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Abstract—Adding communication capabilities to vehicles and road infrastructure has become a major goal in the intelligent transportation systems industry. The IEEE 802.11p amendment has specially been conceived for the Wireless Access in Vehicular Environments (WAVE) architecture. In this paper we study the performance of this standard by the means of extensive simulations and we argue that the current version of the protocol can not cope with high vehicular densities. We propose a simple but efficient modification of the back off mechanism which has an important impact on the quality of communications on the control channel.

I. Introduction

Installing wireless communication devices inside the vehicles and on the roadside appears as the next step in increasing transportation safety and comfort. A Vehicular Ad-hoc Network (VANET) would allow vehicles to exchange messages in order to increase the driver's knowledge about the surrounding environment or to ease the passengers' access to a number of multimedia applications.

While the idea of communicating vehicles is not novel [1], the field has seen a recent revival with the allocation in the United States of 75MHz of spectrum in the 5.9GHz band for dedicated short-range communications (DSRC). Europe followed the example in 2008 when 30MHz from the same 5.9GHz band were allocated for road safety and traffic management. Japan is also planning to use spectrum in the 700MHz band, scheduled to be freed on 2012, for an inter-vehicle communication system.

Several standardization organizations began working on the communication architecture specifications and one of the largely accepted points is that the medium access control (MAC) layer of a VANET should be based on the highly successful and available IEEE 802.11 technology. An amendment to this standard, developed by IEEE 802.11 Task Group p, has been approved and published in July 2010 [2], with the goal to be integrated in a larger wireless access in vehicular environments (WAVE) architecture.

IEEE 802.11p describes several modifications brought to the physical and MAC layers of the original standard. In order to better deal with the problems resulted from the high relative speed between vehicles, the WAVE physical layer operates on 10MHz wide channels, half of the classical 20MHz ones that are currently used by Wi-Fi devices. The available spectrum is therefore structured in multiple 10MHz channels, from which one is used for safety communications only (the control channel - CCH) while the other service channels (SCH) can be used by both safety and non-safety applications.

Safety applications in VANET will be based on the exchange of periodic Cooperative Awareness Messages (CAM). These are broadcast messages that each car diffuses in its neighbourhood with a frequency between 2Hz and 10Hz which is yet to be fixed by the standardization bodies. A CAM contains details like vehicle's location, speed, direction and any other kind of information which could be useful to drivers in the same geographic area. When an important event is detected by a vehicle (e.g an accident, a slippery road), the information has to rapidly be shared with the other network nodes. This can be done by the means of a special Decentralised Environment Notification (DEN) or by attaching the information to a CAM.

However, whether the safety applications will use DEN or CAM piggy-backing, it is certain that all the messages on the CCH will be sent on broadcast mode. This will make a VANET the first large-scale network where communication will be based on broadcast rather than on unicast messages.

In these conditions, the choice of an IEEE 802.11 based technology for this type of network raises some interesting questions. The protocols belonging to this family of standards are well known for their inability to cope with an increased ratio of broadcast messages [3]. IEEE 802.11 was originally conceived and gained its popularity as an access method for wireless local area networks (WLAN) and it usually functions in an use-case totally different from the one foreseen in VANETs. Despite all this, the modifications brought by the IEEE 802.11p amendment focused on the physical layer, while the MAC layer has not seen any important enhancement.

In this paper, we argue in favour of a new decremental back-off strategy, specially conceived to control congestion on the CCH. Our mechanism is based on a fundamental property of VANET beaconing, namely the fact that a CAM can expire when the information it carries becomes outdated.

We begin by discussing the scalability problem of IEEE 802.11p and the possible strategies that aim at solving it. We then present the new back-off scheme, and we prove its superiority when compared with the current version of the standard through an extended set of simulations.

II. IEEE 802.11 Broadcast Scalability

With vehicular densities that can vary from very sparse to more than 150 cars/lane/km, a very important property of the VANET MAC layer ought to be scalability. The classic unicast IEEE 802.11 has long been known to have problems in this area, with the throughput achievable by a station drastically dropping in crowded environments [4].

Moreover, broadcast messages do not benefit from any mechanism meant to alleviate the hidden nodes problems, like the RTS/CTS handshake in the case of unicast traffic. This practically doubles the number of the contending vehicles. To make matters worse, broadcast messages are not acknowledged so collisions can not be detected. Therefore, the single mechanism in the IEEE 802.11 standard which had the role of improving scalability in the case of unicast messages (the binary exponential back-off) can not be used on the VANET control channel. It comes as no surprise then that an IEEE 802.11p-based CCH is saturated solely by beaconing even for medium vehicle density [5].

The scalability problem of IEEE 802.11 was treated in various ways in the MANET/VANET community. The easiest solution is to keep the number of contending nodes under a certain threshold, which can be done by using mechanisms for power control [6]. In this approach, when the access to the medium becomes too difficult, vehicles simply decrease their transmission power in order to reduce the interference area. However, reducing transmission power has some important limits, as the regulatory bodies impose very strict requirements on the minimum area that should be reached by CAMs.

