Mobile WiMAX for vehicular applications: Performance evaluation and comparison against IEEE 802.11p/a

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Vehicular communications have received a lot of attention in recent years due to the demand for applications to improve safety and travel comfort. Nowadays, IEEE 802.11p seems to be the best positioned standard for providing safety services. However, for non-safety services, which usually do not present tight time restrictions but require high data transfer rates, other wireless communication standards such as IEEE 802.16e (Mobile WiMAX) may exhibit better performance. In order to shed light on this question, we developed the physical (PHY) layer of a Mobile WiMAX software transceiver and measured its performance using a channel emulator implemented on an FPGA (Field-Programmable Gate Array) that recreates six different vehicular scenarios, including a highway, urban canyons and a suburban area. Furthermore, we have compared such performance with those obtained with IEEE 802.11p and IEEE 802.11a standards, concluding that, in most of the vehicular scenarios considered, the PHY-layer of Mobile WiMAX exhibits a superior performance. The performance results presented herein can also be used as the input for network simulators to carry out more accurate system-level simulations that should help in making a final decision on which standard should be used in each specific vehicular network.

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1. Introduction

In recent years vehicular communications have attracted a great deal of attention worldwide due to the increasing demand for new applications. Such communication, whose operation lies in the area of ITS (Intelligent Transportation Systems), usually require the exchange of messages between vehicles (Vehicle-to-Vehicle or VTV communications) or between a roadside unit and a vehicle (Road-to-Vehicle or RTV communications).

Vehicular applications can be basically divided into two groups: safety and non-safety applications. Safety applications often demand fast message exchanges and do not use much bandwidth. Examples of such applications include collision avoidance and hard braking warnings, accident reporting or intersection announcements. The IEEE 802.11p standard is probably the best positioned to provide safety services, although other wireless standards, such as IEEE 802.16e or IEEE 802.20, have been considered [1–3]. On the other hand, non-safety applications do not have such tight time constraints and may need higher data transfer rates. Non-safety applications encompass mobile internet access, automatic toll collection, traffic light status notification, speed limit and cruise control, roadsign recognition, travel information management, etc.

For non-safety vehicular applications, the discussion about which is the most suitable wireless access standard remains an open issue. The most cited candidates are the WiFi standards IEEE 802.11a/b/g and IEEE 802.16e (Mobile WiMAX). It is important to note that vehicular communications are likely to be performed in the 5 GHz band since...
both US and European authorities have reserved spectrum for ITS at 5.9 GHz. Due to this, IEEE 802.11b/g are not the preferred choices and the final candidates might be reduced to IEEE 802.11p, IEEE 802.11a and IEEE 802.16e. Motivated by this fact, we have evaluated and compared the performance of these three standards when transmitting over realistic vehicular scenarios.

We have previously evaluated the performance of the IEEE 802.11p PHY-layer [4] in specific vehicular scenarios, while other authors have carried out similar studies for the IEEE 802.11a PHY-layer [5,6]. Moreover, although several papers have suggested Mobile WiMAX as an alternative to IEEE 802.11p for non-safety applications [1,3], we have found no analysis of the performance of Mobile WiMAX when transmitting over the channels that are currently considered as references for evaluating vehicular communications at the 5 GHz band [7]. In order to carry out this task, in the present article we take advantage of the work we developed in [4], where we built a low-cost and flexible FPGA-based vehicular channel emulator that helps to measure the performance of a wireless transceiver in six different situations that include common vehicular environments such as a highway, an urban canyon and a suburban area.

