Vehicular Networking and Channel Modeling: A New Markovian Approach

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Abstract— **Vehicular networking is rapidly growing in the last years, due to its ability of enhancing users everyday-life, in terms of comfort, security and QoS. New services are being implemented and the research activity on the topic is embracing different OSI layers, like the network and application ones. Many efforts have been also given at the PHY layer. In this paper we focus our attention on a new approach for modeling the wireless channel of VANETs communications. In the literature many channel models have been proposed, but most of them work at the bit level or they investigate only some aspects of channel interaction. In this work we provide a high level IEEE802.11p channel model based on Discrete Time Markov Chain (DTMC) modeling, useful in every simulation context. The proposed model is called Markovian Vehicular Channel Model (MVCM) and it is based on the concept of Packet Error Rate (PER) discretization: we do not consider the performance analysis at the bit level, but we derive the proposed model by computing the PER, associated to different observation times. The effectiveness of the proposed idea has been evaluated through a deep campaign of simulations.**

Keywords- VANET, IEEE802.11p, Channel Model, Vehicular Systems, Markov, DTMC, Trace analysis.

I. INTRODUCTION AND RELATED WORK

In recent years, there have been a massive amount of research activities regarding the Vehicular Ad-hoc NETwork (VANET) technology, especially for its potential in terms of comfort and security. Due also to the fast standardization process [1], [2], [3] all the scientific community is interested at finding new solutions for enhancing the networking in vehicular environments. The NET [4], the MAC [3], and the PHY [1], [2] layers of the considered environment have been subject of massive studies in last decade, making the deployment of On-Board Units (OBUs) and Road-Side Units (RSUs) suitable for the enhancement of drivers security, flow Quality of Service (QoS) and service reliability. In this paper, we focus the attention on the PHY layer, considering a markovian approach able to describe the degradation, in terms of PER, introduced during data transmissions among Dedicated Short Range Communication (DSRC) devices in Wireless Access in Vehicular Environment (WAVE). Our contribution is essentially a new channel model for VANETs which relates the parameters of a Discrete Time Markov Chain (DTMC) to the performance of a VANET channel, approaching with the Markovian Trace Analysis (MTA) algorithm [5]. As for many wireless networking architectures, also in VANETs it is very important to take into account channel degradations, because these events can happen frequently, due to the high grade of nodes mobility. Many works in literature, as [6], [7] take into account the modeling of channel conditions in VANET by considering path-loss, multipath fading and shadowing effects, directly related to the distance among the couple of nodes and their relative speed. In these papers, the received signal power is studied by using the classical approaches of Rayleigh or Nakagami on fading and shadowing, without taking into account the relationship between Bit Error Rate (BER) and Packet Error Rate (PER) and boundary conditions (directly related to mobility). In [6] authors conducted a deep study on channel modeling for VANET environment. Their work is based on the WAVE technology and they analyzed the impact of radio propagation model. They showed that the radio channel propagation highly influences the performance and operation of vehicular communication networks, given the low antenna heights and the fast topology changes. In [7], authors proposed a VANET channel model in condition of LOS and NLOS respectively. The proposed model is based on the combination of reflection and diffraction model. Further, they improved the VANET channel model by considering several factors in urban traffic environment. They conducted a series of simulations in order to show the goodness of their proposal. The main goal of [8] is to propose an efficient and realistic channel model for Vehicle to Vehicle (V2V) scenario, in order to improve V2V communication quality. The authors considered the impact of obstacles, static objects and other vehicle obstructions, during the communication. The proposed idea has been validated through simulations in a VANET discrete-event simulator. We based our argumentation on the works proposed in [9], [10], in which the Markov theory has been introduced in order to face the non-deterministic nature of the channel. In particular, in [9] authors propose a deep study of wireless channel showing its behavior varying two parameters: BER and channel capacity. They consider, in this analysis, the concept of SNR range partitioning. Instead, [10] shows a detailed analysis in terms of PER. The proposed analysis allows of evaluating the performance of the channel, measuring packet loss and, then, tuning the model taking into account real observations. In [11], the authors focused on the optimized node selection (e.g., path-routing) over MA mesh backbones when the target is to maximize the end-to-end routed information rate subject to a constraint on the total power available for the relays. In [12], authors developed an approach that relies on the maximization on a per-slot basis of the throughput averaged over the fading statistic and conditioned on the queue state, without resorting to cumbersome iterative algorithms. In [13], the authors compared ten different flooding schemes specially designed for Long-distance real-time video flooding over Vehicular Ad-hoc Networks and select the best in terms of packet arrival ratio and Peak Signal-to-Noise Ratio (PSNR). Additionally, they proposed an improved flooding scheme, to cope with variable vehicle density situations. The attention for channel modeling has been focused also in other kind of environment, where the related issues were considered for different types of telecommunication networks: for example, in [14] and [15], authors studied an approach to model underwater acoustic and UWB systems channels; in [16], [17] and [18], the authors considered channel models to guarantee QoS in IEEE 802.16 wireless mesh scenario.

