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PhySim-11p: Simulation model for IEEE 802.11p physical layer in MATLAB

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ABSTRACT

We present PhySim-11p, a simulation model for the IEEE 802.11p physical layer in MATLAB. The implemented simulation obtains Packet Error Rate (PER) versus Signal-to-noise Ratio (SNR) curves for the different transmission rates allowed by the standard. The model simulates a multi-path channel with Doppler shift, which is composed of Additive White Gaussian Noise (AWGN) and frequency–time selective fading. As a use case, we present the curves of PER versus SNR obtained from our software against nine PER theoretical models. The objective is to find the theoretical model that more closely approximates the simulated results when considering transmission parameters such as the modulation scheme M and the coding rate r. Our software aims to facilitate the study of different physical layer phenoms such as amplifier effects or channel estimation and the possibility of its inclusion in network simulators. Besides, it can be easily set up to model any OFDM physical layer of IEEE 802.11 (e.g., 802.11a).

Code metadata

Current code version	v1.1
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX_2019_390
Code Ocean compute capsule	none
Legal Code License	Creative Commons Zero (CC0)
Code versioning system used	none
Software code languages, tools, and services used	Matlab
Compilation requirements, operating environments & dependencies	Matlab 2017b or higher
If available Link to developer documentation/manual	none
Support email for questions	diego.reinoso@epn.edu.ec

1. Introduction

Nowadays, wireless communication systems are present in practically all places; a clear example is vehicular communications, which play a fundamental role in Intelligent Transportation Systems (ITS). In recent years ITS have been getting more and more interest in name of implementing vehicular ad-hoc networks (VANET) that make possible to manage Vehicle to Vehicle and Vehicle to Infrastructure communications (V2x) reliably and with good speeds [1]. ITS facilitate several applications for vehicles on the road, like improving the user experience with functions such as adaptive cruise control or precise maneuvering [1] and traffic flow [2]. Another important application is road safety with functions such as collision warning or pedestrian detection, which can help in the saving of lives [1]. To implement these applications in vehicular networks, there has to be guarantees regarding the exchange of information, such as in reliability and transmission speed [1,3].

There have been efforts to standardize various vehicular communication technologies at different layers [1]. Currently there is development being made by using cellular technology for ITS solutions, for example LTE-V2x based on Time Division LTE, which is being researched as an ITS solution [4], and heterogeneous

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cellular networks using a 5G infrastructure [5]. Cellular technologies present desirable features like an existing robust architecture and theoretical better performance [4,6], however it fails short in practice, scope or development [7]. IEEE 802.11p is of particular interest since it is the Physical Layer (PHY) and Media Access Control (MAC) sub-layer standard used in the ITS solutions proposed by IEEE [8], ETSI [9] and ISO [1] and is the leading Vehicular Network (VANET) lower layers technology [7,10] with products and implementations already available in the market [11].

802.11p systems allow the inter-connectivity of vehicles and their environment. The IEEE 802.11p standard [12] covers the PHY and MAC sub-layer. It is intended for vehicular applications and modifies certain characteristics of IEEE 802.11 due to the rapidly changing environment of vehicular networks.

The information unit used in the PHY layer is a bit packet, so the best parameter to measure the reliability of transmissions is the Packet Error Rate (PER), which measures the ratio between erroneous packets and the total number of received packets at reception. A packet is erroneous when one or more bits that make it up are erroneous [13]. Determining the PER is very important for the development of upper-layer applications and protocols; therefore, theoretical and simulation models for the PER are required.

MATLAB offers the WLAN Toolbox™ [14] for the design, simulation, and analysis of Wireless Local Area Network (WLAN) communications. It can simulate the PHY of IEEE 802.11ax/ac/ad/ah and 802.11b/a/g/n/j/p standards. Despite its wide variety of options, this toolbox is not a step-by-step implementation of the 802.11p PHY, that our work does provide, and also implies an extra cost for its use.

Physical layer simulation of IEEE 802.11 has been studied extensively in the literature because of its paramount importance. In [15], authors used pre-established blocks in Simulink to find a performance metric by analyzing the PER degradation level data by varying SNR and Doppler Spread. They proposed a Markov model expression that parametrizes the SNR and the Doppler Spread with polynomial regression. The work of [16] analyzes the performance of inter-vehicle communications for different levels of shadowing in a Rician channel. They focused on the Outage Probability over a continuous range of transmission rates, but they do not look into PER or any particular transmission system. [17] studies the impact of channel with interference from other vehicles over the MAC layer of an IEEE 802.11p communication system. The performance metric of their study is the throughput and the different transmission probabilities as a consequence of collisions over the channel. The approach followed did not include any PHY metrics such as PER. Some works take a more general approach to describe PER vehicular channels, without giving a closed-form dependent of the SNR, nor reliant on the choice of transmission speed. For instance, [18] finds a Discrete-Time Markov Chain representation for PER values over several fixed time windows for continuous-time simulations using the PHY layer of IEEE 802.11p. For this, the authors performed PHY and MAC sublayer analysis for data obtained from a Simulink model I, and ends up with a stochastic matrix that gives good results against the simulated data.

