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***Abstract*—The use of inter-vehicle communication is considered the next step to be taken in order to reduce the number of traffic accidents. The design of a versatile and efficient protocol that would manage the access to the control channel reserved for safety applications would represent a significant progress towards a generally accepted technology. However, the solutions proposed hitherto rarely took into account the broadcast nature of the messages produced by the safety applications. Furthermore, the specific properties of periodic vehicular beaconing are yet to be considered by any technical committee or research study. We present the specificities of this type of messages and discuss their impact on the performance of the medium access control layer, using both analytical and simulation tools.**

I. Introduction

Direct vehicle to vehicle (V2V) communication appears as a promising solution for increasing transportation safety and efficiency. Radio devices embedded in cars could lead to the creation of a Vehicular Ad-Hoc Network (VANET), with an important role in enhancing the drivers' awareness about possible traffic problems.

The unanimous acceptance of a generic solution in one of the most diversified industries today largely depends on the capacity of regulatory institutions to provide a powerful, low cost, flexible standard. This standardisation problem became ever more salient in the last few years, with the allocation of spectrum in the 5.9GHz for road safety and traffic management in both the United States and Europe.

In view of the maturity and availability of IEEE 802.11 products, this technology emerged as the main contender for the Medium Access Control (MAC) in VANETs. In July 2010, the IEEE 802.11 Task Group p (TGp) released an amendment to the original standard, specially designed for Wireless Access in Vehicular Environments (WAVE) [1]. At the same time, in Europe, ETSI integrated a slightly modified version of IEEE 802.11p in an European Standard for Intelligent Transportation Systems (ITS) [2].

Both WAVE and the ETSI architecture were conceived to operate on multiple 10MHz physical channels: a unique control channel (CCH) and several service channels (SCH). Although it is still an object of debate whether to use multiple radios or periodic channel switching, the general agreement is that the CCH will be entirely dedicated to safety applications.

The number of applications foreseen in a vehicular network is already impressive [3], and a real implementation would probably fire up even more the search for a *killer app*. However, despite the heterogeneous requirements at the application layer, the CCH is expected to transport only two types of data packets: periodic Cooperative Awareness Messages (CAM), or beacons, and Decentralised Environment Notifications (DEN).

While both CAMs and DENs are broadcast messages, a massive proportion of the studies focusing on novel mechanisms for the VANET MAC layer make the assumption of unicast communication, raising doubts about the efficiency of these solutions in the case of safety applications. Moreover, even the proposals that consider the use of broadcast messages do not take into account specific properties and metrics of the periodic beaconing, specificities that could have an important impact on the performance of the MAC protocol.

In this paper, we discuss the characteristics of vehicular beacons and we formulate analytical relationships taking into consideration the nature of these messages. We also conduct a simulation study, showing that beaconing properties differ from those of simple broadcast messages and that taking them into consideration can highly improve the performance of the MAC layer.

The remainder of this article is organised as follows. In Section II, a succinct presentation of V2V applications is made. Section III discusses the properties of VANET beaconing and presents the analytical framework. Simulation results proving the importance of these properties are presented in Section IV, and Section V concludes this paper.

II. Applications and Requirements

Vehicular network applications are usually divided into three categories: safety applications, traffic management applications and passenger entertainment applications. This section discusses general requirements of these categories; for more details on individual applications, the reader is referred to the overview in [3].

Traffic management and entertainment applications are already available in cars through the use of existing 3G/4G infrastructure. The objective in this case is to enhance the user perceived quality of these applications by the means of V2V communication on a SCH. A convergence with the IP world appears as the right decision in this case and the MAC layer has to deal with a mixture of broadcast and unicast messages.

An important number of safety applications are anticipated in VANETs. They are allowed to use the SCH too, but also benefit from a dedicated CCH. A classical IP solution, where every application produces messages that are treated separately by the lower layers, would create in this case an enormous amount of traffic and it is clearly unfeasible in such a harsh environment. However, despite the high number of proposals and their apparent heterogeneity, the applications in this class generally need the same kind of information: position, speed and direction of neighboring vehicles. Considering these arguments, a *facilities* layer has been included in the ETSI ITS architecture, between the application and transport layers [3].