Other wireless communication standards have been proposed for use in vehicular environments, such as HSDPA (High-Speed Downlink Packet Access) [8], IEEE 802.20 (iBurst) [9] or EDGE Evolution [10], but the peak data rates they offer for broadband communications (14.4 Mbit/s, 16 Mbit/s and 1 Mbit/s, respectively [8,11,12]) are lower than those theoretically provided by IEEE 802.11p, IEEE 802.11a or IEEE 802.16e (27 Mbit/s, 54 Mbit/s and 39.9 Mbit/s, respectively [13–15]). Also, there are several recently developed standards whose performance in vehicular scenarios has yet to be assessed and whose study will constitute an interesting topic for further research. Such new standards seem to offer better global performance than IEEE 802.16e, but they are either in earlier development stages (e.g. LTE [16], IEEE 802.16n [17]) or have not been explicitly designed for vehicular applications (e.g. IEEE 802.11n [18]).

The remainder of this article is organized as follows: Section 2 reviews the most relevant studies on the performance of the Mobile WiMAX PHY-layer in vehicular scenarios. Section 3 presents the implemented software transceivers and briefly describes the main characteristics of the vehicular channel emulator. Section 4 explains the experiments performed. Finally, Section 5 is devoted to the conclusions.

2. Related work: Mobile WiMAX performance in vehicular scenarios

In recent years the popularization and massive distribution of multimedia content has stimulated the development of broadband communication technologies with increasing data rates. Nowadays, wired-access technologies such as cable or DSL (Digital Subscriber Line) supply a high enough data rate for most applications. However, several standards still compete to become the one chosen by the main wireless carriers to provide the next-generation of mobile broadband services.

Vehicular scenarios are one of the most challenging scenarios for broadband wireless communications, since radio interfaces face the challenge of transmitting over highly time-variant channels that often exhibit high delay spreads. Practical evaluation of vehicular communication systems can be directly performed by loading a data communications unit on a vehicle and driving through different environments. This procedure, however, is extremely expensive and, moreover, experiments can be affected by unintended side effects that may be uncontrollable.

In spite of its difficulties, the performance of Mobile WiMAX transceivers over real-world experiments has been reported in [19] and [20]. The work in [19] used a 2 × 2 MIMO (Multiple-Input Multiple-Output) Mobile WiMAX testbed made up with Alcatel-Lucent equipment and measurements were done in the 3.5 GHz frequency band. The experiments were obtained when driving through an area with tall trees and buildings, and involved different types of traffic. A base station antenna was on the roof of the highest building in the area and a mobile station was placed inside a car that drove at a maximum speed of 40 km/h. The experimental results show that MIMO techniques improve reliability since they reduce the number of packet losses. Furthermore, the authors compared the performances of Mobile WiMAX and HSPA (High-Speed Packet Access) concluding that in the case of light files (256 bytes) Mobile WiMAX outperforms HSPA. On the other hand, for larger files (1 MB), HSPA obtains better average throughput thanks to the use of HARQ (Hybrid Automatic Repeat Request) protocols, which significantly decrease the number of retransmissions. It must be noted that for a fair comparison both Mobile WiMAX and HSPA should have made use of HARQ, but at the time of writing the authors had not implemented HARQ for their Mobile WiMAX testbed.

Another example of performance measurements over real channels is [20]. In this case, several tests were conducted using what the authors claim to be the first commercial WiBro network, which worked at 2.3 GHz and used 10 MHz of channel bandwidth. Five measurement environments were considered, including outdoor and indoor spots placed at different distances from the base station. One such scenario considered mobility: the measurements were performed while the user moved in a vehicle around a campus with an average speed of 30 km/h. WiBro performance was also measured when a user traveled around Seoul in a subway and in a bus. The authors measured the UDP/TCP goodput and the RTT (Round Trip Time), comparing them, for some environments, with those obtained using HSDPA. The paper concludes that WiBro provides higher downlink goodput than HSDPA, a good uplink performance and an RTT that in most of the scenarios was far longer than those obtained by commercial WLANs.

Wireless transceivers are more cost-effectively evaluated inside a laboratory performing transmissions over either theoretical channels (i.e. channels that follow a statistical model on which the scientific community has reached a consensus) or empirical channels collected during measurement campaigns. The advantage of this
approach is that channels can be used repeatedly and fair comparisons between different transmission methods can be carried out.