The goal of this work is to provide a vehicular channel model based on Markov chains dynamics. A model of the IEEE802.11p has been implemented, using MATLAB Simulink software, and starting from the IEEE802.11a implementation, that has been opportunely modified. The obtained log-files have been analyzed through the MTA. This paper is organized as follows: section II provides an overview on the main standards regarding the considered environment, section III illustrates the modeling process starting from the Simulink model to the characterization of the Markov chain, then section IV resumes the main obtained results; section V concludes the paper.

II. VANET Standards and Contribution

VANETs are self-organized networks that enable communications between vehicles OBUs and RSUs; the RSUs can be connected to a backbone network, so many other network applications and services, including Internet access, can be provided to the vehicles. The U.S. Federal Communications Commission (FCC) recently allocated 75 MHz of DSRC spectrum at 5.9 GHz to be used exclusively for Vechicle-2-Vehicle (V2V) and Vehicle-2-Roadside (V2R) communications [1], [2], [3]. The primary purpose is to enable public safety applications for saving lives and improving vehicular traffic flow. Private services are also permitted in order to lower the network deployment and maintenance costs to encourage DSRC development and adoption. The DSRC spectrum is divided into seven 10-MHz wide channels (fig. 2).

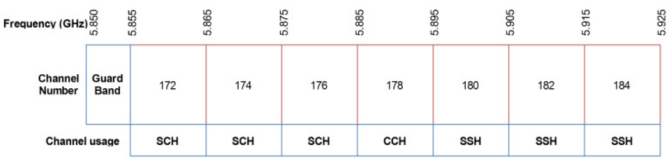

Fig.1: Frequency spectrum subdivision for DSRC.

Channel 178 is the control channel, which is typically restricted to safety communications only. The two channels at the edges of the spectrum are reserved for future advanced accident avoidance applications and high-power public safety communication usages. The remaining ones are service channels and they are available for both safety and non-safety applications.

A) Direct Short Range Communications (DSRC)

Dedicated Short Range Communications (DSRC) are defined as one-way / two-way short to medium range wireless communication channels, which are specifically designed for automotive use and represent a corresponding set of protocols and standards involving everything from PHY to application layer for VANET [1]. The standardization of DSRC began within the American Society for Testing and Materials (ASTM) subcommittee, E17.51, which takes charge of reviewing issues related to vehicle roadside communications [2]. Regarding the spectrum allocation for IEEE802.11p (5.850-5.925 GHz) it has been allocated for DSRC by FCC in the United States, which is slightly overlapping with the medical band. The reasons to choose a 5 GHz band rather than its two lower frequency counterparts in ISM are: a) concerning the 900MHz industrial band, although it has a stronger penetration capability due to a relative low frequency and it is already partially occupied by GSM Network; b) in respect to the 2.4 GHz scientific band, as most 802.11 standards, such as 802.11b/g/n, operate on this frequency, the interference turns out to be severe and makes it infeasible to be adopted by DSRC. Considering a sideband phenomenon and the avoidance of interference to 802.11a, the lower 5 MHz out of the 75 MHz bandwidth is reserved as a guard band. The rest of the 70 MHz is sub-divided into seven 10 MHz channel. Each station continuously alternates between the Control Channel (CCH) and one of the Service Channels (SCHs) or the safety channels. SCHs can be used for either safety (with higher priority) or non-safety applications. For more details to see [1], [2], [3]. The number of OFDM subcarriers is 64, including 48 data subcarriers and 4 pilot subcarriers (used for tracing the frequency offset and phase noise). The total training length is 16 μs. Depending on the data rates (3, 4.5, 6, 9, 12, 18, 24, 27 Mbps), different modulations (BPSK, QPSK, 16QAM, 64QAM) and coding rates (1/2, 1/3, 1/4) are applied. The MAC is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and it is implemented with the RTS/CTS mechanism.