The facilities layer manages a unique view of the surrounding environment and provides all the applications with the information they require. The building block of this approach is the periodic transmission of status beacons, named CAMs in the ETSI framework, by every vehicle. CAMs include information from on-board sensors and their size is estimated at around 500 bytes with security overhead included. A standard beaconing frequency is yet to be decided, but a value between 5Hz and 10Hz is considered necessary to accommodate the needs of the most demanding applications.

In the case the sensors detect an event that has the potential to jeopardise vehicular safety (e.g. a sudden brake), the facilities layer immediately sends a DEN, a special message to inform the other traffic participants and also makes the information available for its local applications.

CAMs and DENs present a strong interest to all surrounding vehicles and therefore they are transmitted in broadcast mode. Hence, the CCH is exclusively used for broadcast messages. Moreover, beacons have properties that distinguish them from simple broadcast messages.

First of all, a beacon that can not gain channel access before the facilities layer produce a new CAM becomes outdated and expires. Keeping this beacon in the MAC queue and eventually transmit it does not only introduce a longer delay for the succeeding messages, but it also delivers information that is no longer true to the other vehicles. Therefore, expired beacons need to be removed from the transmission queue.

The information inside a CAM can also be added to a DEN when such a message is considered necessary. This means that a beacon also expires when the MAC layer receives a DEN for transmission.

Second, performance of MAC broadcast communication in an IP architecture is usually judged based on terms of application throughput and channel access delay. For V2V safety communication, the goal is not to maximise throughput or to reduce jitter, while the delay remains an essential parameter, but it is natively limited by the expiration threshold. In VANETs, the objective is to increase the driver's knowledge about the surrounding vehicular environment. MAC optimisation should consequently focus on metrics such as beacon delivery ratio in the close neighbourhood, the number of expired CAMs, or the number of consecutive messages lost between pairs of vehicles [4].

These properties have never been considered in VANET research so far and their implication can be very deep. For example, because beacons expire when either a new CAM or a DEN is created, there is practically no time spent in the message queue at the MAC layer, besides the potential back-off time. This also means that there is no internal contention between safety messages of different categories, as implied by the use of the IEEE 802.11e traffic classes in the WAVE and ETSI ITS architectures. However, the IEEE 802.11e mechanisms could still have a role in allocating different priorities to certain safety messages, as proposed in [5].

These special characteristics, if correctly understood, have the capacity to highly improve the performance of the MAC layer and they should be taken into account when new solutions are designed and proposed. An opposing argument could come from the fact that optimising the access method from the CCH point of view would perhaps reduce the quality of the applications that use the SCH. A convenient solution in this case would be to use slightly different MAC protocols for CCH and SCH.

However, in the case the implementation of such differentiated mechanisms would be considered too difficult, it is essential to remember that the spectrum has been allocated specifically to improve road safety and therefore the system should be built with safety applications in mind. While it is true that any other non-safety application represents an added value, we consider that these applications should adapt to the CCH requirements instead of imposing even more constraints on an already challenged system.

III. Analytical Model

Several analytical models have been proposed in the case of vehicular communication [6], [7]. As already mentioned, although these models consider broadcast communication, they fail to discuss specific beaconing properties. In this section, we formulate an analytical framework able to estimate CAM collision and expiration probability.

We consider a mean vehicular density of λ veh/km where each vehicle periodically sends beacons with a period of T seconds. We divide this period T in a number of equal time slots, N_T, and the size of a beacon is s. We consider all the beacons are transmitted using the same bit rate, therefore a beacon occupies N_s slots.

We place ourselves in the context of a given node i and we first calculate the probability, P_b, that this node senses the channel as busy at a given moment.

During a period T, all the cars found in node's i carrier-sense range (c_r) will try to send a beacon. However, some of these beacons will expire with a probability P_{exp} and others will collide (from the point of view of node i) with a probability P_{col}. Considering this periodic behaviour, we only need to focus on a single period and we can express P_b as:

$$P_b = N_b / N_T$$

In this case, N_b represents the mean number of busy slots seen by node i and can be calculated as follows:

$$N_b = 2\lambda c_r N_s - 2\lambda c_r P_{exp} N_s - \frac{2\lambda c_r P_{col} E[N_{col}]}{E[n_i]}$$

where N_{col} is the number of slots occupied by a collision and n_i is the number of nodes involved in the collision.