There are other works focused on providing a realistic channel for vehicular communications; however, they do not go into PER derivation as a PHY layer metric. For instance, Akhtar et al. [19] focused on providing a realistic channel for vehicular communications in highway scenarios. They studied the topology and channel modeling of a vehicular environment using realistic data, and proposes modifications to the log-normal shadowing model, to provide a less computationally expensive model to describe a realistic channel for VANETs.

Table 1
Configurations allowed by IEEE 802.11p [12,20].

Modulation Scheme	Bits Per Modulated Symbol (m)	Coding Rate (r)	Data rate v_i [Mbps]
BPSK	1	1/2	3
BPSK	1	3/4	4.5
QPSK	2	1/2	6
QPSK	2	3/4	9
16QAM	4	1/2	12
16QAM	4	3/4	18
64QAM	6	2/3	24
64QAM	6	3/4	27

This article presents PhySim-11p, a simulation model of the IEEE 802.11p PHY in MATLAB to study the effect of PHY components in the PER behavior. The scripts generate graphs of PER versus the Signal to Noise Ratio (SNR) for the different transmission rates allowed by the standard. The simulated channel on our software is composed of Additive White Gaussian Noise (AWGN) and frequency–time selective fading, which results from a multipath channel with Doppler shift. The results of the IEEE 802.11p PHY simulation are compared with the theoretical models to determine the model that best fits the PHY simulation.

The rest of this paper is organized as follows: Section 2 presents a detailed explanation of the software architecture. Then, Section 3 presents the simulation results and discussion. Next, Section 4 presents the impact of this work. Finally, Section 5 includes the conclusions and future work.

2. Software architecture

The scripts and functions designed for the PER models comparison with the simulation of the IEEE PHY 802.11p [12] are implemented in MATLAB and consist of the following:

1. The IEEE 802.11p transmitter and receiver with all the blocks involved at PHY level.
2. The wireless channel.
3. The theoretical models for the calculation of the PER.
4. Auxiliary scripts.

The different functions and scripts involved in the data processing for IEEE 802.11p PHY can be found in detail for the transmitter and receiver in Fig. 1. The theoretical models for the PER calculation in the use case are implemented separately in other scripts. Auxiliary scripts are used to obtain and process the data, in addition to displaying the results.

2.1. IEEE 802.11p PHY implementation

The PHY layer model will follow the training and reception process described in the IEEE 802.11 standard [20], which uses Orthogonal Frequency Division Multiplexing (OFDM). All the elements of the PHY layer are implemented from the signal processing to the creation and preamble appending, header formation, and bit stuffing.

With 10 MHz bandwidth, the eight possible combinations of coding rates and modulation schemes allowed by the IEEE 802.11 standard [20] associated with the different speeds for data transmission are implemented and shown in Table 1.

The same scripts can be used for any implementation of the IEEE 802.11 standard which uses OFDM as the transmission technique, giving a greater scope for future use. The standards that can be used are 802.11a/g/n, considering that they do not work at the same frequency and that also the bandwidth is different. For example, for the 802.11g standard the bandwidth is 20 MHz so the data rate would be the double of the ones shown in Table 1 for the same parameters.

