Performance Analysis of IEEE 802.11p Control Channel

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***Abstract*—The IEEE Task Group has approved recently the 802.11p amendment to enable efficient short range communications for vehicular networks by introducing multiple enhancements at the physical and MAC layer. It defines a control frequency channel for control and most critical data packets and one or several service frequency channels for less critical packets. In this paper, we propose an analytical model for the 802.11p operations in the control frequency. It captures all suggested enhancements important for exchanging data packets generated by road safety applications. We showed through diverse simulations scenarios that our proposed model is able to reproduce expected results. We consider this work as an important step toward understanding the performance of 802.11p-based vehicular communications and the model can be employed in the simulations of safety applications in large scenarios.**

I. INTRODUCTION

The emerging WAVE standard defines the communication specifications for wireless communication in vehicular environments. These specifications include the use of several channels, one dedicated for control and most critical data packets and the others for value-added services. The target applications for this technology are the ones concerning Intelligent Transportation Systems. Among these, the most important and critical is safety. Safety messages, such as collision warning, are specifically broadcast with low delay and high reception probability constraints. In order to investigate the performance of such applications in vehicular environment, it is necessary to perform realistic simulations. However, large scale simulations are computationally expensive and not always it is possible to simulate large scenarios. Moreover, simulations fail to describe the capacity bounds of this technology which are fundamental to assess if the constraints of safety messages are satisfied. In order to address this problem analytical models are required. Literature presents a number of analytical models but none of them considers the case of safety message transmission.

In this paper we present an analytical model for IEEE 802.11p that describes the behavior of the communication on the control channel (CCH) and that allows to simplify simulations in safety scenarios. The proposed model is simple, captures some physical layer conditions (such as radio capture effect and modulation and coding robustness) and is validated against simulations under typical safety scenario conditions. In particular, we compare the behavior of the model by varying the channel load and the distance between communicating stations. The results showed that our simple model can quite accurately describes the behavior for the considered scenarios.

The rest of this paper is organized as follows. In Section II, we present an overview of the related work concerning IEEE 802.11 performance studies. We describe in Section III the analytical model. The simulation results and interpretations are provided in Section IV. Finally, Section V concludes the paper.

II. STATE OF THE ART

A fundamental work on the performance analysis of IEEE 802.11 distributed coordination function (DCF) was presented by Bianchi [1]. The proposed Markov model provides expressions for the saturation throughput and the probability that a packet transmission fails due to a collision as a function of the number of stations, retransmissions and back-off states. However, it does not consider physical layer conditions nor the actual DCF required by the standard. Despite its simplicity, the Bianchi model attracted lots of interest and was considered in a number of works that improved the model by considering clear channel assessment and physical characteristics. Moreover, other works adapted the model to comply with the standards, e.g. Robinson *et al.* adapted it for the IEEE 802.11e amendment.

Other works, such as the one presented by Duffy *et al.* [2], presented an analysis in non-saturated conditions. In particular, with respect to previous models in saturation, Duffy introduced an additional level in the Markov chain to represent the states were the packet has not arrived at the MAC layer. Although this model allows to represent the transmission in both non-saturated and saturated conditions, the random back-off counter is decremented despite the medium condition. The analysis presented by Engelstad [3] allows to address this inconsistency with the standard, by decrementing the back-off counter only when the medium is idle. Nevertheless, Engelstad's model does not consider the case when a packet arrives at the MAC layer and the medium is busy. In our proposed model we will consider also this case, thus describing more closely the behavior of the packet transmission.

All the models presented above assume that all stations have the same physical layer (same transmission power, same coding...) and that if more than one station transmits a packet in a certain slot time, all the packets will be lost. This might be not true, as presented by Kochut [4]. In fact, when a station is close to the receiving station and the other transmitting station is not, the packet transmitted by the closest station has higher chances to be correctly received.

A step further toward a realistic description of the packet transmission was done by Manshaei [5], who proposed to add the physical layer constraints to the MAC model for expressing the MAC throughput saturation and the packet loss probability.

