the generation of AWGN error sequences only. In this approach, there are no transitions in the Markov chain, due to the random nature of AWGN. Therefore, during the entire simulation, the Markov chain stays in state A. In other words, all blocks are affected by errors with the same probability, as shown in Fig. 4(b). As in the hybrid errors example, the bit stream is divided in seven blocks. However, in this approach, all blocks are affected uniformly.

These two approaches are simulated using the simulation model, designed according to the flowchart presented in Fig. 5. This flowchart describes the functional blocks of the error sequence generator that was implemented. After reading the parameters, the error generator calculates the size of each block in order to divide the transmission bit stream. The next step consists of calculating the number of errors that must be inserted into the blocks. This value is obtained based on the error probabilities and on the sojourn time of the Markov chain. In the following step, the error sequence generation procedure begins with the selection of a block to be processed. One bit of the selected block is then randomly chosen and its value inverted. This procedure is repeated until the total number of errors of the given block is attained. The error sequence generation is applied for all the remaining blocks. After all blocks are processed, a new bit stream containing the error sequence is generated.

The simulation tool receives parameters in order to simulate the behavior of the RF channel. The definition of these parameters is important to guarantee that the results reflect the realistic behavior of a mobile WiMAX RF channel. These parameters are explained in the following description of our simulation scenario.

3.3. Simulation scenario

Here we present the simulation scenario we used to evaluate our hybrid error model. Towards this objective, we explain three important ideas. First, we introduce the Markov chain that models the behavior of the mobile WiMAX RF channel. Second, we explain the relationship between the two states of the Markov chain, focusing primarily on the probability of transition between states, and consequently on how to calculate the sojourn time of each state during the simulations. The third idea covered in this section is the probability of errors during each state.

This idea is key because the variation in the probability of errors permits the generation of hybrid errors, which is the main objective of this study. Finally, we propose a simulation scenario and present configuration parameters of the simulated mobile WiMAX network.

The proposed scenario focuses on modeling the behavior of the RF channel through the generation of error sequences. Therefore, we model the simulation of the RF channel using a two-state time-discrete Markov chain, which is an adaptation of Gilbert’s model. The difference from Gilbert’s model is that in our proposal, both states of the Markov chain may be affected by errors, while in Gilbert’s approach, only one state is affected by errors. A graphical representation of the Gilbert’s Markov chain is given in Fig. 6. In our proposed hybrid model, during state A the RF channel is considered to be affected by well known AWGN errors, while during state B burst error sequences are generated.

Each state of the Markov chain has associated transition and error probabilities. The probability of a transition from state A to state B is defined as \( P_{BA} \), while \( P_{AA} = 1 - P_{BA} \) is the probability of staying in state A. On the other hand, \( P_{AB} \) and \( P_{BB} = 1 - P_{AB} \) are transition probabilities relative
to state B. Considering the transition probabilities it is possible to calculate the state sojourn for states $A(S_A)$, and $B(S_B)$ using Eqs. (19) and (20), respectively.

$$S_A = \frac{1}{1 - P_{A|A}}.$$  \hfill (19)

$$S_B = \frac{1}{1 - P_{B|B}}.$$  \hfill (20)

In order to obtain the state sojourn in units of time, we need to consider the frame duration ($T_F$) and the number of symbols ($n_s$) transmitted within a frame. Thus, we can calculate the permanence in states $A$ ($T_A$) and $B$ ($T_B$) using Eqs. (21) and (22), respectively.

$$T_A = \left(\frac{1 - P_{A|A}}{n_s}\right) T_F,$$  \hfill (21)

$$T_B = \left(\frac{1 - P_{B|B}}{n_s}\right) T_F.$$  \hfill (22)

The calculated state sojourn time is one of the parameters used to define scenarios that simulate the behavior of the RF channel in diverse RF channel propagation conditions. Calculating this value is important, because our simulations are based on the generation of error sequences in which the number and distribution of errors are dependent on the duration of each state of the time discrete Markov chain. Moreover, each state of the Markov chain has an associated error probability, obtained using the models presented in Section 3.1.

The parameters for our simulations were calculated based on related works that have assessed these parameters as a result of realistic measurements. The main references that we have found in this subject are Bhagwat et al. [19], Fantacci and Scardi [20], and Wang and Moayeri [21]. However, the first two references consider the context of Wireless Local Area Networks (WLAN) and thus have limitations for simulating the RF channel in Wireless Metropolitan Area Networks (WMAN), as WiMAX. On the other hand, Wang and Moayeri presented a work that considered generic radio communications. Therefore, we based the calculations of our simulation parameters on this work.