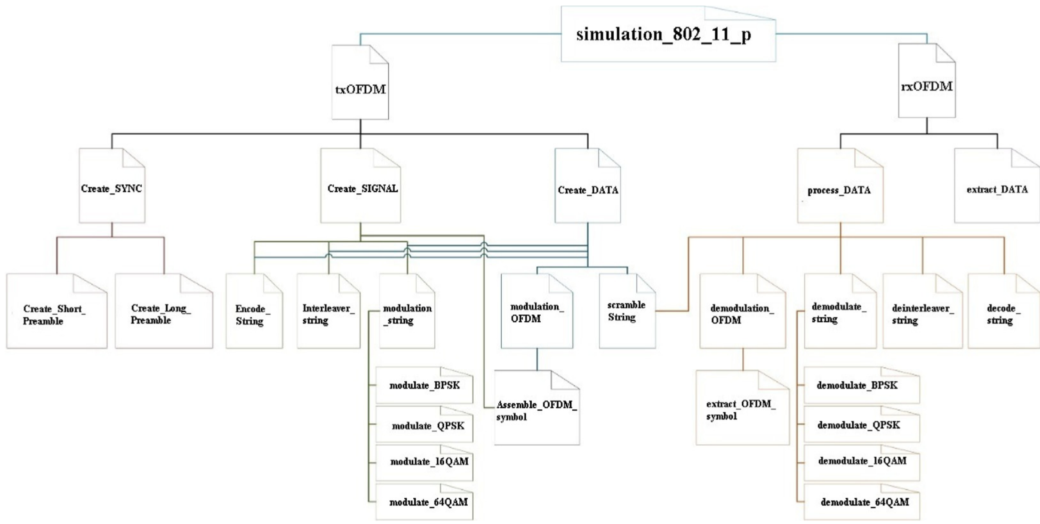

Fig. 1. Structure of the functions and scripts of the IEEE 802.11p PHY layer simulation.

2.1.1. Main simulation

The **simulation_802_11_p** script is the main script which performs the following tasks:

- Setting up transmission parameters such as number of packets, number of bits per packet, SNR range and channel type.
- Calling on the transmission and reception scripts.
- Simulating the transmission, sending, wireless channel and reception of packets according to the established parameters.
- Calculating performance parameters such as Bit Error Rate (BER), PER and number of errors for each configuration.

2.1.2. Transmission

For the implementation of the packet transmission according to the diagram presented in Fig. 1, the **txOFDM** function is used, which calls for the **Create_SYNC**, **Create_SIGNAL** and **Create_DATA** functions that generate the preamble, header and payload of the packet, respectively.

The **Create_SYNC** function creates the short preamble and the long preamble through independent functions. It then appends both to obtain the preamble for the Physical Layer Convergence Protocol (PLCP) Protocol Data Unit (PPDU). The generation of the preamble is given by the IEEE 802.11-2012 standard [12]. The **Create_SIGNAL** function returns the header of the PPDU according to the IEEE 802.11-2012 standard, which is formed by a single OFDM symbol. The **Create_DATA** function returns the DATA field of the PPDU. It generates the SERVICE (16 bits) and Tail (6 bits) fields and the padding bits. It then appends all of them to the PPDU payload according to the IEEE 802.11-2012 standard.

The transmission of a randomly generated bit string, grouped in packets of equal size, is simulated. These bits pass through the process described in Fig. 2 in order. First, a scrambler shuffles the data with respect to an initial seed. Then, a convolutional encoder adds redundancy bits to implement error correction capabilities. Next, an interleaver permutes the bits inside the packet to avoid burst errors. Then, a modulator assigns complex symbols to groups of bits within the packet depending on the modulation scheme chosen and its corresponding constellation diagram. Next, an OFDM symbol assembler assigns each modulated symbol to its corresponding OFDM symbol sub-carrier. It is followed by the Inverse Fast Fourier Transform (IFFT) and the appending of the cyclic prefix to reduce multipath effects. Finally, the data is transmitted over the wireless channel. Reception follows the inverse processes for the recovery of the original bits.

Table 2
PDP of the Rural line-of-sight channel.

	Tap 1	Tap 2	Tap 3	Units
Power	0	−14	−17	dB
Delay	0	83	183	ns
Doppler	0	492	−295	Hz
Profile	Static	HalfBT	HalftBT	

Table 3
PDP of the Urban line-of-sight channel.

	Tap 1	Tap 2	Tap 3	Tap 4	Units
Power	0	−8	−10	−15	dB
Delay	0	117	183	333	ns
Doppler	0	236	−157	492	Hz
Profile	Static	HalfBT	HalftBT	HalftBT	

Table 4
PDP of the Highway line-of-sight channel.

	Tap 1	Tap 2	Tap 3	Tap 4	Units
Power	0	−10	−15	−20	dB
Delay	0	100	167	500	ns
Doppler	0	689	−492	886	Hz
Profile	Static	HalfBT	HalftBT	HalftBT	

2.1.3. Wireless channel

The wireless channel is composed of AWGN noise and frequency–time selective fading. In vehicular communications is common that the transmitted signal propagates to the receiver through different paths therefore, a multi-path channel is the proper way to model this behavior. The multi-path channel generates frequency selective fading in the received signal. Aditionally, in vehicular communications the transmitter, receiver or both are moving causing Doppler shift in the received signal. This effect generates a time selective fading. Therefore, a more accurate way to model vehicle to vehicle communications is using a channel with frequency–time selective fading which is modeled by its Power Delay Profile (PDP). For the simulation, four scenarios are considered and its PDP are presented in Tables 2–5 [21]. These tables present the power, delay, Doppler shift and Doppler spectra profile of the four scenarios. The Doppler spectra profile can be static or can have a half-bathtub (HalfBT) shape.