More recent works have focused on vehicular communication characterization and on proposing mechanisms to improve the IEEE 802.11p performance, e,g. by changing the Enhanced Distributed Channel Access parameters. In [6], the authors presented results that show that, whereas vehicle density has a significant impact on aggregate throughput, average delay and packet loss, vehicle speed is not a significant factor. The authors of [7] and [8], showed that STDMA allows higher performance with respect to CSMA in the considered scenarios. In [9], the authors investigated the channel access scheme and propose to extend the service channel interval. They showed that their approach increases the channel bandwidth and decreases the channel bit error. In [10] the author proposed to reduce the number of high priority messages. In [11], the authors proposed to assign priority according to either the number of neighbors that a node can have or its speed. Finally, in [12], the authors proposed to dynamically adjust the back-off window size according to the channel condition.

Although literature presents a number of works on IEEE 802.11p transmission models, they mainly consider point-to-point traffic with retransmissions. In this work, instead, we focus on safety scenarios that consider broadcast messages without retransmission. For such scenarios, we propose an analytical Markov model that accurately describes the access to the CCH.

III. MODEL ANALYSIS

A. Model description

Assumptions: The model concerns non-saturated channel condition. A packet can be en-queued in the buffer at any time and its arrival time probability q in the buffer can be described by a Poisson distribution. The MAC access mode is CSMA/CA and a packet is transmitted when the back-off is 0 and whatever the medium state is. In particular, the back-off counter is decremented after a slot T if the sensed medium is idle. In this model retransmissions are not provided at the MAC layer.

Transition modeling between MAC States: The network is composed by n stations. Each station can buffer only one packet and can transmit it on a slot with a probability τ if and only if the back-off counter $k = 0$. If the back-off counter reaches the value of 0 and there is a packet to transmit, the station transmits it. Else, the MAC station remains at that state until packet arrives. When the MAC station receives a packet, it will sense the medium. If the medium is idle (with a probability p'), the station will send the packet in the following slot. Else, the station launches a random back-off counter. The probability of packet collision is p. The resulting Markov chain is given in Fig. 1 and the associated transition probabilities are reported in Tab. I.

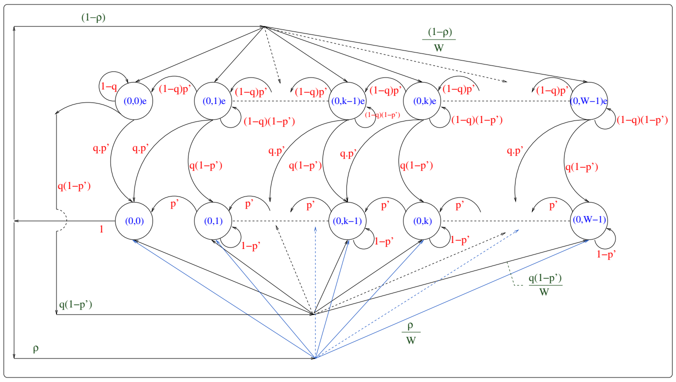


Fig. 1: Markov chain model.

TABLE I: Resulting transition probabilities.

Transition Probability	Expression
$P\left[(0,k)\mid(0,k)\right]$	$1-p'$
$P\left[(0,k-1)\mid(0,k)\right]$	$(1-\tau)^{n-1}=p'$
$P\left[(0,k)\mid(0,0)\right]$	ρ/W
$P\left[(0,k)_e\mid(0,0)\right]$	$(1-\rho)/W$
$P\left[(0,k)_e\mid(0,k)_e\right]$	$(1-q)(1-p')$
$P\left[(0,k-1)_e\mid(0,k)_e\right]$	$(1-q)\,p'$
$P\left[(0,0)_e\mid(0,0)_e\right]$	$1-q$
$P\left[(0,0)\mid(0,0)_e\right]$	$q.p'$
$P\left[(0,k)\mid(0,0)_e\right]$	$q(1-p')/W$
$P\left[(0,k)\mid(0,k)_e\right]$	$q(1-p')$
$P\left[(0,k)\mid(0,k-1)_e\right]$	$q.p'$