Mobile WiMAX transceivers have been evaluated over theoretical vehicular channels in [21,22]. In [21], the way in which different types of terrains and vehicle movement patterns affect the propagation characteristics of 3.5 GHz Mobile WiMAX equipment is analyzed from a theoretical perspective. The authors carried out such an investigation because they consider Mobile WiMAX to be suitable for networked vehicular applications due to its inherent wide coverage, which minimizes the rate of handover and, thus, data loss due to disrupted communications. It is also interesting to compare the effects of different terrains on a WiMAX-based vehicular network, since the terrain over which the network is deployed influences the propagation of the signal.

To perform the measurements, QualNet is used as a network simulator and NCTUs as vehicular simulator. Three types of terrain were considered: flat (the terrain had no obstacles that might interfere with the transmitted signal), urban (with dense and high-rise buildings) and rural (with sparse and low-rise buildings). Furthermore, a speed of up to 50 km/h was considered in five different speed/acceleration profiles for rural and urban environments. As a result, the authors were able to study average throughputs and packet latencies, concluding that the reduction of LOS (Line-Of-Sight) due to the effects related to each terrain seemed to affect the network performance more than vehicular mobility.

Simulations over a theoretical channel are also performed in [22], where a FEC (Forward Error Correction) scheme for a live Mobile WiMAX-based video surveillance system is presented. The authors consider that the existing wireless technologies, including WiMAX, fail to deliver high data rates at high vehicular speeds, especially due to multipath fading. To address the dynamic nature of the mobile communications environment, they propose using a FEC scheme whose block size is adapted to suit the current channel conditions. Their system consisted of a public train, which acted as a mobile node, and several base stations that were placed on train platforms. The simulations were conducted using ns-2 and the implemented channel took into account that the train began to move after a stop and gradually increased its velocity, reaching a top speed of 70 km/h. The results obtained show that the use of the FEC proposed yields higher throughputs and lower jitters than other schemes.

In contrast to the above-mentioned papers, a channel model obtained from empirical measurements is used in [3]. There, the authors compare the performance of several channel estimation methods applied to an IEEE 802.16e transceiver that transmits through two VTV channels modeled from data collected at a frequency of 5.12 GHz. Such channels are described in [23] and consider two typical vehicular environments: a high traffic density highway and an urban area. The performed simulations use the uplink PUSC (Partial Usage of Subchannels) mode and show that the proposed channel estimation techniques give a good tradeoff between performance and computational complexity.

Finally, there are several papers in the literature that compare the results obtained using empirical channels and real-world measurements. For instance, [24] develops a Mobile WiMAX downlink physical layer simulator that transmits over the 3GPP-SCM channel model for urban microcells [25]. To validate the simulation results, the authors compared them with data obtained through a measurement campaign in a real urban cell scenario. In the simulated environment, the transceiver was configured to transmit data to three mobile stations which traveled at 40 km/h, recreating a situation very similar to the one faced during the measurement campaign. After comparing the simulated and the empirical results, it is concluded that their Mobile WiMAX simulator could be used to predict the performance (in terms of packet error rate versus signal-to-noise ratio) for a range of environments, transmit power levels and antenna configurations.

Although all the references mentioned provide a good idea about the capacities of Mobile WiMAX for transmitting in certain vehicular environments, their conclusions are only partially valid for the future VTV and RTV communications. On the one hand, most of the papers focus on the study of transceivers that do not work at 5.9 GHz, the frequency where ITS applications are likely to be developed. On the other hand, most of the channels analyzed consider either very generic or very specific environments. There is a lack of a proper Mobile WiMAX performance evaluation through different environments representative of the most common vehicular scenarios.