B) EDCA for 802.11p

As IEEE 802.11p is designed only for a VANET environment, it adopts Enhanced Distributed Channel Access (EDCA), while maintaining some modifications. The Multi-channels are the greater difference of 802.11p at a MAC layer from its counterparts, where for all channels a set of traffic categories for QoS guarantee purposes is provided.

Figure 2 shows an illustration of an EDCA mechanism at 802.11p MAC layer. There are still four Access Categories (ACs) labeled from AC[0] to AC[3]. Under the CCH interval, each one can be explained as follows:

- AC[0]: concerns information aimed at establishing new non-safety-related connections via SCHs;

- AC[1]: concerns the information from other vehicles for help, but this is not safety application;
- AC[2]: concerns presence and speed information broadcasted by vehicles;
- AC[3]: with highest priority, it is used for emergency information, especially for collision avoidance application.

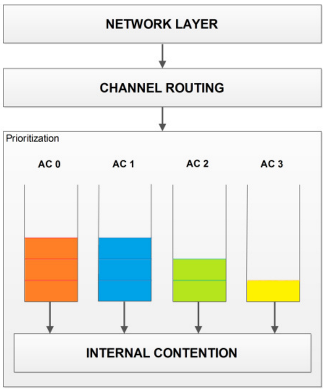

Fig.2: Priority EDCA for a SCH/CCH channel.

The goal of this work is to provide a high level vehicular channel model based on Markov Chains (MCs) theory [19], which is suitable in different simulation context. In order to model DTMC, in accordance with ([10],[20]), we employ packet error log-file analysis, where, in our scenario, a packet is a sequence of bits. Thus, the log-file is a sequence containing information about the correctness of packet transmissions. In [10], the authors considered only two states: the *Bad* macro-state and the *Good* state, even if they extend the former in more states if the stationary property is not satisfied. In particular, in the log-file a "1" represents a wrong packet and so a Bad state, while a "0" represents a correctly transmitted packet (that is a Good state). Contrary to [10], in our analysis we introduce the concept of link quality in terms of PER: we do not analyze the single packet, but we fix a time window (consisting in a given number of packets) and we evaluate the link quality computing the PER relative to the specific window. The model is based on the use of a DMTC, in which a chain state represents an accurate channel description. Our proposal has been called Vehicular Markov Channel Model (VMCM) and it has been compared with the classical Gilbert-Elliot Model (GEM), in order to demonstrate how a higher accuracy can be obtained when considering a higher number of states.

III. CHANNEL MODELING PROPOSAL

First of all a deep overview of the considered Simulink model is given, as well as a description of the way the MTA approach has been considered in our proposal.

A. VANET standard modeling in MATLAB

The IEEE 802.11p physical layer for VANETs has some specifications that are very similar to the IEEE 802.11a standard, but some changes are introduced. The channel bandwidth is 10MHz, instead of 20MHz, so the parameters in the time domain of IEEE 802.11p are doubled if compared with the ones of IEEE 802.11a.