B. Model mathematical interpretation

As shown in Fig. 1, the considered Markov chain have two different types of states: $b\,(0,k)_e$ represents the states when no packet is waiting to be transmitted while $b\,(0,k)$ represents the states when a packet is waiting to be sent. The states $b\,(0,k)_e$ can be written as a function of the state $b\,(0,k)$:

$$b\,(0,k)_e = \frac{(1-\rho)}{1-(1-q)\,(1-p')}\,\frac{b\,(0,0)}{W}\left(\frac{1-T^{W-k}}{1-T}\right) \tag{1}$$

where $k = [1, ..., W-1]$ and $T = \frac{(1-q)p'}{1-(1-q)(1-p')}$

The state $b\,(0,0)_e$ has a different formulation than the other states and can be written as follows:

$$b\,(0,0)_e = \frac{(1-\rho)}{q}\,\frac{b\,(0,0)}{W}\left(\frac{1-T^{W}}{1-T}\right) \tag{2}$$

After writing the expressions for the states when the buffer is empty, we can derive the expression for the state probabilities $b\,(0,k)$ with $k = [1, ..., W-1]$.

$$b\,(0,k) = \frac{W-k}{W}\,\frac{1}{p'}\left[b\,(0,0) + q\,(1-p')\,b\,(0,0)_e\right] - b\,(0,k)_e \tag{3}$$

Once we wrote the expressions of all the states (as a function of the basic state $b(0,0)$), we need to impose the normalization:

$$1 = \sum_{i=0}^{W-1} \left[b(0,i)_e + b(0,i) \right] \tag{4}$$

The normalization allows to write the state $b(0,k)$ as function of the fundamental parameters of the Markov chain p', q, W. Hence, the expression of $b(0,0)$ can be written as

$$b(0,0) = \frac{1}{1 + \frac{W-1}{2p'} + \left(1 + \frac{W-1}{2p'} q(1-p')\right) \frac{1-q}{q} \frac{1}{W} \frac{1-T^W}{1-T}} \tag{5}$$

Since the transmission of a packet can happen only when at state $b(0,0)$, the probability τ that a station transmits a packet is $\tau = b(0,0)$.

C. Model throughput expression

For the throughput expression, we followed the same physical layer approximations as in [5] and we obtained the following expression

$$Z(p_k, \tau_k) = \frac{\tau_k (1-p_k) L}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1-P_s) T_c} \tag{6}$$

The numerator of Eq. 6 represents the average number of useful bits transmitted in a slot time, whereas the denominator corresponds to the average duration of a slot. σ is the physical slot time of 802.11 MAC layer. T_s and T_c are respectively the duration of a slot when a packet is successfully transmitted and the duration of a slot when two ore more packets collides. L is the payload size. With P_{tr}, we denote the probability that at least one of the n stations is transmitting. P_s denotes the probability that such transmission is successful.

IV. PERFORMANCES ANALYSIS

A. Model validation

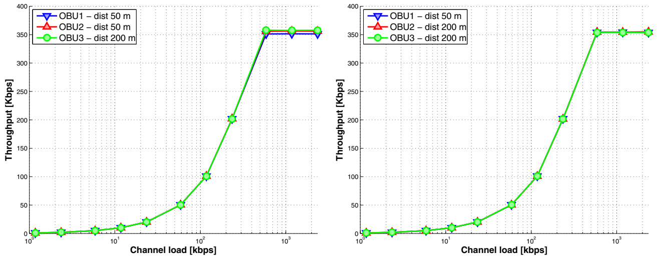
In this Section we present a number of scenarios that validate the model introduced in Section III. The performance of all the scenarios were investigated by using the network simulator Qualnet 4.5 [13] and the obtained results have a confidence interval of 95%. In order to simulate the transmission in a vehicular environment, we modified the IEEE 802.11a implementation of QualNet according to [14]. In Tab. II we present the parameters used for the simulations.

In the scenarios we investigate the reception throughput that a RSU obtains with respect to other stations that are transmitting messages for an increasing channel load.

First scenario. We consider the case of two vehicles positioned respectively at 50 (Fig. 2a) and 200 (Fig. 2b) meters from a RSU, and a third one placed first at 50 and then 200 meters. None of the stations use any mechanism of auto-rate fallback. We observe that the throughput is practically the same for all the vehicles, despite the distance from the RSU. This corresponds to the results presented by Heusse *et al.* [15].