In this paper we will focus on obtaining PHY-layer performance results, since they constitute the basis on which simulations run for higher layers. Regarding the PHY layer, the most important performance metrics are the Bit-Error Rate (BER) and the Frame-Error Rate (FER) versus Signal-to-Noise Ratio (SNR) or Signal-to-Interference plus Noise Ratio (SINR). These performance metrics adequately characterize the PHY layer and can be used as input to network simulators such as QualNet or ns-2. Network simulators usually implement the MAC layer of wireless communications standards, but they model the PHY layer by just using simple BER calculation expressions which do not take into account complex scenarios such as the vehicular environments we consider in this work. As indicated in [26], BER results obtained through sophisticated PHY layer simulations can be incorporated in QualNet (in the form of lookup BER/FER Vs SINR tables) to obtain much more realistic network simulations.

From a general perspective, the impact on network simulation when using realistic PHY metrics was analyzed in [27]. There, the authors consider a set of factors at the PHY layer that are relevant to the performance evaluations of higher layer protocols. Such factors include signal reception, path loss, fading, interference and noise computation, and preamble length. The authors quantify the impact of these factors under typical scenarios used for the performance evaluation of wireless ad hoc routing protocols. Their experimental results show that the factors at the PHY layer not only affect the absolute performance of a protocol but, because their impact on different protocols is non-uniform, it can even change the relative ranking among protocols for the same scenario.
3. Performance evaluation system

Our evaluation system consists of two main components that are connected through the PCI bus of a regular PC. The first component is the software transceiver. In order to decrease the development time required we decided to use MATLAB and Simulink for implementing three different transceivers compliant with the standards IEEE 802.11p, IEEE 802.11a and IEEE 802.16e. The second component is the vehicular channel emulator, which was implemented using another rapid-prototyping tool: Xilinx System Generator. To perform the evaluation we have taken advantage of the ability of System Generator to exchange data between a design running in the FPGA and a software implementation that is executed on a PC. In fact, during the measurements described in Section 4 we ran MATLAB/Simulink software transceivers while the vehicular channel emulator was running on an external FPGA.

In the ensuing subsections the different components of the evaluation system are described, the designs of the transceivers are detailed and the main characteristics of the vehicular channel emulator are explained. The IEEE 802.11p/a transceivers and the emulator are only mentioned briefly, since they are described in depth in [4].

3.1. Implemented transceivers

3.1.1. Mobile WiMAX

In our development we focus on the physical (PHY) layer referred to in the IEEE 802.16e standard as Wireless-MAN-OFDMA. Fig. 1 depicts the block diagram of the evaluation system, which shows that Mobile WiMAX has been defined in a similar way to other regular OFDM (Orthogonal Frequency-Division Multiplexing) communication systems. In fact, our implementation uses a variation of OFDMA (Orthogonal Frequency Division Multiple Access) called SOFDMA (Scalable OFDMA) that makes it possible to work with multiple users simultaneously and which can be adapted to different environments and circumstances.

Among the different Mobile WiMAX working modes, in our experiments the transceiver operates in a mode called Downlink PUSC (Partial Usage of Subcarriers). In this mode, the 512 subcarriers are divided into 360 subcarriers for data, 60 for pilots and 92 for the guards and the DC. Each fourteen adjacent subcarriers over two OFDMA symbols constitute a cluster or resource block (24 subcarriers for data and 4 for pilots). Furthermore, each OFDMA symbol is divided into fifteen subchannels but, for the sake of simplicity, we assigned all subchannels to a unique user.

3.1.1.1. Mobile WiMAX MATLAB/Simulink transmitter. Fig. 1(left) depicts the transmitter block diagram. We have followed closely the indications given in Section 8.4 of [30], although we have made modifications in order to simplify the design and reduce simulation time. Such differences are described below.

First, a Random Integer Generator (RIG) block generates equally likely data bits. For each transmission, the model generates enough bits to fill the desired number of OFDMA symbols to be transmitted. An IEEE 802.16e transmitter works with slots instead of symbols: one slot is equal to two consecutive OFDMA symbols. Hence, the minimum number of OFDMA symbols to be transmitted is two. Also, it should be noticed that in our tests we have considered that a fair comparison between the different standards should be performed measuring the FER (FEC block error rate). Since each FEC block contains 48 data bits and there are 720 data subcarriers for each slot (two OFDMA symbols), using QPSK and a rate 1/2 code, it is concluded that in each slot the transmitter sends 15 FEC blocks.