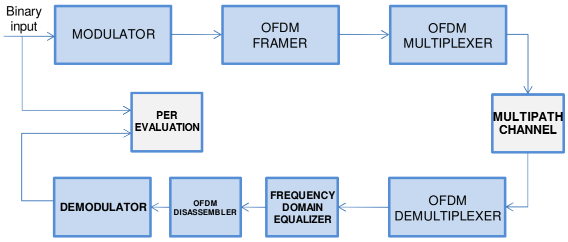

Fig.3: MATLAB/Simulink conceptual scheme of the IEEE802.11p.

Figure 3 illustrates the general structure of the IEEE802.11p MATLAB/Simulink model, considered in this paper for generating data and packet error log-files. Once the binary data is created, the modulator operates the padding operation (changing the dimension of input matrix: rows are in the frequency domain and columns are in the time domain), the convolutional encoding (the poly2trellis function is used, with parameters 7 and [171 133]), the puncturing operation (in order to obtain code rates different from 1/2), interleaving (for minimizing the effects of burst errors) and the assignment of a point of the QAM signal constellation to each binary word. At this point, frames are assembled by adding the pilot and training symbols (in particular, four pilots are inserted between the subcarriers, while the training sequence is added to the subcarriers). The signal is serialized by the multiplexer block, in order to transmit time-domain samples of one symbol. The multipath channel model consists in a Rayleigh-fading channel with Additive White Gaussian Noise (AWGN), implemented by a Finite Impulse Response (FIR) filter with time-variant coefficients, able to convolve the transmitted signal with the channel matrix to obtain the output signal (SNR and DS values can be set in this block). On the receiver side, the signal is converted again from serial to parallel using a demux and to restore the transmitted signal the frequency-domain equalizer is used, able to apply the inverse of the channel frequency response. The disassembler separates data subcarriers from pilot subcarriers, while the OFDM demodulator carries-out inverse operations (zero insertion and Viterbi decoding).

B. Markovian modeling approach and VMCM

A DTMC is defined as a discrete-time stochastic process assuming discrete values such as process evolution starting from observation time depending only on the current state ([21],[22],[23]). This concept can be expressed by:

$$\begin{aligned} &P(X_n = x_n \,|\, X_{n-1} = x_{n-1}, X_{n-2} = x_{n-2}, \ldots X_0 = x_0) = \\ &= P(X_n = x_n \,|\, X_{n-1} = x_{n-1}) \end{aligned} \tag{1}$$

Starting from (1), we can write:

$$p_{i,j} = P(X_n = j \mid X_{n-1} = i) \tag{2}$$

where $p_{i,j}$ is the probability that the process is in the state j at the time t_n if at the time t_{n-1} it is in the state i. These probabilities can be rewritten in a matrix form as follows:

$$\mathbf{P} = \begin{bmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,n} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n,0} & p_{n,1} & \cdots & p_{n,n} \end{bmatrix} \tag{3}$$

P is called transitions probability matrix and it can be proofed that it is a stochastic matrix ([21],[22],[23]), so the sum of the elements of each row is always 1:

$$\sum_{j=0}^{n} p_{i,j} = 1 \qquad i = 0,1,\cdots,n \tag{4}$$

In particular, $p_{i,i}$ measures the constant trend to leave the state i, in fact, from Markov chain theory, we know that the mean i state sojourn time is exponentially distributed with a law of parameter $p_{i,i}$ ([21],[22],[23]). Furthermore, p_{ij}/p_{ii} is the conditional probability to select the j state leaving the i state.

Finally, we can affirm that a generic stochastic process is a DTMC if it satisfies the stationary propriety (that is transaction probabilities are time-invariant), the mean state sojourn time are exponentially distributed and the number of states is finite ([21],[22],[23]). In accordance to [23], we observe that VANETs channel characterization can be captured by a packet error trace, where, in our scenario, a packet is a sequence of bits. In our work, a packet is correctly received if no wrong bits are detected and consequently a packet is not correct if almost a bit is erroneously received in the sequence. Thus, the trace is a sequence containing information about whether a particular packet was transmitted correctly or not. Starting from [22], we inserted the analytical treatment of PER link quality: starting from the log-file and fixing a time window W for the observation of the transmitted packets, it can be evaluated by computing the PER belonging to W. This method is repeated for the complete log-file, obtaining a new log-file (indicated with "secondary-log-file") within the sequence of PER, one for each observation window W. Each W has a length t_W, and if t_W=1 the original log-file is calculated again (t_W is expressed in packets unit). Once the sequence is obtained, the allowable values of PER have to be processed with the technique of discretization, in order to define a set of states for the DTMC: each DTMC state is allocated to a particular range of PER.