There are two situations when a collision can happen. The first one is when two or more nodes positioned in the carrier sense range of each other begin transmitting on the same slot. The duration of the collision in this case is equal to the duration of a beacon, N_s and the probability of the event is P_{ccs}. The second possibility is that two of the colliding nodes are hidden from one another. When this arrives, the duration of the collision is uniformly distributed between 1 slot and N_s slots and its probability is P_{ch}. We therefore have:

$$P_{col} E[N_{col}] = P_{ccs} N_s + P_{ch} N_s / 2$$

If we assume that a collision usually occurs between no more than two stations, which is reasonable especially in a linear network, then $E[n_i] \approx 2$, we can write:

$$N_b \approx 2\lambda c_r N_s (1 - P_{exp} - P_{ccs}/2 - P_{ch}/4)$$

In order to have an expired beacon, the node needs to try to access the medium during a busy slot. This will trigger a backoff of b. If during the next T slots there are less than b idle slots, the message will not be sent before the reception of the next beacon from the application layer. We can therefore calculate P_{exp} as follows:

$$P_{exp} = P_b \sum_{b=1}^{CW} \frac{1}{CW} P_i(b)$$

where $P_i(b)$ is the probability to have less than b idle slots in a beacon period:

$$P_i(b) = \sum_{j=0}^{b-1} \binom{T}{j} (1 - P_b)^j P_b^{T-j}$$

The probability for a node i to transmit in a slot k can be therefore calculated as:

$$P_{ik} = (1 - P_{exp})/T$$

If we consider node i has j transmitting neighbours inside its carrier sense zone, a collision with one of these nodes occurs when at least one other vehicle transmits in the same slot as i:

$$(P_{ccs} \mid j\ neighbours) = (1 - P_{exp})(1 - (1 - P_{ik})^j)$$

Node i can also collide with vehicles inside its interference zone i_r. However, in this case a collision happens when the hidden node starts transmitting in any of the s slots occupied by node's i beacon or in the s-1 preceding slots. We therefore have:

$$(P_{ch} \mid j\ neighbours) = (1 - P_{exp})(1 - (1 - P_{ik})^{j(2s-1)})$$

The number of transmitting neighbours j is unknown, but its mean value is $N_{ccs} = 2\lambda c_r (1 - P_{exp})$ in the case of the nodes inside the carrier sense range and $N_{ch} = 2\lambda(i_r - c_r)(1 - P_{exp})$ in the case of the hidden nodes. We can write in this case:

$$P_{ccs} = \sum_{j=0}^{\infty} (P_{ccs}|j) \frac{N_{ccs}^j}{j!} e^{-N_{ccs}}$$

$$P_{ch} = \sum_{j=0}^{\infty} (P_{ch}|j) \frac{N_{ch}^j}{j!} e^{-N_{ch}}$$

This model can be used for the study of several MAC layer mechanisms. In the remaining of this section, we give a numerical example focused on the influence of the minimum contention window (CW_{min}) on the beaconing reception probability ($P_{ok} = 1 - P_{exp} - P_{ccs} - P_{ch}$).

The relationship between the optimal CW_{min} and the number of contending stations has been demonstrated in [8] in the case of saturated unicast traffic. Nevertheless, the importance of this parameter has been somehow neglected in the VANET community and the ETSI congestion control framework does not include at the present time any mechanism for an adaptive contention window [2].

We are interested on the evolution of the reception probability in high density scenarios (city intersections, highway traffic jams). In these situations, the resulted beaconing traffic can approach or even exceed the channel capacity.

We use the numerical values from Table I and we adopt an iterative method to solve the system and to obtain the results shown in Figure 1. For some numerical values, our method oscillates between two local solutions and in these cases we chose the most meaningful one. However, all these points are situated on the decreasing region of every curve, therefore the search for an optimal value of the contention window is not influenced.