The generated bits are randomized using a randomizer that is initialized for each FEC block. Although the standard states that padding with 0xFF shall be added if the amount of data to be transmitted does not fit the amount of allocated data, padding is never performed since we always generate the exact amount of data. The randomization process is carried out by XOR-ing the generated bits with a sequence obtained from a 15-bit randomization vector whose initialization value is indicated in Section 8.4.9.1 of [30]. The randomized bits are convolutionally encoded with the industry-standard generator polynomials \( g_0 = 133 \) and \( g_1 = 171 \). In the tests we used a rate 1/2 encoder but, in the event of other rates being needed (2/3 and 3/4 are supported), puncturing can be employed using the patterns given by the standard.

Block interleaving is then carried out in a two-step permutation. The first permutation ensures that adjacent coded bits are mapped onto non-adjacent subcarriers, while the second permutation ensures that adjacent coded bits are mapped onto less and more significant bits of the constellation to avoid long runs of bits with low reliability.

After block interleaving, the bits are Gray-mapped into QAM symbols and interleaved twice subsequently. The first interleaving stage affects the QAM data symbols contained in one slot (i.e. two adjacent OFDMA symbols) while the second stage reorganizes the QAM data symbols inside each OFDMA symbol. With respect to the pilots, the standard uses a Pseudo-Random Binary Sequence (PRBS) generator during their modulation. However, since this generator is only used to provide additional security, we decided not to include it in our design in order to reduce complexity and simulation time.

The interleaved QAM data symbols are placed into their corresponding subcarriers in each OFDMA symbol. Notice that the positions of pilots and data change depending on whether they are placed into an odd or an even OFDMA symbol according to the structure imposed by the Downlink PUSC mode. Once the OFDMA symbol is built, the IFFT is performed and a 1/4 cyclic prefix (CP) is added.

Finally, a preamble is appended to the whole frame. Although the preamble is always transmitted in order to comply with the requirements of the standard, it is not used in reception since we assume perfect time synchronization and we have not implemented any algorithm that might need it. Moreover, note that the vehicular channel emulator operates in baseband, so there is no IF stage, neither at the transmitter nor at the receiver.

3.1.1.2. Mobile WiMAX MATLAB/Simulink receiver. The receiver block diagram is shown on the right of Fig. 1. The first step is the addition of white Gaussian noise in order to
obtain BER (Bit Error Rate) and FER curves versus $E_b/N_0$ values. The $E_b/N_0$ parameter is the received bit energy to noise power spectral density ratio commonly referred to as received signal-to-noise ratio (SNR) per bit.

After removing the preamble and the CP, the FFT is applied to each OFDM symbol and the channel is estimated. Although we have tested different channel estimation techniques, we will only describe the simple method we used in the experiments presented in Section 4: we extract the pilots and divide them by their respective transmitted values (which are known at the receiver), obtaining the estimated channel coefficients for the pilot subcarriers. Such estimates are linearly interpolated to obtain the channel frequency response for the remaining subcarriers. Moreover, to improve channel inversion, an MMSE (Minimum Mean Square Error) equalizer [31] is used.

The equalized symbols are de-interleaved (at slot and symbol levels) and then sent to a soft detector whose output LLRs are also de-interleaved and decoded using a Viterbi block. Finally, the decoded bits are de-randomized applying an XOR gate, using the same PN sequence generated at the transmitter side, and the final bits are obtained.

3.1.2. IEEE 802.11p and IEEE 802.11a

The standard IEEE 802.11p [28] is an amendment to IEEE 802.11-2007 [29] and is technically compatible with the specifications given by ASTM E2213-03 [13], which address the challenges that arise when providing wireless access in vehicular environments. Its Medium Access Control (MAC) and PHY layers are very similar to those used in the Wireless Local Area Network (WLAN) standard IEEE 802.11a [14], but they use a lower overhead to allow faster exchanges of safety messages.

