Study of beaconing for car-to-car communication in vehicular ad-hoc networks

Alexey Vinel
Saint-Petersburg Institute for Informatics and Automation
Russian Academy of Sciences
Saint-Petersburg, Russia
vinel@ieee.org

Dirk Staehle
Department of Distributed Systems
University of Wuerzburg
Wuerzburg, Germany
dstaehle@informatik.uni-wuerzburg.de

Andrey Turlikov
Saint-Petersburg State University of Aerospace Instrumentation
Saint-Petersburg, Russia
turlikov@vu.spb.ru

***Abstract*—IEEE 802.11p is currently being developed international standard, which specifies physical (PHY) and medium access control (MAC) protocols for car-to-car and car-to-infrastructure communication and should become a basis for safety-related and infotainment applications in future vehicular ad-hoc networks (VANETs). In VANETs beaconing is one of the most important communication modes, which is used to advertise the presence of a car to its neighbor cars. For different applications timely and successful delivery of beacons containing speed, direction and position of a car is extremely important. In this paper, we present analytical methods for car-to-car communication analysis and investigate the influence of beacon generation rate on the mean beacon transmission delay and probability of a successful beacon reception in the IEEE 802.11p-based network in both saturated and unsaturated cases.**

Keywords - car-to-car communications; vehicular ad-hoc networks; periodic broadcasting; analytical modeling; IEEE 802.11p.

I. INTRODUCTION

Car-to-car (C2C) and *car-to-infrastructure* (C2I) communications is practically important area and naturally extremely hot research field. Work is this area is being performed by many industrial, governmental and academy bodies around the world (e.g. European project Car2Car [1]). International standardization is particularly performed by the IEEE 802.11p working group [2]. IEEE 802.11 Distributed Coordination Function (DCF) protocol [3] is used as a basis for a new standard. The core idea of C2C and C2I is to provide communication protocols in order to exchange different kinds of information between vehicles, different road sensors, road signs and signals and even pedestrians. Information transmitted across the vehicular ad-hoc network (VANET) can be of two types: *commercial / entertainment / information services* (e.g. on-board Internet access) and *safety-related / critical* (e.g. crash of the cars in the direction of movement, icy road on the closest turn, etc.).

In VANETs each network node (typically vehicle) has to be *constantly aware about its surroundings* (e.g. other vehicles speeds/directions). This is why each car periodically transmits in a broadcast mode short status messages (*beacons*). The following *tradeoff* exists when one implements *beaconing* in VANETs:

1) For safety-related applications, *more frequent information update* between vehicles (what means higher frequency of generation of beacon messages) is needed.

2) On the other hand, transmission delay and probability of collisions increase, when *too many packets* are transmitted by IEEE 802.11 DCF protocol.

First *analytical analysis methods* for the IEEE 802.11 DCF were presented in the pioneering works of Bianchi [4] and Conti [5]. These results provided the framework for the exhaustive analysis of IEEE 802.11 protocol, which was conducted by different authors in the last ten years. Nevertheless, VANETs introduce new challenges and C2C communications still require further study, especially if one considers safety-related applications.

Critical information dissemination in IEEE 802.11p VANETs is investigated in detail in works of Torrent-Moreno et al. [6] – [8] and are summarized in his PhD-dissertation [9]. In [9] Torrent-Moreno studies broadcasting of beacons in IEEE 802.11p VANETs only *by means of simulation*. *Analytical methods* for broadcasting in IEEE 802.11 are developed by Lyakhov and Poupyrev in [10] and [11]. Under the assumptions of Poisson packets arrival process and using the mathematical apparatus of Markov-chains, they have developed a method to estimate the mean notification time in IEEE 802.11 network, when broadcasting mode is used.

Broadcasting in IEEE 802.11 in application to vehicular ad-hoc networks recently has been performed by Ma, Chen and Refai for the *saturated* [12], [13] as well as for the *non-saturated case* [14], [15]. For the non-saturated case, given that Poisson beacons arrival process is assumed, they consider a user as M/G/1 queuing system. First and second moments of beacon service time have been computed by means of

Dr. Alexey Vinel acknowledges the support of Alexander von Humboldt Foundation for the funding of this work, which was done in part during his stay at the University of Wuerzburg, Germany.