Another solution would be to control the transmission time of a beacon. As the size of the beacon will be more or less fixed, the only parameter that could be changed is the data rate. A higher data rate would mean a lower collision probability due to hidden nodes and an increase in the number of vehicles that could be served [7]. However, a message sent with a higher data rate also requires a higher signal-to-noise ratio at the destination in order to be received so the coverage area is also reduced in this case. Therefore data rate control suffers from the same limitations as transmission power control.

Reducing CAM message frequency in high vehicular density was also proposed but, as it can be seen in [5], even the minimum imposed beaconing frequency of 2Hz can produce too many messages for IEEE 802.11p in certain situations.

The final parameter that we can try to control is the time the channel is idle because of nodes backing-off (T_{idle}). In the ideal case, there would be no idle time between messages with the exception of the DCF Interframe Space ($DIFS$). This would require either a perfect synchronization between network nodes or a null back-off time for any node that senses the channel as busy when it wants to transmit. The first option is not feasible in a dynamic and distributed environment like the one we are studying. The second option would only increase the number of collisions because all the vehicles which would try to access the medium during the same busy period would begin transmitting at the same time.

There has been a lot of work addressing the optimum value for T_{idle} in the case of unicast messages and it has been shown in [8] that the channel is best used when the time the medium is idle equals the time it is busy due to collisions (T_{col}).

In the case of broadcast messages, the minimal contention window (CW_{min}) is always used for back-off. CW_{min} has a very important impact on T_{idle} and it is widely known that the value used in the current standard is far from optimal [8]. Several algorithms have been proposed in order to dynamically adjust the contention window to its optimal value. The basic idea is to increase the contention window when $T_{idle} < T_{col}$ and to decrease it in the opposite situation. The fact that, in the case of broadcast messages, collisions can not be recognized from transmissions which failed because of channel errors makes this mechanism very difficult to implement in VANET.

III. Proposed Back-off Mechanism

In this paper we focus on the back-off mechanism on the VANET control channel. We argue that the current algorithm is totally unadapted to a vehicular environment and represents an important obstacle in the development of a scalable MAC protocol. As we already mentioned, a lot of new algorithms have been proposed with the aim of improving the back-off mechanism in IEEE 802.11. Despite all this, the standard was not modified to take into account these suggestions, mainly because of two important arguments. First of all, the short RTS and CTS messages are not only a solution for the hidden nodes problem, but they also diminish considerably the collision time. As the system reaches its optimum when $T_{col} = T_{idle}$, it means that the average back-off time can also be reduced in this case.

Second of all, the standard has been designed to work in WLANs, with a central access point and a reduced number of stations (15-20 maximum). The devices in a WLAN are mainly laptops and hand-held gadgets so a large part of the traffic is produced by multimedia applications. With strict requirements on the delay, these applications were given a higher priority by reducing CW_{min} for certain categories of messages (video, voice). The current mechanisms (described in the IEEE 802.11e standard) allow for a fast access to the channel when the number of contending nodes is small, while managing to cope with increased demand by the means of the binary exponential back-off (BEB).

In a broadcast environment we can use neither the BEB, nor the RTS/CTS handshake and therefore the modification of the back-off mechanism has again become a subject of interest. Recent papers ([7],[9],[11]) have proposed different methods of dynamically adjusting CW_{min} in order to cope with vehicle density. In all these approaches, the authors assume that they can somehow estimate the duration of the collisions on the channel. This is not a valid premise for broadcast messages because there is currently no real-time method which could find a difference between a message dropped after a collision and one dropped because of a radio propagation error.

Most important, these studies do not take into account the profile of the applications which will use the control channel.

They seek for a contention window that would maximize the saturation throughput of the network, even though, in the case of beaconing on the CCH, the system is clearly unsaturated and the throughput is not an essential metric.

In [10] we have proposed to adapt the contention window based on an estimate of the number of neighbours. However, this solution is not compatible with a security framework founded on changing pseudonyms and, as we shall discuss further on, it does not solve a critical issue of the V2V MAC layer, that we call "'the ghost node problem'".

The value of the optimum CW_{min}, as proven in [8], is given by:

$$CW_{min} = N\sqrt{2T_t}$$

where N is the number of contending nodes and T_t is the total transmission time. However, this formula stands only for saturated networks or for arrival rates greater than a specific threshold [12], which is not normally the case for CAMs.

Furthermore, this optimization is made with the idea of throughput in mind. This was crucial when analyzing the behaviour of a WLAN, but it is less important when studying the performance of a MAC protocol on the CCH. The goal of traffic safety applications is not to deliver large amounts of data, but to extend as much as possible the knowledge the driver has about the vehicular environment. In this type of network, it is essential for beacons to be correctly received in the close neighbourhood. An important property of the MAC protocol has to be its capacity to deal with "ghost nodes", vehicles that are invisible to other vehicles for large time periods because of repeated beacon collisions [13]. Even if an optimum CW_{min} would be estimated and used, in a crowded environment collisions would be unavoidable and the risk of losing consecutive beacons would still exist.