In Figure 1, we can notice that the reception probability is not initially influenced by the increase of CW_{min}. This is because the probability for a beacon expiration is very low and the number of collisions remains constant. As the contention

TABLE I
NUMERICAL VALUES FOR DIFFERENT PARAMETERS IN THE MODEL

N_T	N_s	λ	c_r	i_r
1000	10	210-250	250 m	350 m

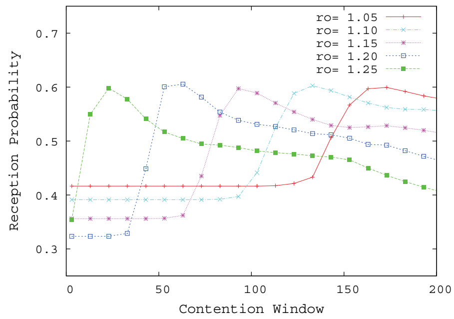

Fig. 1. Reception probability for beacon messages as a function of CW_{min} for different values of the network load

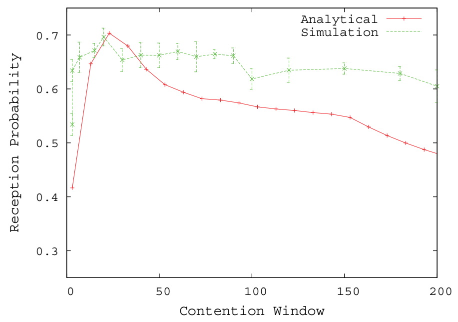

Fig. 2. Simulation and analytical results for beaconing reception probability as a function of CW_{min} for a network load of 1.25 (95% confidence itervals are also shown for simulation results)

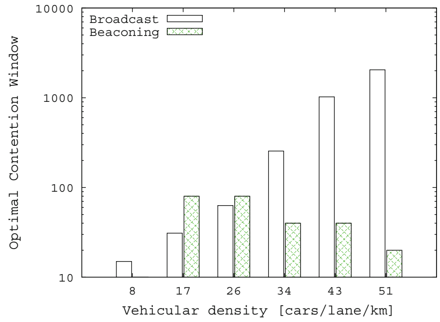

Fig. 3. Optimal value of CW_{min} for pure broadcast and beaconing (please notice the log-scale of the y-axis)

window grows, beacons begin to expire, the collision probability decreases and the reception probability rises sharply. However, after a certain point, the number of expired beacons outgrows the number of avoided collisions and the reception probability begins a slow but steady decrease.

Another observation we can make is that the optimal value for CW_{min} decreases when the network load is increased. This behaviour is the opposite of what happens in the case of normal broadcast messages, where an expiration threshold does not exist [8].

It is also clear that a small value contention window results in low performance and this raises some interesting questions concerning the values currently proposed for CW_{min} [2]. These values, between 3 and 15 depending on the traffic class, have been defined with multimedia applications in mind where the main goal was to reduce jitter for video and voice flows. On the other hand, safety applications have different requirements and the density of the vehicular network can vary much more than the one of a classical WLAN. Therefore, taking into consideration the results we presented in this section, we argue that the minimum contention window in IEEE 802.11p should be adjusted in order to take into account the characteristics of the safety beaconing.

IV. Simulation Results

The analytical model described in the previous section helps us gain insight into the novel challenges raised by the vehicular environment. However, several assumptions and simplifications were needed to reduce the complexity of the equations. Hence, we have decided to also conduct a simulation study that will test the consistency of our model.

For these simulations, we have turned to the Java in Simulation Time (JiST) framework and its Scalable Wireless Ad hoc Network Simulator (SWANS) [9]. Real maps have been extracted from the U.S. Census Bureau's MAF/TIGER database and the Street Random Waypoint (STRAW) car-following model [10] has been used to control vehicular mobility. A probabilistic radio propagation model with shadowing where the fast fading component depends on the number of vehicles [11] has been chosen and the IEEE 802.11p amendment has been integrated in the MAC layer.

We begin by measuring the reception probability for several vehicular densities, while varying the value of CW_{min}. Figure 2 shows the results for one of these densities: 51 vehicles/km/lane on average (the other results have been omitted for clarity, but they show a similar trend). Using a beaconing frequency of 10Hz, this corresponds roughly to a network load of 1.25, therefore the corresponding results from the analytical model are also plotted.