978-1-4244-3437-4/09/$25.00 ©2009 IEEE

probability generating functions approach. In contrast to papers of Lyakhov, Ma has also introduced into the analysis some aspects of highway scenarios (mobility of cars, fading channel, etc.).

In [16] Vinel et al. have modeled IEEE 802.11p VANET as D/M/1 queue and roughly estimated mean beacon transmission delay (D) and beacon reception probability (P). According to the [15] the following requirements have to be met for the above metrics for the safety-related applications: $P > 0.99$ and $D < 500$ ms. From works [12] – [16] one can come to a conclusion: in typical configuration mean delay D requirements are met by the IEEE 802.11p, but probability P is lower than the required threshold.

Firstly, this means that more investigations of broadcasting in VANETs are needed and development of new analytical methods, which will be more precise and will help to develop the ways for improving the performance, is of a great importance. Secondly, since for typical beacon arrival rates values system operates far from saturation point and there are almost no queues of beacons in the MAC-layer buffers of stations, consideration of *queues* (like in existing works [12] – [16]) makes few sense.

Moreover, due to the nature of beacon messages, which include information about position of the car (e.g. obtained from the on-board GPS system), its speed and direction, it is reasonable to assume, that if new beacon is arriving and previous has not been yet transmitted, then new beacon *replaces* an old one. There is no need to transmit the information, which is not up-to-time any more.

Therefore, the contribution of our work in IEEE 802.11p VANET analysis is the following. We introduce a *new analytical method* to evaluate the performance of beaconing in VANETs. This method is simple, precise and corresponds to the features of vehicle-to-vehicle communications assuming *at most one beacon at a time* in the MAC-layer buffer.

The paper is organized as follows. In Section II we summarize the principles of broadcasting in IEEE 802.11. Section III is the core of this paper, where assumptions of our model and our analytical approach are presented. Numerical results discussions are included in Section IV.

II. Broadcasting in IEEE 802.11

Let us provide the reader explanation of IEEE 802.11 broadcasting protocol, what is needed to understand the further analysis [3]. IEEE 802.11 DCF introduces carrier-sense-based random multiple access scheme called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with a version of Binary Exponential Backoff (BEB) applied for the collision resolution. There are no any acknowledgments mechanisms for broadcasting in IEEE 802.11 DCF. Station starts to transmit DATA frame, which contains a beacon, only if the following conditions hold:

1) Channel is free during DIFS (Distributed InterFrame Space) since the last sensed transmission in the network. EIFS (Extended InterFrame Space) is used instead of DIFS whenever PHY layer indicates, that frame transmission did not result in a correct Frame Check Sequence (FCS).

2) Backoff time of the station is expired.

3) There are packets to transmit in the queue of a station.

Particularly, when new packet arrives, the station either immediately transmits it, if the channel is idle, or goes into the backoff state. Following [10] we refer to this immediate transmission as *asynchronous*, which is different to *synchronous*, performed after the backoff. On transition to the backoff state, *backoff counter* is set into the initial value b, which is called the backoff time, measured in the slot of duration σ (SlotTime) and uniformly chosen from $(0,\ldots,W\!-\!1)$. Value W, which is referred to as *contention window*, does not increases (what is different from the unicast transmission), because broadcast transmission is not acknowledged and therefore MAC-layer retransmissions are not performed.

III. System Model

A. Assumptions of the model

For simplicity reasons, we assume, that there are *fixed number of vehicles* (denoted as $n - 1$) in the communication range of each vehicle (therefore in total the group of n vehicles is considered, Fig. 1). Moreover, carrier-sense range equals to communication range (this assumption is reasonable since for typical configuration setup – carrier-sense range is a bit larger, than communication range [9], p. 30). All these vehicles "see" the channel in the same way. Integration of realistic cars movement model [9] into the analytical analysis is a complex problem and is out of this paper scope. In [15] it is assumed, that vehicles are placed on the road according to Poisson point process, but no explanation for such an assumption is provided there.

We refer to a vehicle, which has a beacon to transmit, as an *active* one, other vehicles are called *inactive*. Bernoulli beacons arrival process is assumed. A probability, that a vehicle generates a beacon for the slot duration is denoted p.