In our implementations we focus on the PHY layer and, at such a level, the main difference between IEEE 802.11a and IEEE 802.11p is that the 20 MHz bandwidth used in IEEE 802.11a is reduced to 10 MHz in IEEE 802.11p. Although the mentioned bandwidth reduction results in a loss of data transfer rate, it provides an important advantage when overcoming the effects of vehicular channels: the OFDM symbols are longer in the time domain and the system can deal with larger delay spreads, thus being able to avoid ISI (Inter-Symbol Interference). Therefore, if we ignore the IEEE 802.11p ACR (Adjacent Channel Rejection) and the SEM (Spectrum Emission Mask) requirements,
the practical implementation of a basic IEEE 802.11p transceiver is straightforward: it suffices to double all the OFDM timing parameters used by IEEE 802.11a devices.

The design of our IEEE 802.11p/a transceivers (whose key parameters are shown in Table 1) and the interface that connects them to the emulator have been described in Section 4 of [4]. In a nutshell, it can be said that the system consists of a transmitter that generates and sends data to the receiver passing through the vehicular channel emulator, in a way similar to the system depicted in Fig. 1.

3.2. FPGA-based vehicular channel emulator

The channel models implemented on the FPGA-based vehicular emulator are described in [7]. This work presents the channel models of six different 5.9 GHz high-speed environments that cover some of the most common situations where VTV and RTV communications may take place.

Table 2 summarizes the main characteristics of the channels. For each model, the following parameters are shown: the speed of the vehicle, Rician $K$ for the Rician paths, overall $K$ factor (i.e. the ratio of the deterministic power over the total random power of all taps), maximum frequency shift for all paths, maximum fading Doppler (i.e. maximum half-width of the fading spectral shapes of all the paths of each channel) and LOS Doppler of the Rician paths.

The models can be grouped into three major scenarios: urban canyons (VTV-Urban Canyon Oncoming, RTV-Urban Canyon), expressways (VTV-Expressway Oncoming, RTV-Expressway, VTV-Expressway Same Direction With Wall) and suburban surface streets (RTV-Suburban Street).

Such channels were implemented in a channel emulator based on a Virtex IV FPGA. The FPGA is placed inside a Nallatech BenADDA-IV development kit which has the following main features: it permits the use of Xtreme-DSP slices of up to 400 MHz, it has two 14-bit ADCs and two 14-bit DACs (able to work up to 105 MSamples/s and 160 MSamples/s, respectively) and 4 MB of ZBT-RAM, whilst its internal clock reaches up to 105 MHz (the kit can also use an external clock). Another interesting feature of the kit is that it can be either connected to a PC (via the PCI bus) or it can be used in stand-alone mode.

Since the vehicular channel emulator design and its characteristics have been described in previous work, we will not give any further details, encouraging the interested reader to consult references [4,7].

4. Experiments

Performance evaluation of the PHY layer implementation of the software transceivers was carried out by passing the signals they produce through the FPGA-based vehicular channel emulator. Taking advantage of the Xilinx Xtreme DSP software kit capabilities measurements are performed using the co-simulation mode: the transmitter and the receiver are implemented in MATLAB and Simulink, while the channel emulator runs on an FPGA.

In order to achieve a fair comparison we set the same transmission parameters for every transceiver. A rate 1/2 FEC is used and the subcarriers are filled with QPSK modulated symbols. The receiver assumes perfect time synchronization and, after estimating the channel using a pilot-aided scheme, an MMSE linear equalizer is applied. The remaining transceiver parameters are shown in Table 1.