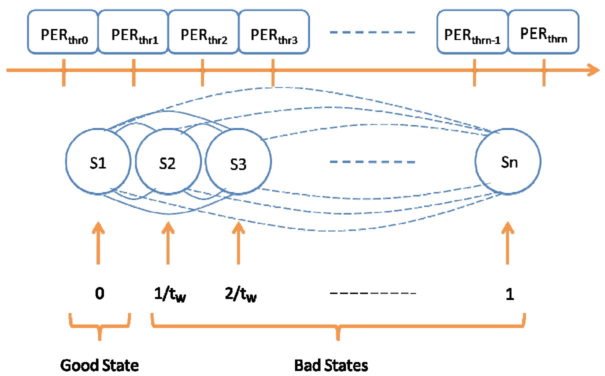

Fig.4: PER values discretization.

Figure 4 shows the procedure of PER discretization after the secondary-log-file has been carried obtained. Each state s_j is assigned to the PER range $[PER_{thrj-1}, PER_{thrj})$. Another important operation to be performed is to determine the number of PER ranges and, thus, the number of thresholds for PER discretization: on the basis of these thresholds, we can decide the association of the current processed time window to a specific state. A possible method is to set the number of states $n=t_W+1$ and, if in a time window W the number of wrong packets is j (with $0 \leq j \leq t_W$) then the assigned chain state is s_j. Thus, we could have discrete values of relative PER. This scheme is valid because it allows to tie the channel quality directly to the number of wrong packets in the considered observation window and we can write:

$$\frac{j\ wrong\ packet}{t_w} \rightarrow PER_{\mathrm{REL}} = \frac{j}{t_w} \rightarrow \text{we are in the "}s_j\text{" } state \tag{5}$$

As seen in [5],[10],[22], in this specific methodology, the addition of new states increases the precision of the model, until a transient state $s_{transient}$ is inserted. A state s_i is transient if from state i we could reach some state s_j, from which it is impossible to get back to state s_i, that is:

$$\exists\, s_j \in S \ \ such\ that\ \ s_i \rightarrow s_j \ \ and \ \ s_j \not\rightarrow s_i \tag{6}$$

where S is the state set and a generic state s_j is reachable from state s_i (denoted with $s_i \rightarrow s_j$) if $p_{si,sj} \neq 0$.

The stationarity condition (independence from time) of the process has been also established through the method proposed in [24] by *Bendat-Piersol*: the secondary-log-file has been processed into time intervals equally divided, calculating the mean value for each interval; then the number of runs of mean values above and below the median value of the series has been evaluated. The *Kolmogorov-Smirnov* (KS) test [25] has been used to computing the correctness of an exponential approximation for the distributions of the state sojourn times: we indicate with st_i the sojourn time associated to $s_i \in S$. The last passage in this method is the calculation of the elements of T. Once the secondary-log-file has been obtained, $p_{i,j}$ can be evaluated as follows:

$$p_{i,j} = \frac{tr_{s_i,s_j}}{tr_{s_i}} \qquad i,j = 0,1,\ldots,t_W \ \ s_i, s_j \in S \tag{7}$$

where $tr_{si,sj}$ is the number of transitions from state s_i to state s_j and tr_{si} is the total number of transitions from state s_i to any other state $s_k \in S$. In this way the model is completely defined. In this phase, we do not consider the value of t_W=1 because, as earlier described, it will result in the Good-Bad (GB) model and the secondary-log-file will be the same as the original log-file. Considering an average Signal-to-Noise Ratio (SNR) of 20dB, we started from t_W=2 and for t_W=3 a transient state $s_{transient}=s_4$ has been obtained. In addition, running the *Bendat-Piersol* test on the secondary-log-files (for the considered values of t_W) the stationarity property has been always verified. Using eq.7, the transition matrices illustrated in fig. 5 have been obtained (P_W indicates the obtained matrix considering a number of states equal to $n=t_W+1$).