Let us additionally introduce the following assumption: probability of transmission by active vehicle in a randomly chosen idle slot is constant for all the vehicles and does not change during the time. We denote this probability as π. It is easy to show (see [4], [14]) that probability π for broadcast mode can be approximated as follows:

$$\pi = \frac{2}{W+1}. \tag{1}$$

We assume that there are three possible situations in the channel (idle, success and collision) and additionally use the following notation:

T_s – duration of successful transmission ($T_s = T_h + L / R +$ DIFS $+ \delta$, where L (bits) is length of beacon packet, R is a channel data rate, δ is propagation delay, T_h is duration of a Preamble and PLCP header);

T_c – duration of collision ($T_c = T_h + L / R +$ EIFS $+ \delta$);

$s = T_s / \sigma$ – number of slots used by the successful transmission;

$c = T_c / \sigma$ – number of slots wasted by the collision;

e – probability of beacon packet distortion by noise ($e = 1-(1-BER)^L$, it is assumed, that the header is received successfully always, events of erroneous reception of different bits are independent, BER stands for the bit error rate).

We are interested in the computation of the following performance metrics:

1) *Mean beaconing delay* (D) is the time from the moment the beacon was issued until it has been transmitted.

2) *Probability of successful beacon delivery* (P). We assume, that beacon can be lost due to one of the following reasons:

- beacon distortion by noise;
- collision of a beacon with other beacons;
- new beacon arrives to the active vehicle (in this case new beacon replaces the old one and the old one is assumed to be lost – "killed").

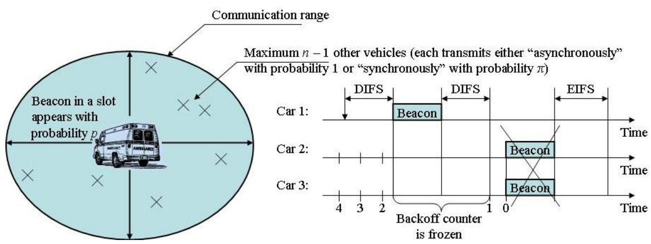

Fig. 1. General illustration of the model

B. Low load and saturated cases analysis

First we consider the following two extreme cases: there is a very low number of cars (system almost empty) – 1) and there are always n active stations in the system – 2):

1) If one car transmits a beacon in the empty system, then obviously we have the following simple result for the probability of successful beacon reception and mean transmission delay:

$$P_0 = 1 - e, \tag{2}$$

$$D_0 \approx T_s - DIFS. \tag{3}$$

This means, that beacon will be transmitted asynchronously (immediately without any backoff delay) and can be lost only due to the noise in the channel.

2) If there are always n active vehicles under consideration, then the following approach can be applied. Taking into account the fact, that due to our assumptions beacons are coming to the vehicles with probability p, then the average number of beacons arriving into the system for slot duration is $\lambda = pn$. On the other hand average number of beacons, which are successfully transmitted (per slot) is

$$\mu = \frac{sP_s}{sP_s + cP_c + P_e}, \tag{4}$$

where $P_s = n\pi(1-\pi)^{n-1}(1-e)$, $P_e = (1-\pi)^n$, $P_c = 1 - P_s - P_e$ – are the probabilities of a successful transmission, empty channel and collision respectively.

Therefore for the overloaded queuing system (when $\lambda > \mu$) probability of successful beacon delivery is

$$P_{sat} = \mu / \lambda = \\ = \frac{s\pi(1-\pi)^{n-1}(1-e)}{p[sn\pi(1-\pi)^{n-1}(1-e) + c(1-(1-\pi)^n - n\pi(1-\pi)^{n-1}(1-e)) + (1-\pi)^n]}. \tag{5}$$

Mean beacon transmission delay can be computed using approach similar presented in paper [16] (formula (6)) – we simply multiply the mean number of slots needed to perform one beacon transmission and average duration of an interval between two consequent backoff counter decreases:

$$D_{sat} = [\frac{W-1}{2}[P_e + sP_s + cP_c] + (1-\pi)^{n-1}(1-e)s + \\ + (1-(1-\pi)^{n-1}(1-e))c]\sigma. \tag{6}$$

Therefore, now are able to compute the performance metrics in the extreme cases of low and high beacon generation rates. There is an analysis for the arbitrary beacons generation rate below.