The **ricianWChannel** function generates one of the four wireless channels presented in Tables 2–5 [21]. This function returns an object with the channel parameters and other information

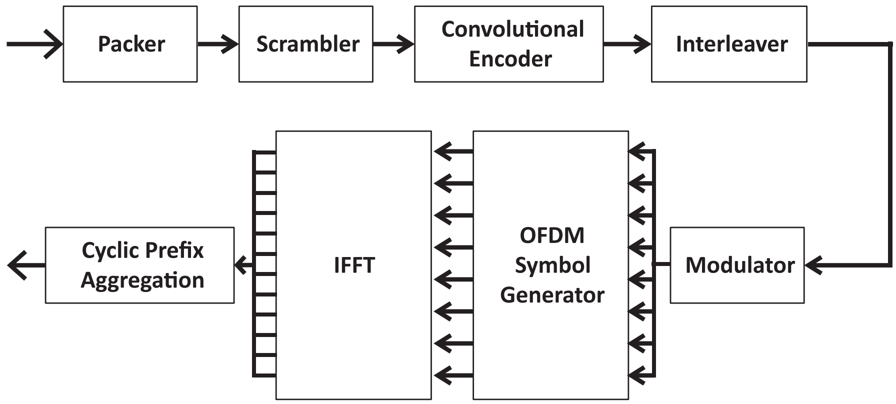

Fig. 2. OFDM transmitter block diagram.

Table 5
PDP of the Highway non-line-of-sight channel.

	Tap 1	Tap 2	Tap 3	Tap 4	Units
Power	0	−2	−5	−7	dB
Delay	0	200	433	700	ns
Doppler	0	689	−492	886	Hz
Profile	Static	HalfBT	HalftBT	HalftBT	

to compute the frequency response of the channel. In the **simulation_802_11_p** script, after obtaining the signal to transmit, the channel is applied to it and then, the AWGN noise is added. Before the data processing in the receiver, the channel effect is compensated by dividing the signal with the frequency response of the channel, which we assume is known in the receiver.

2.1.4. Reception

For the implementation of packet reception according to the diagram presented in Fig. 1, the function **rxOFDM** is used, which calls for the functions **extract_DATA** and **process_DATA** for the extraction of the DATA field from the packet and its respective processing.

The **extract_DATA** function returns the OFDM symbols of the DATA field that was extracted from the packet according to the IEEE 802.11 standard [12]. The **process_DATA** function returns a bit payload by performing the reverse process done in transmission, including demodulation, deinterleaving, decoding and descrambling according to the IEEE 802.11-2012 standard. This process is shown in Fig. 3. The **extract_OFDM_symbol** function is also used in **process_DATA** to obtain an array of symbols in the frequency domain. This function extracts the samples that do not correspond to the cyclic prefix and redistributes it according to the IEEE 802.11 standard. Finally, data is extracted from the sub-carriers and the DC sub-carrier.

2.2. Theoretical models of PER

For each model, a function has been developed that takes the SNR value, the modulation scheme, the coding rate and the packet length as input parameters. At the output the value of the PER calculated with the respective equations of each model is obtained. Other additional parameters that are necessary for the implementation of the mathematical models are taken from the specifications of the IEEE 802.11p standard [12].

2.2.1. Mathematical models for BER calculation

Some of the models for the calculation of the PER require BER values depending on the SNR and the modulation scheme. To obtain these BER values, three theoretical models are considered and presented below.

(a) **Theoretical BER model # 1**
The first theoretical BER model performs the calculation of the BER value according to [22]

$$b_e(\gamma) = c_m Q(\sqrt{k_m \gamma}) \tag{1}$$

where γ is the SNR, $Q(\cdot)$ is the Q function [23], c_m and k_m are constants that depend on the modulation scheme defined in the IEEE 802.11 standard. For the different modulation schemes, the BER formulas that are used are the following

$$\begin{aligned} BPSK: \quad & b_e(\gamma) = Q\left(\sqrt{2\left(\frac{10}{v_t}\right)\gamma}\right), \\ QPSK: \quad & b_e(\gamma) = Q\left(\sqrt{2\left(\frac{10}{v_t}\right)\gamma}\right), \\ 16QAM: \quad & b_e(\gamma) = \frac{3}{4}Q\left(\sqrt{\frac{4}{5}\left(\frac{10}{v_t}\right)\gamma}\right), \\ 64QAM: \quad & b_e(\gamma) = \frac{7}{12}Q\left(\sqrt{\frac{2}{7}\left(\frac{10}{v_t}\right)\gamma}\right). \end{aligned} \tag{2}$$