Following Wang and Moayeri, we consider $P_{A|A} = 0.995$, and $P_{B|B} = 0.96$. In addition, we assume a frame duration of 10 ms and a channel bandwidth of 10 MHz. According to the WiMAX Forum System Evaluation Methodology [22], in this scenario, each frame is composed of 99 transmission symbols. Therefore, we can calculate the state sojourn time using Eqs. (21) and (22). We obtain as a result the permanence of state A, $T_A = 20.2$ ms, and the permanence of state B, $T_B = 2.52$ ms.

Other parameters, which are also relevant to our simulations, are presented in Table 2. These parameters are based on typical values encountered in the literature [11]. We have considered OFDMA and OFDM physical interfaces, in order to simulate mobile and nomadic WiMAX networks, respectively. Moreover, the FFT sizes have been chosen to reflect those of mandatory implementation to guarantee devices interoperability: 1024 for OFDMA, and 256 for OFDM. In terms of FEC techniques, we have selected the more robust coding rates considering the error correction capabilities, i.e., CC 1/2 and RS(64,48). The modulation constellation 64-QAM and the insertion of the more robust CP, i.e. 1/4, were also considered in the simulations. Finally, we guarantee confidence interval of 95%.

We used the proposed simulation scenario to evaluate the performance of mobile the WiMAX channel encoding mechanism. Specifically, we considered two questions:

1. How does the hybrid error model affect the correcting capabilities of mandatory FEC schemes compared to AWGN-only?
2. How does using the hybrid error model affect the performance of interleaving techniques compared to using an AWGN-only model?

### 4. Performance evaluation

The main focus of this section is to discuss the impact of hybrid and AWGN error models on mobile WiMAX networks. This discussion is based on a performance evaluation of the channel encoder of WiMAX networks. We also consider aspects of nomadic networks to highlight technological advancements and shortcomings of their mobile counterparts.

In order to answer the questions presented above, we compared the two error models by measuring their impact on two simulation cases: one evaluating the effectiveness of FEC techniques in both mobile and nomadic WiMAX networks, and the second evaluating interleaving techniques in mobile WiMAX networks.

<table>
<thead>
<tr>
<th>Table 2: Simulation parameters.</th>
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<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td><strong>Physical Interface</strong></td>
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<tr>
<td><strong>Channel Bandwidth</strong></td>
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<tr>
<td><strong>FFT size</strong></td>
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<tr>
<td><strong>FFT used</strong></td>
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<td><strong>Frame duration</strong></td>
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<td><strong>Cyclic prefix</strong></td>
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<td><strong>Modulation</strong></td>
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<td><strong>Convolutional Encoding</strong></td>
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<td><strong>Confidence Interval</strong></td>
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</table>
4.1. Error models evaluation considering FEC capabilities

First we examined FEC effectiveness in nomadic WiMAX networks under the two error models. In nomadic networks, FEC capabilities are defined through the application of concatenated error correction codes. We simulated the application of Reed-Solomon codes concatenated with Convolutional Codes, the mandatory configuration for the nomadic WiMAX standard. Fig. 7 shows the impact of hybrid vs. AWGN errors on nomadic FEC behavior. As can be seen, for injected error rates of $10^{-4}$ or lower, no residual error rate is observed, because the error correction codes are able to correct all errors that might be generated. However, as we increase the injected error rate, FEC effectiveness deteriorates under hybrid error simulation as evidenced by the steep rise in residual errors. For example, an injected error rate of $10^{-3}$ causes a residual error rate of approximately $3 \cdot 10^{-4}$ when hybrid errors are simulated, and near to zero (i.e., in the order of $10^{-6}$) when AWGN is simulated. In other words, the hybrid error model generates about 66% more errors than the traditional AWGN-only simulation. This behavior is observed due to the occurrence of burst errors with background AWGN. When the injected error rate is increased further, the impact of burst errors intensifies, with the hybrid error scenario generating 82% more errors than the AWGN model.
Next we evaluated FEC behavior in mobile WiMAX networks. In this scenario, the FEC encoding capabilities were implemented with Convolutional Codes only, as mandated by the mobile WiMAX standard. This reliance on CC is explained by the hardware limitations of mobile devices, notably their power consumption restriction, and limited processing capacity, which render the performance of concatenated codes unacceptable.