C. Unsaturated case Markov-chain analysis

Let us assume that the time axis is slotted into slots of duration σ. We introduce the following discrete time three-dimensional Markov chain to model the system behavior:

$$\{i(t), j(t), k(t)\}, \tag{7}$$

where $i(t)$ – number of active vehicles, $j(t)$ – number of slots until the channel becomes idle, $k(t)$ – current collision multiplicity (all variables are computed by the beginning of slot t, in the following text for simplicity index t will be omitted). The following bounds are valid for the above random variables:

- number of active vehicles: $0 \le i \le n$;
- number of slots:
  - if $i = 0$, then $j = 0$;
  - if $i > 0$, then $0 \le j \le \max(c, s)$;
- collision multiplicity:
  - if $j = 0$, then $k = 0$;
  - if $i > 0$, then $1 \le k \le i$.

The total number of states in this chain can be computed as follows: $1+n+\sum_{k=1}^{n} k \max(c,s)$, where (1+$n$) corresponds to the states $\{i, 0, 0\}$.

Denote a probability that m from i active vehicles are transmitting in a slot ($0 \le m \le i$) as:

$$a(m,i) = \binom{i}{m} \pi^m (1-\pi)^{i-m}; \tag{8}$$

and probability, that l new packets are arriving, if there are i active vehicles ($0 \le l \le n-i$) as:

$$b(l,i) = \binom{n-i}{l} p^l (1-p)^{n-i-l}. \tag{9}$$

Now we can write out transition probabilities of the considered Markov-chain. We classify them into *three groups*:

a) Transitions from idle states $\{i, 0, 0\}$:

$$\begin{gathered} \Pr\{i,0,0 \mid i,0,0\} = a(0,i)b(0,i); \\ \Pr\{i,s,1 \mid i,0,0\} = (1-e)a(1,i)b(0,i); \\ \Pr\{i,c,1 \mid i,0,0\} = ea(1,i)b(0,i); \\ \Pr\{i+1,s,1 \mid i,0,0\} = (1-e)a(0,i)b(1,i); \\ \Pr\{i+1,c,1 \mid i,0,0\} = ea(0,i)b(1,i); \\ \Pr\{i+l,c,l+m \mid i,0,0\} = a(m,i)b(l,i),\ l+m \ge 2. \end{gathered} \tag{10}$$

Note, that in probabilities (10), it is taken into account that asynchronous transmissions occur immediately after the generation of the packet.

b) Transitions from states, when one slot is left till the end of current transmission (either successful or collisional) $\{i, 1, k\}$:

$$\begin{gathered} \Pr\{i-k+l,0,0 \mid i,1,k\} = a(0,i-k+l)b(l,i); \\ \Pr\{i-k+l,s,1 \mid i,1,k\} = (1-e)a(1,i-k+l)b(l,i); \\ \Pr\{i-k+l,c,1 \mid i,1,k\} = ea(1,i-k+l)b(l,i); \\ \Pr\{i-k+l,c,m \mid i,1,k\} = a(m,i-k+l)b(l,i),\ m \ge 2. \end{gathered} \tag{11}$$

c) Transitions from states, when more than one slot is left till the end of current transmission (either successful or collisional) $\{i, j, k\}$ ($j \ge 2$):

$$\Pr\{i+l, j-1, k \mid i,j,k\} = b(l,i). \tag{12}$$

Let us denote the stationary distribution of the considered Markov chain (7) as follows:

$$\rho(I,J,K) = \lim_{t\to\infty} \Pr\{i(t)=I, j(t)=J, k(t)=K\}. \tag{13}$$

Detailed analysis of the opportunities to get the closed-form solution for this Markov-chain is out of this paper scope. We compute this distribution by means of iteration method.