(b) **Theoretical BER model # 2**
The second theoretical BER model considers the energy per bit to noise power spectral density ratio E_b/N_0 value per OFDM symbol is given by [24]

$$\gamma_s = 0.8 \log_2(M)\frac{AB}{v_t}\gamma = \frac{8\ \mathrm{m}}{v_t\ [\mathrm{Mbps}]}\gamma \tag{3}$$

where γ is the SNR value, v_t is the transmission speed in Mbps and m is the number of bits per symbol depending on the modulation scheme (BPSK, QPSK, 16QAM, 64QAM). Then, the following approximations of the BER b_e for each type of modulation are obtained

$$\begin{aligned} BPSK: \quad & b_e^{BPSK}(\gamma_s) = Q(\sqrt{2\gamma_s}), \\ QPSK: \quad & b_e^{QPSK}(\gamma_s) = Q(\sqrt{\gamma_s}), \\ 16QAM: \quad & b_e^{16QAM}(\gamma_s) = \frac{3}{4}Q\left(\sqrt{\frac{1}{5}\gamma_s}\right), \\ 64QAM: \quad & b_e^{64QAM}(\gamma_s) = \frac{7}{12}Q\left(\sqrt{\frac{1}{21}\gamma_s}\right). \end{aligned} \tag{4}$$

(c) **Theoretical model of BER # 3**
The third model performs the BER calculation with help of MATLAB. The berawgn(.) function of MATLAB is used to

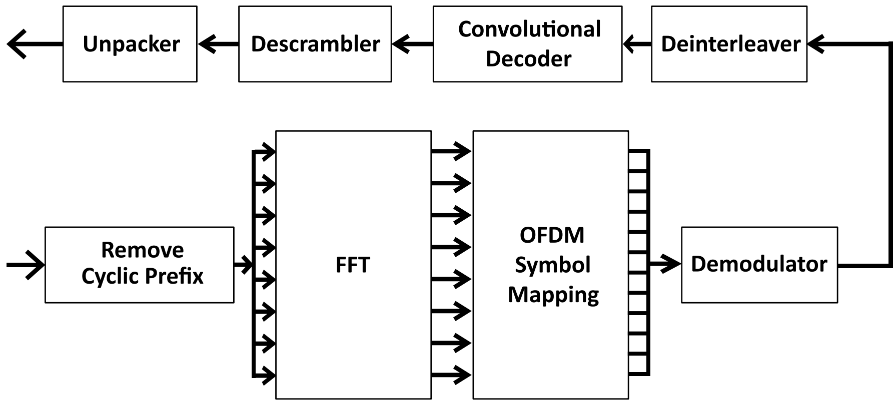

Fig. 3. OFDM receiver block diagram.

calculate this value. The equations for the different modulation schemes used can be found in the MATLAB help.

2.2.2. Mathematical models for PER calculation

After the BER models were specified, now the description of each theoretical model is presented in the following.

(a) **Model 1: Model for vehicular networks by interpolation** [25]
This model is a mathematical analytical model for the calculation of PER, and is given by

$$PER(\gamma, L) = \frac{1 - \tanh(a_R(L) - b_R(L)(\gamma + c))}{2} \tag{5}$$

where γ is the SNR in dB, L is the length of the packet in bits, c is an offset constant, $a_r(L)$ and $b_r(L)$ are parameters obtained as a function of the modulation scheme and coding rate.

(b) **Model 2: Model without coding over an AWGN channel using EVT** [22]
This model is a mathematical analytical model using Extreme Value Theory (EVT) for the PER calculation. This model is described from an SNR value and it is given by

$$PER(\gamma) \approx 1 - \exp\left(-\exp\left(-\frac{\gamma - a_N}{b_N}\right)\right) \tag{6}$$

where γ is the SNR, a_N and b_N are constants that depend on the modulation scheme.

(c) **Model 3: Model of non-homogeneous errors at PHY layer** [13]
This model is a predictive theoretical model of PER that considers the non-uniformity of errors at the output of the PHY layer due to the convolutional decoding process. The output bits depend on the input bits and the constraint length of the code k, for IEEE 802.11p [20] k = 7.
The PER value is given by

$$PER(\gamma, L) = 1 - (1 - \lambda(\gamma))^L$$

where γ is the SNR and L is the length of the packet in bits.