We can see that the two sets of results present a matching behaviour. However, the reception probability found through simulation is considerably higher than the theoretical one, specially for large values of CW_{min}. This is a direct consequence of the capture effect modelled in the simulator but difficult to describe using an analytical framework. The capture effect implies that two or more radio signals received at the same time by a node do not necessarily result in a collision. In fact, if the received power of one of the signals is much higher than the power of the others, the corresponding message can still be correctly decoded, resulting in a higher number of received beacons.

Another difference between the simulations and the analytical model comes from the assumption that the channel busy probability, P_b, is independent for every slot. As a matter of fact, we calculate P_b as a mean value over an entire beaconing period (N_T), and we apply this probability for every individual slot. However, as a transmission can last for more than one slot, the probability for a slot to be busy depends on the state of the previous slot. As a consequence, the number of nodes that find the channel occupied when trying to transmit is uniformly distributed over N_T in the analytical model. This means that the number of nodes choosing a back-off period at a certain moment is also uniformly distributed (unlike in simulation, where the number of contending nodes accumulates during a message transmission) and therefore the value of the contention window has a smaller influence on the collision probability. This artefact of the model can be easily noticed in Figure 1, where the reception probability is initially constant, although CW_{min} increases. In simulations, this phenomenon does no longer exist and the number of received CAMs is sensible to the adjustment of the contention window from the beginning.

Despite these hypotheses made to reduce its complexity, the analytical framework can still accurately predict the impact of different parameters on the MAC layer performance. For example, the decreasing trend of the optimal contention window with increased network load is confirmed by the simulation results shown in Figure 3. This figure compares the results obtained through simulation for simple broadcasting and safety beaconing. In the first case, the metric we used in order to establish the optimal CW_{min} was the saturation throughput, while for beaconing we measured the CAM reception probability at less than 200 meters from the sender.

The results in the broadcast case are in line with those predicted by the Bianchi model [8], the optimal contention window increasing with the vehicular density. On the other hand, for beaconing, we can observe a steady decrease, as predicted by our model. However, it is interesting to notice that the optimal CW_{min} can be found in a relatively small interval (between 20 and 100) for a large range of vehicular densities. In these conditions, solutions like those proposed in [12] or [13], based on increasing CW_{min} with the goal of improving the reception probability do not seem suitable.

V. Conclusion

For a long time, VANETs have been considered just an instantiation of classical Mobile Ad-Hoc Networks (MANETs). Starting with the acronym and continuing with different protocols and mechanisms, the vehicular networks research community tried to directly apply solutions originally developed for generic MANETs.

In this paper, we argue that the safety applications that will be built on V2V communication possess specific properties and requirements, which also propagate to the MAC layer of the network. We discuss some of these characteristics and present some of the contradictory decisions taken by the standardisation bodies focused on ITS and vehicular communications.

We propose an analytical model that takes into consideration the specificities of safety beaconing, the first model of this kind to our knowledge. By the means of an explicit example, the search for an optimal minimum contention window for the back-off mechanism, we verify the accuracy of the model, by comparing its results with those of a simulation tool often used in vehicular networks research. Despite using inherent approximations, such a theoretical framework proves to be a powerful tool in the first stages of design of VANET MAC layer mechanisms.

A second point emphasised in this paper is the improvement brought by a correctly chosen contention window. The standardised congestion control solutions are currently focused on mechanisms originally designed for MANETs, like transmission power control or data rate adjustment. While these solutions also show promising results in a vehicular context, we consider that they are not sufficient in high density scenarios and we feel that novel mechanisms that take into account the profile of the safety beaconing traffic are also needed.

Our results show that the CW_{min} values currently proposed in the ETSI and IEEE standards highly reduce the reception probability of safety messages. We consider that mechanisms with the capacity to solve this problem (e.g. [5]) should be included in the IEEE 802.11p protocol, with the risk of perturbing other non-safety applications.

As a future work, we plan to further develop and improve the analytical model in order to facilitate the study of V2V communications. We will also continue to search for MAC layer enhancements designed with the characteristics of the vehicular environment in mind.

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