Using stationary distribution of the considered Markov-chain we can easily compute needed performance metrics. For example, the mean number of the beacons in the system is

$$N = \sum_{i=1}^{n} i \sum_{k=1}^{i} \sum_{j=1}^{\max(c,s)} \rho(i,j,k). \tag{14}$$

Applying Little's law and taking into account, that this is a system with looses, we obtain the mean delay for the beacon transmission (assuming new beacons does not "kill" the old ones)

$$D = N\frac{n}{(n-N)\lambda}\sigma = \frac{N}{(n-N)p}\sigma. \tag{15}$$

IV. Numerical Results

We summarize the values of parameters, which we used for the experiments in Table II. Intensive discussions on the choice of these values can be found in [9], p. 24. IEEE 802.11p draft PHY-layer constants are taken from [9], p. 121.

TABLE I. Parameters of Study

Parameter	Value
R	6 Mbps
σ	16 µs
SIFS	32 µs
δ	<< 1 µs
DIFS	64 µs
W	16
L	500 bytes x 8 = 4000 bits
T_h	32 µs + 8 µs = 40 µs
EIFS	32 µs + 112 µs + 48 µs + 64 µs = 248 µs
BER	10^{-4}, 10^{-5}, 10^{-6}

We use our Matlab® simulation program for IEEE 802.11p broadcast. Due to the page limit, we do not include details of validation of this model. However, it is worthy to mention, that we have not found significant differences between the simulation and analytical results for different sets of input parameters.

Below we give some examples of the obtained numerical results. We depict the performance metrics for highly congested system (Fig. 2, 3) for different number of vehicles n in the system (in other words there are $n-1$ "neighbors" of some particular car in the system) and different quality of the channel / robustness of coding and modulation scheme (different BER values). We assume that beacons arrive to a vehicles with intensity 20 packets per second, what corresponds to the requirement of safety-related applications [9], therefore $p = 3.2 \cdot 10^{-4}$. For unsaturated case (Fig. 4) we model the system behavior for $n = 10$.

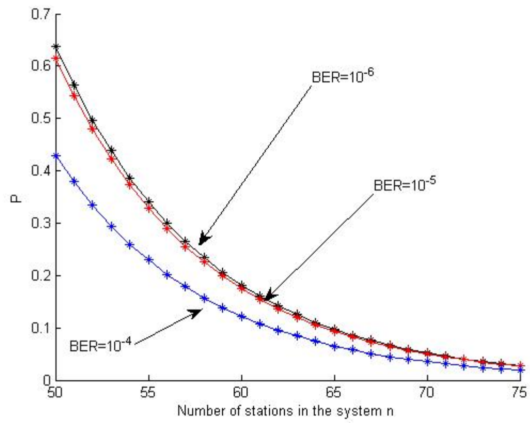

Fig. 2. Probabilities of successful beacon reception for the saturation case

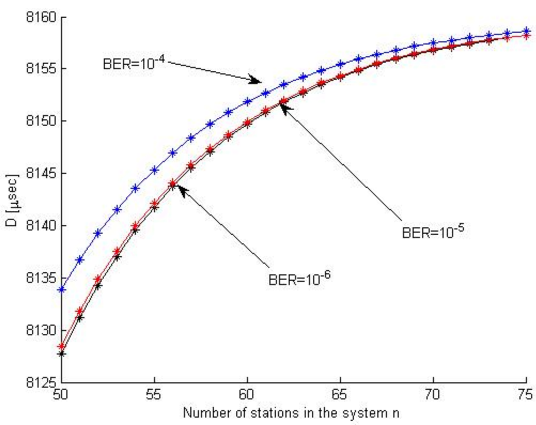

Fig. 3. Mean beacon transmission delay for the saturation case

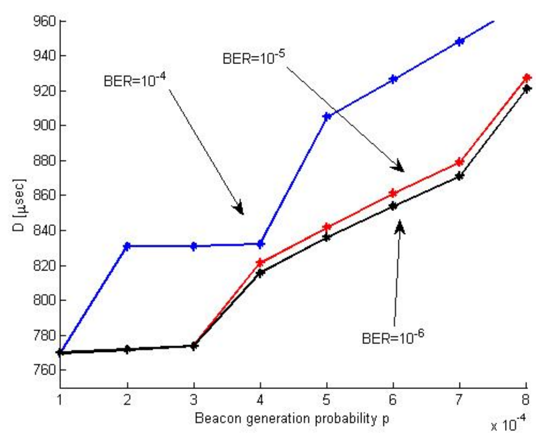

Fig. 4. Mean beacon transmission delay for the non-saturation case

V. CONCLUSION

We have introduced some new analytical methods to study beaconing in vehicular ad-hoc networks. Numerical results demonstrate that these methods can be used to estimate the probability of successful beacon delivery and mean beacon transmission delay to check the car-to-car application requirements. We see that in typical scenarios, delay requirements are met, but probability of successful beacon reception is rather low. The disadvantage of the proposed Markov chain for the analysis of unsaturated case is the large number of its states. More computationally efficient approaches for the non-saturated case are worth investigating in the future.