(d) **Model 4: Model of PER upper bound for OFDM systems, with BER equation #1**
This model describes how to calculate an upper bound of the PER in IEEE 802.11p systems. The BER value for this model is calculated independently with the theoretical model of BER #1 and the PER is ultimately parameterized with respect to the SNR and the length of the packet (L) considering convolutional code parameters such as free distance and free distance path length. The PER value is given by [24]

$$PER \leq 1 - \left(1 - \sum_{d=d_{free}}^{d_{free+9}} a_d P_d^{mod}\right)^L \tag{7}$$

where d_{free} is the free distance, a_d is the number of paths of length d, and P_d^{mod} is a parameter defined as

$$P_d^{mod} = \begin{cases} \sum_{k=(d+1)/2}^{d} \binom{d}{k} \left(b_e^{mod}\right)^k \left(1 - b_e^{mod}\right)^{d-k} & \text{d odd} \\ \sum_{k=d/2+1}^{d} \binom{d}{k} \left(b_e^{mod}\right)^k \left(1 - b_e^{mod}\right)^{d-k} + \frac{1}{2}\binom{d}{d/2} \left(b_e^{mod}\right)^{\frac{d}{2}} \left(1 - b_e^{mod}\right)^{\frac{d}{2}} & \text{d even} \end{cases} \tag{8}$$

where b_e^{mod} is the BER for the modulation scheme *mod*.

(e) **Model 5: Model of PER upper bound for OFDM systems, with BER model #2**
It uses Eq. (7) of model 4, but instead of using the theoretical model of BER #1, the previously described theoretical model of BER #2 is used.

(f) **Model 6: Model of PER upper bound for OFDM systems, with BER model #3**
It uses Eq. (7) of model 4, but instead of using the theoretical model of BER #1, the theoretical model of BER #3 is used.

(g) **Model 7: Model without coding over an AWGN channel, with BER model #1.**
This model describes a general way for obtaining PER without considering coding schemes on AWGN channels. The BER value for this model is calculated independently with the theoretical model of BER #1 and the PER is given by [22]

$$PER(\gamma) = 1 - (1 - b_e(\gamma))^L, \tag{9}$$

where γ represents the SNR, $b_e(\gamma)$ the BER of each modulation scheme used in IEEE 802.11p and (L) the packet size in bits.

(h) **Model 8: Model without coding on AWGN channel, with BER model #2.**
It uses Eq. (9) of model 7, but instead of using the theoretical model of BER #1 the theoretical model of BER #2 is used.

(i) **Model 9: Model without coding on AWGN channel, with BER model #3.**
It uses Eq. (9) of model 7, but instead of using the theoretical model of BER #1 the theoretical model of BER #3 is used.

2.3. Auxiliary scripts

Auxiliary scripts are designed for the treatment, analysis and presentation of the data obtained with the 802.11p PHY and theoretical PER models.

For the evaluation of the PER theoretical models, the function **evaluate_models** is defined, which chooses the desired theoretical model and executes it for each SNR value of the SNR range entered and saves the results in a PER vector, which is the output parameter.

The **PER_Extension** script extends the SNR domain of simulated PER values; this extension is done to be able to graphically represent the PER of each configuration together with the results of the theoretical models.

For the collection and consolidation of data resulting from the previous scripts, the function **Data_Consolidation** is created. This function imports the data files generated previously and renames them in a structured way for ease of manipulation, saving all the data in a .mat file.

Finally, for the presentation of results, a **Selec_grap** function is created, which shows the results graphically. It is possible to choose between showing only the simulation results, the results of each theoretical model of the PER or the comparison between simulation and theoretical models for each configuration. Additionally, it allows the selection of the wireless channel for the figures of the simulation results. The four options available are: 1. Rural Line-of-Sight (LOS), 2. Urban LOS, 3. Highway LOS and 4. Highway Non-line-of-Sight (NLOS).

The simulation of the IEEE 802.11p PHY returns a dataset to graph the results. This simulation takes a total of approximately 40 h for every wireless channel so the previously generated dataset is given. If the user wishes to generate the data again, the **simulation_802_11_p** script can be executed. With the generated dataset, only the **Selec_grap** script is executed to observe the results.

3. Simulation results and discussion

In this section several figures present the results obtained with the 802.11p PHY simulation and theoretical models. To obtain these results the **Selec_grap** auxiliary script is used. This script generates eight different figures for each data transmission rate configuration allowed by the standard with the selected fading channel. However, we present only results for two data transmission rates and two channels due to length constraints. Additionally, the script obtains the PER figures for both linear and logarithmic scale, but we present in the following the results only in linear scale.

Fig. 4 presents the results of the PER versus SNR for 16QAM modulation, coding rate 1/2 (12 Mbps transmission rate) and rural LOS channel. It includes each of the nine theoretical models (labeled Model 1, Model 2, …) in dashed lines. It also includes the results of the 802.11p PHY simulation (labeled Simulation) in black solid line. We can observe that Model 9 obtains the closest PER compared to the 802.11p PHY simulation.