Fig. 8 shows the behavior of CC in mobile WiMAX networks when the transmission is affected by hybrid errors and AWGN. Again, residual error rates are higher under hybrid error simulation than AWGN alone. These results accurately reflect the vulnerability of mobile networks to both burst errors and AWGN due to the mobility of stations. The results also highlight a key challenge posed by mobile WiMAX technology, namely that reliance on a single correction code to accommodate the limited processing capacity of mobile devices leads to higher residual error in mobile transmissions. Indeed, a comparison with Fig. 7 reveals that mobile WiMAX networks typically experience higher residual error rates than nomadic networks.

Finally, we quantified the effect of hybrid errors on FEC mechanisms in nomadic and mobile WiMAX networks. Our aim is to show the impact of design decisions implemented in the mobile WiMAX technology. The graph in Fig. 9 confirms that compared to nomadic systems, mobile
systems have worse correction capabilities. In quantitative terms, nomadic systems are able to correct approximately 33% more errors than mobile systems when an injected error rate of $10^{-3}$ is considered. This difference increases to 45% as the injected error rate increases from $10^{-3}$ to $10^{-2}$. Robustness of error correction in nomadic systems is obtained through the concatenation of RS and CC. However, employing concatenated FEC schemes demands higher processing power, which is generally not available in mobile devices.

Analyzing the results presented in this section, we can see that simulating the occurrence of hybrid errors is suitable for the analysis of FEC capabilities in WiMAX networks. These simulation results tell us that hybrid errors cannot be ignored. This affirmation is based on the nature of nomadic and mobile wireless transmissions that are typically affected not only by AWGN, but also by burst errors. Therefore, we can conclude that for the context analyzed in this section, hybrid errors bring a simulation scenario that is more realistic than the traditional approach of simulating only the occurrence of AWGN.

4.2. Interleaving performance evaluation

In our simulations to evaluate the effectiveness of interleaving techniques, we used 1152 columns, the value suggested for 64-QAM in the IEEE 802.16 standard. Moreover, we varied the number of rows with the goal of analyzing the behavior of different interleaving configurations. Fig. 10 shows that interleaving has no effect over channels affected by AWGN alone due to the random distribution of the errors in this model.

On the other hand, Fig. 11 shows that the application of time diversity techniques over transmissions affected by hybrid errors improves the performance of the FEC mechanism. For example, and interleaving size of (1152,6) improves error correction capability by about 75% for an injected error rate of $10^{-2}$, compared to no interleaving. Another observation is that interleaving blocks of 1152 columns and just 2 rows have no significant impact in the analyzed scenario. This occurs because using two rows brings a relatively small diversity, i.e., the errors are not sufficiently spread over time to provide error correction improvements.

In other simulations we detected that when the number of rows is greater than 6, e.g., block length of (1152,8), no major gains are observed if compared with (1152,6) interleaving size. It is also important to note that there is a trade-off between the interleaving block size and the processing power demanded for the operation. Thus, applying block sizes larger than (1152,6) is generally not a good idea because the small gain obtained does not justify the increase in the processing power.

Fig. 12 compares the impact of error sequence generators with and without the application of interleaving techniques. First, in Fig. 12 (a) we can see the case when interleaving is not applied. Compared to AWGN simulation alone, the proposed error model generates about 25% more residual errors with an injected error rate of $10^{-3}$ and up to 50% more with an injected error rate of $10^{-2}$. This behavior is explained by the natural characteristics of both error models. Since the proposed hybrid error model generates burst errors with background AWGN, a higher residual error rate is to be expected, especially when there are no interleaving techniques to distribute the burst errors through time.

Next, we compared the effect of hybrid and AWGN errors with interleaving. In this case, we applied the best interleaving size supported by the IEEE 802.16 standard is applied to the transmissions affected by hybrid errors, in comparison with transmissions affected only by AWGN. Analyzing the graph in Fig. 12(a) we can see that in scenarios affected by hybrid errors, for injected error rates between $10^{-4}$ and $10^{-2}$ a maximum residual error rate in
the order of $10^{-4}$ is observed, while simulating AWGN in the same environment yields a lower residual error rate. On the other hand, for injected error rates in the range of $10^{-3}$ and $10^{-2}$, which are typical in mobile WiMAX networks, the AWGN model generates substantially more residual errors, reaching values about 20% higher than in hybrid error scenarios.