Additionally, for the sake of fairness, instead of comparing performance in terms of PER (Packet Error Rate), we obtained the FEC Frame Error Rate (FER) when all the transceivers make use of the same FEC block size. Thus, a maximum of 100,000 48-bit FEC blocks are averaged for different $E_b/N_0$ values (the simulation stops for each $E_b/N_0$ value when 100 erroneous FEC blocks are detected).

4.1. Mobile WiMAX BER/FER performance

4.1.1. Performance over AWGN and Rayleigh fading channels

In order to obtain a performance reference for the implemented transceivers, we evaluated them over two non-vehicular environments. Figs. 2 and 3 show, respectively, the transceivers’ performance over an AWGN channel and a frequency-flat Rayleigh block fading channel.
whose coefficients were constant during 15 FEC blocks (i.e. one Mobile WiMAX slot).

For both channels, IEEE 802.11p and IEEE 802.11a produce roughly the same results. This behavior was to be expected since the transceiver is the same in all aspects apart from the bandwidth. However, the IEEE 802.16e transceiver yields much better results, especially in the AWGN channel, even though the transmission parameters are the same in all transceivers. This is because channel estimation is far more accurate in the case of the IEEE 802.16e transceiver. Indeed, Fig. 4 shows the Mean Squared Error (MSE) between the estimated and the true channel for the IEEE 802.11p (the same results were obtained with IEEE 802.11 a) and IEEE 802.16e transceivers when considering an AWGN channel. IEEE 802.16e better estimates the channel thanks to the use of sixty pilots (i.e. for 360 data subcarriers one pilot is used for each group of six data subcarriers), while IEEE 802.11p makes use of only four pilots (since there are 48 data subcarriers, there is one pilot for each group of twelve data subcarriers).

### 4.1.2. Performance over vehicular channels

Figs. 5–10 depict the BER and FER curves for the three transceivers when transmitting over the six vehicular channels described in Section 3.2. In general, it can be
observed that the IEEE 802.16e transceiver produces better results (both in terms of BER and FER) than IEEE 802.11p, while the IEEE 802.11a transceiver obtains the worst global results. Also, notice that due to the limited coherence time of the vehicular channels, there is always a residual channel estimation error which produces the error floor that can be observed in all figures. This is in contrast to the performance curves corresponding to the static frequency-flat channels used in Figs. 2 and 3, where there is no error floor.

In urban environments (channels VTV-Urban Canyon Oncoming and RTV-Urban Canyon) Mobile WiMAX outperforms IEEE 802.11p/a in terms of BER and FER for $E_b/N_0$ values below 20 dB (see Figs. 5 and 6). Also, notice that Mobile WiMAX requires the lowest $E_b/N_0$ values to reach a target FER of 10%.

In surface streets (RTV-Suburban Street) Mobile WiMAX also performs better than the other standards (see Fig. 7). For instance, to reach an FER of 10% Mobile WiMAX requires 8.6 dB, while IEEE 802.11p and IEEE 802.11a need, respectively, 11.1 dB and 14.6 dB.

In expressways (VTV-Expressway Oncoming, RTV-Expressway, VTV-Expressway Same Direction With Wall) the results depend on the channel. In VTV-Expressway Oncoming (see Fig. 8) IEEE 802.11p clearly outperforms Mobile WiMAX at both low and high values of $E_b/N_0$. IEEE 802.11p and Mobile WiMAX both exhibit a similar
performance when considering RTV-Expressway channels (see Fig. 9): Mobile WiMAX is slightly better than IEEE 802.11p while the situation reverses form for high $E_b/N_0$ values. Finally, in the case of VTV-Expressway Same Direction With Wall, Mobile WiMAX clearly obtains a major gain over IEEE 802.11p/a: for example, it requires an $E_b/N_0$ of 6.2 dB less than that of IEEE 802.11p (7.6 dB vs 13.8 dB) to obtain an FER of 10% (see Fig. 10).