Fig. 5 presents the results of the PER versus SNR for 64QAM modulation, coding rate 3/4 (27 Mbps transmission rate) and rural LOS channel. In this case Model 7 is the closest to the 802.11p PHY simulation.

Fig. 6 presents the results of the PER versus SNR for 16QAM modulation, coding rate 1/2 (12 Mbps transmission rate) and highway NLOS channel. We can observe that the PER of 802.11p PHY simulation is at the right of all models for $PER < 0.8$. Model 8 is the closest to the PHY simulation but with a big SNR difference of about 4 dB for $PER = 0.1$.

Similarly, Fig. 7 presents the results of the PER versus SNR for 64QAM modulation, coding rate 3/4 (27 Mbps transmission rate) and highway NLOS channel. We can observe a similar trend compared to the previous figure. In this case, model 1 is the closest to the PHY simulation but with a bigger SNR difference of about 5 dB for $PER = 0.1$. From these results, we can observe that the highway NLOS channel is the one that has the biggest impact over the PER, resulting in shifting the curve to the right. Thus, requiring higher SNR for achieving the same PER.

From the results, we can observe that for different combinations of transmission rate and channel, the closest theoretical model is different in each case. Therefore, we can select the closest theoretical model depending on the transmission rate and channel for best results. Also, we can introduce SNR offsets to the theoretical models in order to obtain a model that is the closest for all transmission rates.

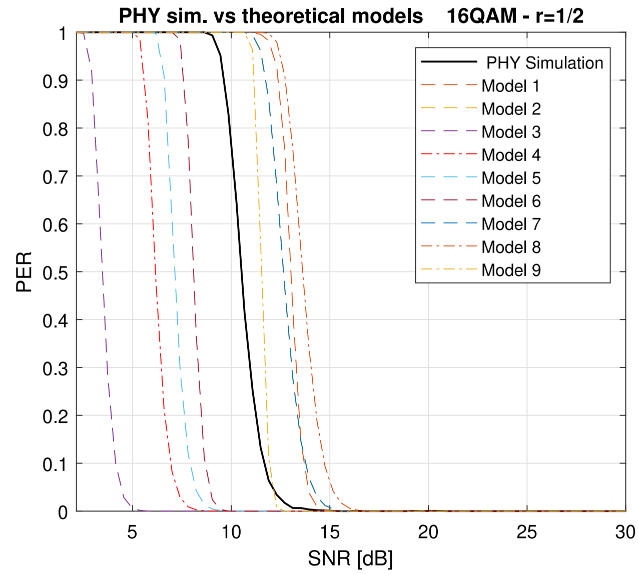

Fig. 4. Comparison of theoretical models with 802.11p PHY simulation for 16QAM, $r = 1/2$ (12 Mbps), rural LOS channel.

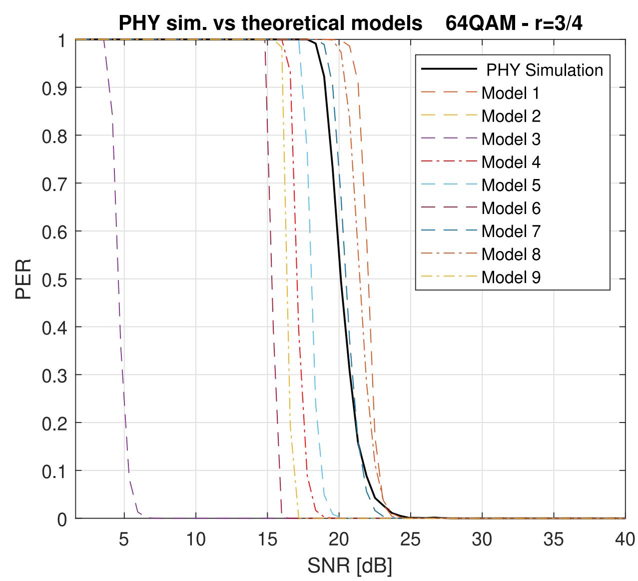

Fig. 5. Comparison of theoretical models with 802.11p PHY simulation for 64QAM, $r = 3/4$ (27 Mbps), rural LOS channel.