This behavior can be explained because the AWGN error model generates an error sequence in which errors are distributed randomly through time. Thus, when injected error rates are low (i.e., between $10^{-4}$ and $10^{-3}$), the interleaving mechanism is more efficient than expected. This approach is very optimistic considering realistic RF channel conditions, since the increase in the residual error rate in this situation is smooth. However, increasing the injected error rate, we observe an increase in the residual error rate that is higher than that observed in hybrid error scenarios, which we consider a pessimistic approach. Therefore, we can conclude that hybrid error model presents a behavior that is more realistic than AWGN to evaluate the performance of interleaving techniques.

5. Conclusions and future perspectives

In this article we demonstrated, in quantitative terms, the impact of hybrid errors over mobile WiMAX networks. To provide the context for our study, first we described in detail the channel encoding mechanism for mobile WiMAX networks. Then, we presented a simulation methodology that allowed us to analyze specific issues such as the performance of interleaving techniques, the impact of variations in hybrid error duration, and the improvement achieved by mobile technologies if compared with nomadic WiMAX networks, especially in terms of FEC capabilities.

Regarding the impact of hybrid errors compared with error sequences generated using the AWGN model, results demonstrate that hybrid errors represent with more fidelity the behavior of realistic RF channels, specially in the context of mobile WiMAX networks. We conclude that future research needs to consider hybrid error sequence generation in evaluations of FEC performance, rather than relying on AWGN simulation alone. Another important finding of this study is that no effect is observed when time diversity is applied to transmissions affected by AWGN. In contrast, interleaving improves correction capability by about 75% in cases where errors are modeled according to the hybrid model.

Directions for future investigations include extending the presented simulation methodology to simulate other aspects of both nomadic and mobile WiMAX systems. One approach is to consider information about the RF channel conditions to guarantee QoS. This information can be used to adapt the FEC encoding and modulation rates with the goal to permit an optimized use of network resources and to improve the use of cognitive radio techniques, resulting in a better use of the wireless channel capacity. Another important direction is to consider physical conditions to take more precise decisions with respect to the admission of new connections and to prioritize traffic on the scheduling process. Finally, considering FEC encoders, it should be interesting to study the performance of other encoders that are supported by WiMAX networks, such as CTC and LDPC, in terms of error correction capabilities and processing power demanded for the operation.

References


Rafael Kunst is a Ph.D. student at the Institute of Informatics of the Federal University of Rio Grande do Sul (UFRGS). He received his M.Sc. degree in Computer Science, from the same university, in 2009. He is currently an Assistant Professor at Lasalle University (Unilasalle) and at the University of Santa Cruz do Sul (UNISC), Brazil. His research interests include wireless networks and next generation networks, with main focus on error control and quality of service.

Cristiano Bonato Both is a Ph.D. student at the Institute of Informatics of the Federal University of Rio Grande do Sul (UFRGS), Brazil. He received his M.Sc. degree in Computer Science from the Pontifical Catholic University of Rio Grande do Sul, Brazil, in 2003. He is currently an Assistant Professor at the University of Santa Cruz do Sul, Brazil. His research interests include wireless networks, next generation networks, traffic control on broadband computer networks.

Lisandro Zambenedetti Granville is an associate professor at the Institute of Informatics of the Federal University of Rio Grande do Sul (UFRGS), Brazil. He received his M.Sc. and Ph.D. degrees, both in computer science, from UFRGS in 1998 and 2001, respectively. He has served as a TPC member (2003–2008), General Co-Chair (2004), and Steering Committee member (2005–2008) for the Brazilian Symposium on Computer Networks (SBC/LARC SRBC). Currently, he is member of the Brazilian Internet Committee (CBB.br) and Technical Program Chair of the IEEE Communications Society Technical Committee on Network Operations and Management (CNOM). He has served as a TPC Co-Chair of IEEE/IFIP 2010 (TPC Co-Chair) and IFIP/IEEE DSOM 2007 (TPC Co-Chair). His main areas of interest include management using of Web services, network monitoring and configuration, P2P-based services and applications, and network virtualization.

Juergen Rochol is an Associate Professor at the Institute of Informatics of the Federal University of Rio Grande do Sul (UFRGS), Brazil. He received his M.Sc. degree in Physics, and his Ph.D. degree in Computer Science, both from UFRGS in 1972 and 2001, respectively. His research interests include wireless networks, next generation networks, optical networks, and traffic control on broadband computer networks.