TABLE II: Simulation parameters used in all the scenarios.

Simulation Parameter	Value
Frequency	5.87 GHz
Channel bandwidth	10 MHz
RSU Tx power	23 dBm (=200 mW)
RSU antenna height	2.4 m
RSU antenna gain	3 dB
MS Tx power	23 dBm (=200 mW)
MS antenna height	1.5 m
MS antenna gain	0 dB
Type of antenna	Omnidirectional
Propagation model	Two-ray
Fading model	Ricean ($K = 10$)

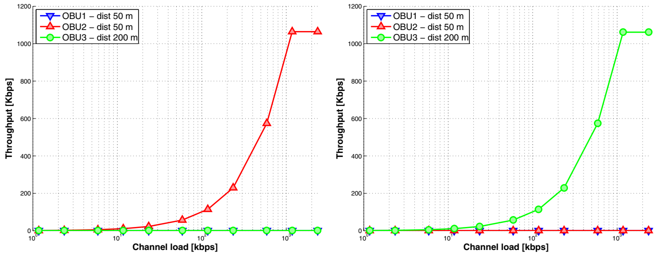


(a) Two vehicles close to the RSU and one distant.

(b) One vehicle close to the RSU and two distant.

Fig. 2: Evolution of the reception throughput of the RSU when no auto-rate fullback mechanisms are used. The considered channel transmission rate is 3 Mbps.

Second scenario. We modified the first scenario to consider the case where two vehicles transmit with frequency of 1 Hz, while a third one increases the load on the channel by transmitting with higher rate. In Fig. 3 we present two cases where the latter vehicle is either close (Fig. 3a) or far (Fig. 3b) from the RSU. Simulation results show that the throughput evolution for this vehicle has the same behavior as the one presented in the previous scenario. Instead, the reception throughput for the other two vehicles is very limited because of the low data rate and, only marginally, of the distance from the RSU.

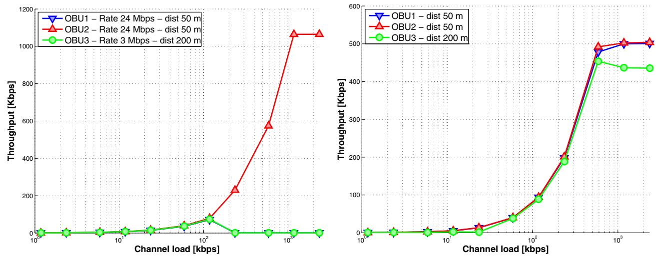


(a) One of the close vehicles increases its transmission rate.

(b) The farthest vehicle increases its transmission rate.

Fig. 3: In this scenario, two vehicles transmit at very low rate, while the third increases it until the channel saturates.

Third scenario. In this scenario we investigate the impact of the auto-rate fallback on the performance. In the first case, whose performance are showed in Fig. 4a, we consider the case were the two vehicles close to the RSU have the channel basic rate set to 24 Mbps, while the distant one is set on 3 Mbps. The RSUs has the auto-rate fallback enabled and obtains most of the income data from one of the close vehicles. In the second case, we consider the case where all the stations use the auto-rate fallback. In Fig. 4b we observe that the farthest vehicle obtains the less throughput in saturation phase. This behavior can be explained by considering that the auto-rate fallback mechanism adapts the modulation scheme in order to decrease the packet error probability.



(a) In this study case, only the RSU uses auto-rate fallback.

(b) All the stations have the auto-rate fallback mechanism activated.

Fig. 4: In this scenario, we investigate the impact on the throughput of the auto-rate fallback mechanism.

B. *Model implementation and results*

In order to verify the performance of the proposed model, we implemented it on Matlab 7.9.0 and we considered the case of two vehicles at 3 meters and one at 100 meters from the RSU that transmit broadcast messages increasing the rate. We observe that the results depicted in Fig. 5 correspond to the ones shown in Fig. 4b. In fact, all the curves are composed by three parts: a part in where the throughput is low, one where it increases exponentially, and a final part of saturation, where the throughput reaches it maximum value.