$$P_2 = \begin{vmatrix} 0.821 & 0.1432 & 0.0358 \\ 0.763 & 0.2093 & 0.0277 \\ 0.817 & 0.1371 & 0.0459 \end{vmatrix} \qquad P_3 = \begin{vmatrix} 0.69371 & 0.2113 & 0.09499 & 0 \\ 0.71335 & 0.19723 & 0.08942 & 0 \\ 0.74945 & 0.23573 & 0.01482 & 0 \\ 1 & 0 & 0 & 0 \end{vmatrix}$$

Fig.5: The obtained P matrices for t_W=2 and t_W=3.

It is evident, from Fig. 5, how s_4 in T_3 (4 states model) is a transient state and it is not necessary to be considered in order to improve model precision. Fig. 6 illustrates how the cdf function of the Wrong Packets (WP) distribution for the T_2 model assumes similar values respect the empirical cdf. Instead, for the T_3 model we can see as the efficiency degrades respect the T_2 model and the empirical curve, so we can affirm that T_2 model is the best fitting model for this case.

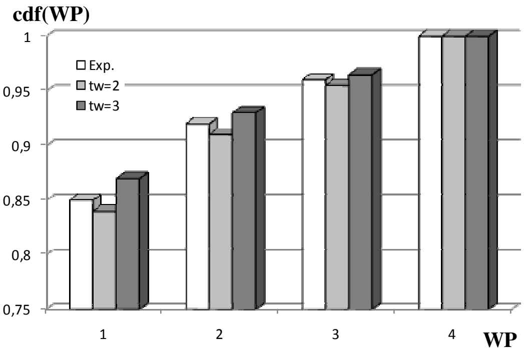

Fig.6: Wrong Packets cdf trend for experimental results and t_w=2, t_w=3.

Another important step is the analysis of the states sojourn time: we apply K-S test in order to verify the exponential distribution of the sojourn time. All states sojourn time pass the K-S test, but, due to lack of space, we show in Fig. 7 only results for s_0. In particular, the exponential distribution that minimizes standard error [24] is an exponential one with μ=5.50726, which introduces a standard error of 0.1658.

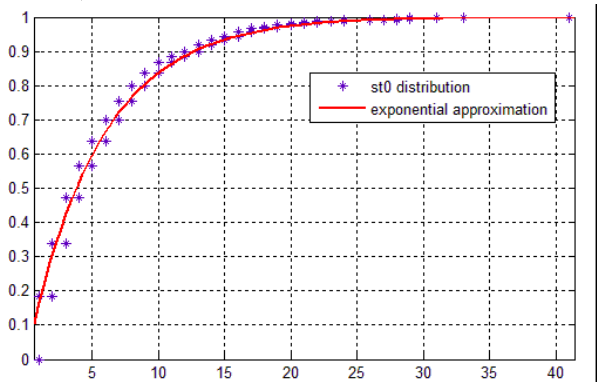

Fig. 7. sst_0 cdf for t_W=3 and its exponential approximation.

IV. PERFORMANCE EVALUATION

In the following, we show the goodness of our approach comparing the artificial log-file obtained using our model with the experimental and classic GB model log-files.

Assuming that the first state of the complete evolution is a good state (no-degradation), that is to say the generation starts always from s_0, if the trace passes the stationary test, we can proceed with the following steps:

- *Set the windows size;t_w;*
- *Let the number of packets N:*
- *If current state is s_i, then choose the next state s_j from the i-th row of T;*
- *Create a new window W of size t_W and randomly distribute the wrong packets, according to the QD of state s_i;*
- *Set the current state as s_j..*

Note the assumption of choosing always s_0 as initial state is not restrictive because independently of this, the model dynamically evolves following transition probabilities.