REFERENCES

[1] Car2Car consortium http://www.car-to-car.org/

[2] Status of Project IEEE 802.11 Task Group p http://www.ieee802.org/11/Reports/tgp_update.htm

[3] IEEE 802.11, 2007 IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN MAC and PHY Specifications.

[4] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE JSAC*, 18(3), pp. 535-547, Mar. 2000.

[5] F. Cali, M. Conti, E. Gregory "IEEE 802.11 Wireless LAN: Capacity Analysis and protocol enhancement," Proc. INFOCOM'98, San Francisco, 1998. P. 142-149.

[6] F. Schmidt-Eisenlohr, M .Torrent-Moreno, J. Mittag, H. Hartenstein "Simulation Platform for Inter-Vehicle Communications and Analysis of Periodic Information Exchange," Proc. of the 4th Annual IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS), Obergurgl, Austria, January 2007

[7] M. Torrent-Moreno, S. Corroy, F. Schmidt-Eisenlohr, H. Hartenstein "IEEE 802.11-Based One-Hop Broadcast Communications: Understanding Transmission Success and Failure under Different Radio Propagation Environments," Proc. of the 9-th ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM), Pp. 68-77, Spain, October 2006.

[8] M. Torrent-Moreno, J. Mittag "Adjusting Transmission Power and Packet Generation Rate of Periodic Status Information Messages in VANETs," Proc. of the third ACM International Workshop on Vehicular Ad Hoc Networks, pp. 90 - 91, Los Angeles, CA, USA, Sep. 2006.

[9] M. Torrent-Moreno "Inter-Vehicle Communications: Achieving Safety in a Distributed Wireless Environment: Challenges, Systems and Protocols", PhD-dissertation, Universitätsverlag, Karlsruhe, 2007.

[10] A.I. Lyakhov, P. Poupyrev, "Evaluation of Broadcasting Technologies Performance in IEEE 802.11 Networks," Proc. Int. Workshop "Distributed Computer and Communication Networks" (DCCN-2005). Sofia, Bulgaria, April 23-29, pp. 84-94, 2005. (in Russian)

[11] A. Lyakhov, V. Vishnevsky, P. Poupyrev, "Analytical Study of Broadcasting in 802.11 Ad Hoc Networks," Proc. 2nd Int. Conf on e-Business and Telecommunication Networks (ICETE 2005)", October 3-7, 2005, Reading, U.K. Vol. II, pp.86-91.

[12] X. Ma, X. Chen, "Saturation Performance of IEEE 802.11 Broadcast Networks," IEEE Communication Letters, Vol. 11, Issue 8, pp. 686-688, August 2007.

[13] X. Chen, H. H. Refai, X. Ma "Saturation Performance of IEEE 802.11 Broadcast Scheme in Ad Hoc Wireless LANs," Proc. of the 66th IEEE Vehicular Technology Conference (VTC), October 2007.

[14] X. Ma, X. Chen, and H. H. Refai, "Unsaturated Performance of IEEE 802.11 Broadcast Service in Vehicle-to-Vehicle Networks," Proc. of the 66th IEEE Vehicular Technology Conference (VTC), October 2007.

[15] X. Ma, X. Chen, and H. H. Refai, "Delay and Broadcast Reception Rates of Highway Safety Applications in Vehicular Ad Hoc Networks," Proc. of IEEE INFOCOM, Mobile Networks for Vehicular Environments Workshop, May 2007.

[16] A. Vinel, V. Vishnevsky, Y. Koucheryavy "A simple analytical model for the periodic broadcasting in vehicular ad-hoc networks," Proc. of 4th BWA Workshop, co-located with IEEE GLOBECOM 2008, New Orleans, USA, Nov. 2008.