4.1.3. Discussion: IEEE 802.16e or IEEE 802.11p?

The BER/FER versus $E_b/N_0$ curves depicted in the previous subsection indicate that the PHY Layer of Mobile WiMAX outperforms that of IEEE 802.11p in most of the reference channel models used as benchmarks in vehicular communications. The only clear exception is the performance over the VTV-Expressway Oncoming channel where the performance of IEEE 802.11p is much better than that.
of Mobile WiMAX. For the RTV-Expressway channel, the PHY Layer performance of both standards is quite similar. In the remaining four scenarios the PHY Layer of Mobile WiMAX is considerably better than that of IEEE 802.11p.

An explanation of this behavior is the superior robustness to high channel delay spreads of the Mobile WiMAX PHY Layer. In IEEE 802.11p, assuming a bandwidth of 10 MHz and 64 subcarriers, a 1/4 cyclic prefix will lead to a guard time of 1.6 μs. In the case of Mobile WiMAX, a transceiver that uses 10 MHz of bandwidth and 512 subcarriers has a 1/4 cyclic prefix that lasts 12.8 μs. Thus, the OFDM symbols used in Mobile WiMAX can equalize channels with a larger delay spread.

Another advantage of the Mobile WiMAX PHY Layer is that the maximum data rate that it can reach is 39.9 Mbits/s while this value is only 27 Mbits/s in the case...
of IEEE 802.11p. Regarding bandwidth, both PHY Layers admit 10 MHz, but Mobile WiMAX shows more flexibility by offering different bandwidths. Depending on the band class, a bandwidth of 3.5, 5, 7, 8.75, 15 or 20 MHz can be selected, it thus being more suitable for adapting its transmission to the various radio spectrum regulations that exist all around the world.

On the other hand, it should be mentioned that the PHY layer of IEEE 802.11p supports larger vehicle speeds. Indeed, IEEE 802.11p is designed to transmit 1000 byte data packets with an FER lower than 10% at a maximum Doppler shift of ±2100 Hz, what means that a top speed of roughly 385 km/h can be reached when using the 5 GHz band (the transmitter and receiver would drive at almost 193 km/h). On the other hand, the WiMAX Forum mobility profile requirements [15] specify that each Mobile WiMAX terminal should be able to exchange data at a maximum speed of 120 km/h (which already coincides with the maximum permitted traveling speed in many countries). Therefore, it can be stated that, theoretically, IEEE 802.11p is more appropriate for high speed environments. This explains the superior performance of IEEE 802.11p over the VTV-Expressway Oncoming, which is the channel with maximum Doppler shift (see Table 2).

Finally, notice that in this work we have focused on the PHY-layer performance of the standards analyzed. A final decision about which is the best standard for a specific vehicular network will depend on many other factors that are beyond the scope of this work such as infrastructure deployment costs, support of the automotive industry, energy consumption, handover efficiency, regulations of the radio spectrum, higher layer constraints and son on. However, the results presented herein provide a set of PHY-Layer metrics that can be used as the PHY model for a network simulator, which in turn can be used to carry out analyses of the whole vehicular network.

5. Conclusions

We have detailed the design and development of a Mobile WiMAX software transceiver and we have evaluated its PHY layer performance when transmitting over six reference vehicular channels which have been implemented on an FPGA-based channel emulator. The channels consider different scenarios that include common environments such as highways, urban canyons and suburban areas. Furthermore, the performance of Mobile WiMAX has been compared with that obtained by IEEE 802.11p and IEEE 802.11a transceivers in vehicular, Rayleigh fading and AWGN channels. The results obtained in non-vehicular channels illustrate the importance of obtaining a good estimation of the channel coefficients: Mobile WiMAX attains better results than IEEE 802.11p and IEEE 802.11a thanks to doubling the number of pilots per data subcarrier. Regarding the vehicular measurements, it can be concluded that, in the chosen experimental conditions, Mobile WiMAX outperforms IEEE 802.11p and IEEE 802.11a in most reference vehicular channels. Nevertheless, further research on non-PHY layer related factors should be performed to determine which standard is better for each specific vehicular scenario.

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