Starting from procedure previously described, we obtained the three states of the MVCM, defined by P_2 matrix in Fig.5. Therefore, we generated an artificial log-file using P_2 and we compare it with the artificial trace obtained from classic GB model and with experimental log-file. In Fig. 8, we compare the occurrences of correct received packets in these log-files. We can see as the distribution of the correct packets in the artificial log-file obtained by our model is similar to the distribution of experimental log-file

Fig. 9 represents another confirmation of the goodness of the proposed model: in fact, a comparison of wrong received packet occurrences, obtained from artificial (both GB and MVCM) and experimental log files is shown.

Table I shows the obtained statistical parameters (mean μ and variance σ^2) for experimental data, GB and MVCM models. It can be seen how μ_{MVCM} and σ^2_{MVCM} are very close to $\mu_{Experimental}$ and $\sigma^2_{Experimental}$. In addition the standard error introduced by MVCM is 0.00015, lower than the one introduced by GB equal to 0.0057.

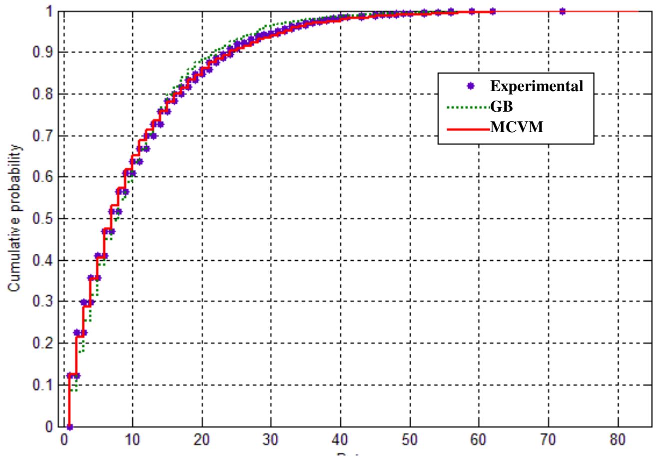

Fig.8. Correct packets distribution for artificial and experimental logs.

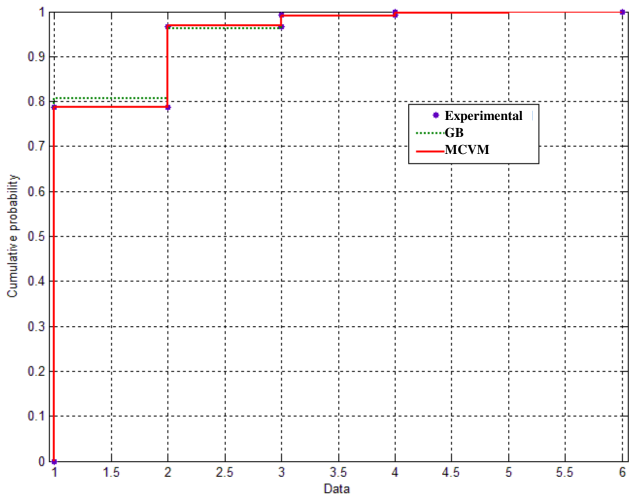

Fig. 9. Wrong packets distribution for artificial and experimental logs.

TABLE I. ERROR TRACE STATISTICS

Trace type	**μ**	σ^2
Experimental	1.25596	1.57743
GB model	1.24374	1.54688
MVCM	1.25603	1.57761

V. CONCLUSIONS

In this paper we presented a new markovian approach for modeling the wireless channel of a VANET environment; differently from classical models, working at the bit level, the proposed approach is able to model the PER behavior through the deployment of a DTMC. We enhanced the well-known GB model, considering a multi states channel, deeply analyzing a log file based on PER evolution. The proposed MVCM has been tested generating artificial log-files through an IEEE802.11p MATLAB implementation. Simulations have shown that the MVCM fits better experimental traces respects to the GB model, as confirmed by the standard error. By making further experiments, we noticed that the number of additional states, needed to obtain a higher granularity, depends on the boundary conditions (like the SNR, the Doppler Shift and different PHY parameters, such as FEC, coding rate, data rates and modulation schemes).

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