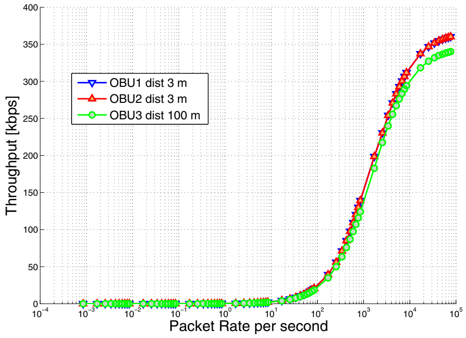


Fig. 5: Evolution of the throughput according to our model.

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V. CONCLUSION

In this work we presented a simple and approximated model of the IEEE 802.11p protocol by modeling the IEEE 802.11e MAC layer and by taking into account the physical characteristics of the protocol. Despite the fact that our model is not exhaustive since it does not consider all the physical layer features, nor unicast transmission, it still describes the behavior of the transmission on IEEE 802.11p. This means that this model can be used as a simple tool in the cases where vehicular transmission on the control channel does not need to be accurately described. For example, this tool can be used in the study of the optimal placement of roadside units. In fact, for this problem, transmission performance is just one of the multiple metrics (e.g., deployment plan, user's service satisfaction analysis, etc...) to consider and an accurate description of the communication part might not be needed.

REFERENCES

[1] G. Bianchi. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE JSAC*, 18(3):535–547, 2000.
[2] K. Duffy and D. Malone and D.J. Leith. Modeling the 802.11 distributed coordination function in non-saturated conditions. *IEEE Communications Letters*, 9(8):715–717, 2005.
[3] P.E. Engelstad and O.N. Østerbø. Non-saturation and saturation analysis of IEEE 802.11 e EDCA with starvation prediction. In *ACM MSWiM*, pages 10–13, 2005.
[4] A. Kochut and A. Vasan and A.U. Shankar and A. Agrawala. Sniffing out the correct physical layer capture model in 802.11 b. In *IEEE ICNP*, pages 252–261, 2005.
[5] M.H. Manshaei and G.R. Cantieni and C. Barakat and T. Turletti. Performance analysis of the IEEE 802.11 MAC and physical layer protocol. pages 88–97, jun. 2005.
[6] T. Murray and M. Cojocari and H. Fu. Measuring the performance of IEEE 802.11 p using ns-2 simulator for vehicular networks. In *IEEE EIT*, pages 498–503, 2008.
[7] K. Bilstrup and E. Uhlemann and E.G. Strom and U. Bilstrup. Evaluation of the IEEE 802.11 p MAC method for vehicle-to-vehicle communication. In *IEEE VTC*, pages 1–5, 2008.
[8] K. Bilstrup and E. Uhlemann and E.G. Strom and U. Bilstrup. On the ability of the 802.11 p MAC method and STDMA to support real-time vehicle-to-vehicle communication. *EURASIP Journal on Wireless Communications and Networking*, 2009:1–13, 2009.
[9] S.Y. Wang and C.L. Chou and K.C. Liu and T.W. Ho and W.J. Hung and C.F. Huang and M.S. Hsu and H.Y. Chen and C.C. Lin. Improving the channel utilization of IEEE 802.11 p/1609 networks. In *IEEE WCNC*, pages 1–6, 2009.
[10] S. Eichler. Performance evaluation of the IEEE 802.11 p WAVE communication standard. In *IEEE VTC*, pages 2199–2203, 2007.
[11] W. Alasmary and W. Zhuang. Mobility impact in IEEE 802.11 p infrastructureless vehicular networks. *Ad Hoc Networks*, 2010.
[12] Y. Wang and A. Ahmed and B. Krishnamachari and K. Psounis. IEEE 802.11 p performance evaluation and protocol enhancement. In *IEEE ICVES*, pages 317–322, 2008.
[13] QualNet Network Simulator. http://www.scalable-networks.com.
[14] I.C. Msadaa and P. Cataldi and F. Filali. A Comparative Study between 802.11p and Mobile WiMAX-based V2I Communication Networks. pages 186–191, jul. 2010.
[15] M. Heusse and F. Rousseau and G. Berger-Sabbatel and A. Duda. Performance anomaly of 802.11b. volume 2, pages 836–843 vol.2, mar. 2003.