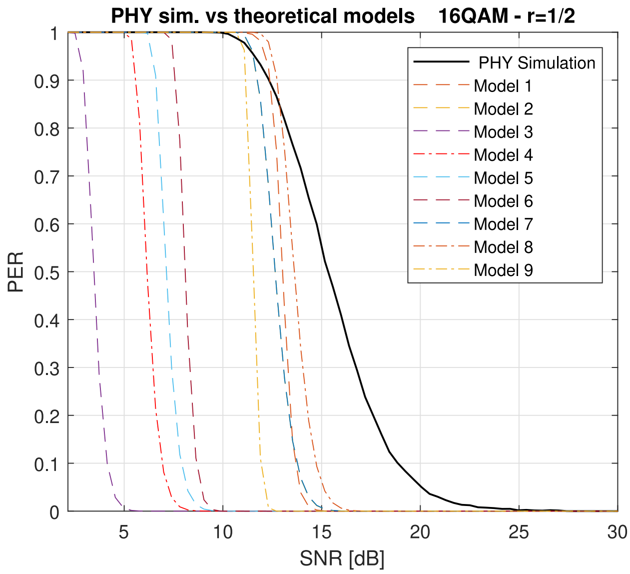

Fig. 6. Comparison of theoretical models with 802.11p PHY simulation for 16QAM, $r = 1/2$ (12 Mbps), highway NLOS channel.

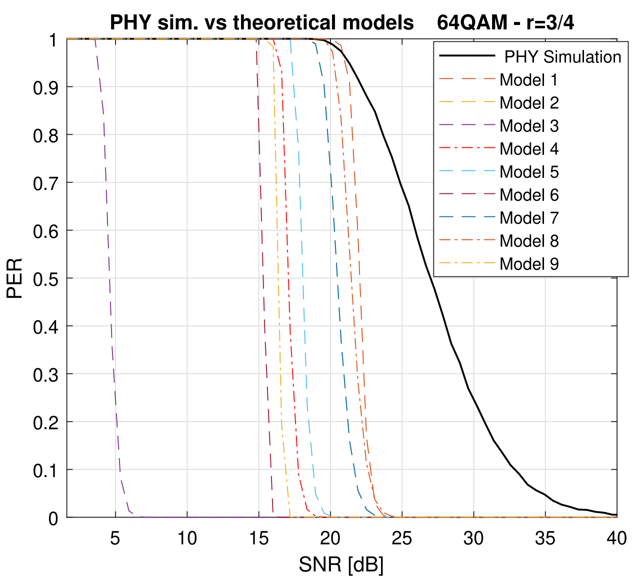

Fig. 7. Comparison of theoretical models with 802.11p PHY simulation for 64QAM, $r = 3/4$ (27 Mbps), highway NLOS channel.

4. Impact

PhySim-11p allows the visualization of the PER for each of the different modulation schemes with their respective coding rates. In MATLAB there is no example that computes the PER with the four modulations (BPSK, QPSK, 16QAM, 64QAM). Even in the examples offered by the WLAN toolbox [14] there is none with the characteristics of the implemented simulation model. Additionally, the simulation of several theoretical models of the PER is included for comparison with the PHY simulation. Moreover, four channel models with frequency–time selective fading are available and give a more complete simulation tool for vehicular communications.

The same implemented scripts can be used for any implementation of the IEEE 802.11 standard which uses OFDM as the transmission technique, giving a greater scope for its use in other research topics. The standards that can be used are 802.11a/g/n, considering that they do not work at the same frequency and that also the bandwidth is different. For example, for the 802.11g standard the bandwidth is 20 MHz so the data rate would be the double of the ones shown in Table 1 for the same parameters.

Another objective of this simulation model is to obtain a better approximation of the PER to be included in a network simulator such as NS3. Network simulators are important tools to model the behavior of a network and they are widely used for research. However, they usually use very simplified or even inaccurate models of the PHY. The complete IEEE 802.11p PHY cannot be implemented in NS3 due to complexity constraints. For this reason, obtaining the theoretical model that best fits the simulated PHY would improve the results obtained in the network simulator. This work is the first step to bring more accuracy to the PHY models used in network simulators.

The code of PhySim-11p is provided in full so other researchers can use it to add other features to the PHY layer such as the effect of high power amplifiers, more realistic channels, channel estimation, etc. The same theoretical models can be used to select the one that best fits to any modification of the PHY.

5. Conclusions and future work

In this article, we presented a simulation model for obtaining the PER in the 802.11p PHY layer with MATLAB. We also presented the implementation of nine theoretical PER models with the aim of analyzing which is the closest model to the 802.11 PHY simulation.

According to the theoretical models studied, none of them adapt precisely and accurately to all modulation scheme configurations and coding rates. However, different models can be used by cases, with SNR offsets to obtain the expected results.

Compared to the MATLAB WLAN toolbox, our simulation model is open source, free, and allow the access to all scripts and functions used for the 802.11p PHY simulation. Additionally, it gives several theoretical PER models.

For future work, we plan to model the effect of the High Power Amplifier (HPA) in the transmitter.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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