An important property of CAMs is that they have a limited lifetime. If the MAC layer is not able to send a beacon before the next one enters the MAC queue, its transmission has to be canceled because it would not only waste bandwidth, but it would also deliver outdated information to the other vehicles. A high value of CW_{min} would increase the time a beacon waits at the MAC layer before transmission and it would raise the probability that the beacon expires.

In order to better understand the behaviour of IEEE 802.11 in the case of beaconing, we model the protocol by the means of a non-ergodic Markov chain as shown in Figure 1.

When a beacon is received from the upper layers, the medium is busy with a probability P_b. In this case, a back-off time between 0 and CW is chosen randomly. If the channel is idle (with a probability $\bar{P}_b$), the message is sent and it has a probability P_c to collide with another message.

For every beacon, the probability P_r to be received at the destination is:

$$P_r = 1 - P_c - P_e$$

where P_e is the probability that the beacon expires.

A message expires if it does not reach state 0 before $t = T$. If we consider $P_k^{(i)}$ as the probability to be in state k at $t = i$,

we have:

$$P_e = 1 - \sum_{i=0}^{T} P_0^{(i)}$$

The initial back-off is chosen randomly, therefore:

$$P_0^{(0)} = P_k^{(0)} = \frac{P_b}{CW}$$

For any other i, we can write:

$$P_0^{(i)} = P_1^{(i-1)}\bar{P}_b$$

Concerning $P_1^{(i)}$, and with the assumption $CW < T$, we need to consider two cases:

- $i \le (CW - 1)$. We simply have:

$$P_1^{(i)} = P_k^{(0)} = \frac{P_b}{CW}$$

- $i > (CW - 1)$. The probability to sense the channel busy also plays a role:

$$P_k^{(i)} = P_k^{(i-1)}P_b + P_{k-1}^{(i-1)}\bar{P}_b \qquad (1)$$

Therefore we can write:

$$P_e = 1 - P_b\bar{P}_b - \frac{P_b}{CW}(1 - \bar{P}_b) - \sum_{i=CW-1}^{T-1}\bar{P}_b P_1^{(i)}$$

The computation of $P_1^{(i)}$ is possible using (1) but it would be too laborious for the scope of this paper. However, we can notice that the probability a beacon expires is more important for high values of CW and it decreases when the difference between T and CW grows.

On the other hand, to avoid collisions, a node needs to send the message in one of the T slots that has not been chosen by any other station:

$$P_c = 1 - \left(\frac{CW - 1}{CW}\right)^{M-1}$$

where M is the number of contending nodes.

We can notice that, in this case, the probability of a collision decreases when CW increases and this effect is more important for higher values of M. In order to achieve the best performance, the MAC protocol would therefore need to guarantee a balance between collisions and expired beacons. Because, as we explained, collisions are hard to control in the vehicular environment, our proposal is focused on the expired beacons, an information easy to access by the MAC protocol.

Instead of beginning with a small contention window and increasing it for every consecutive collision, we start with a relatively large value for CW and we divide it by 2 every time a CAM message expires. Once the node transmits a beacon, the contention window resets to the original value.

This approach has several interesting properties. First of all, it diminishes the number of collisions, by reducing the probability that two back-off timers expire on the same slot. Second of all, it alleviates the problem of "ghost nodes" by increasing the transmission priority for vehicles which already experienced a series of expired CAMs. Finally, a very important characteristic is that an event-driven message can be easily given a higher priority than a normal beacon.
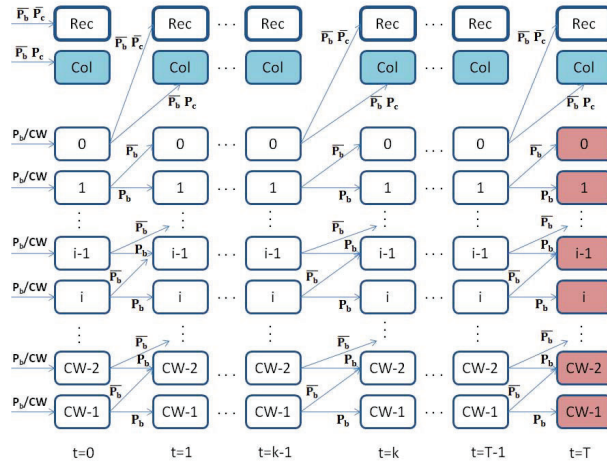
Fig. 1. Markov chain representation of beaconing on IEEE 802.11. In blue, the states where a beacon collides, in red those where it expires
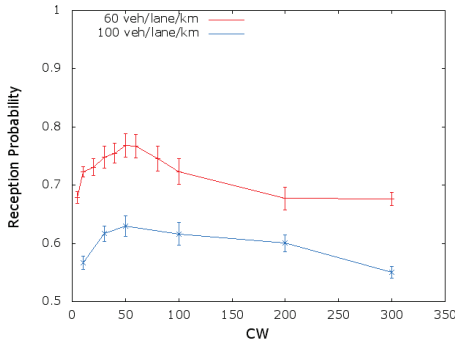

Fig. 2. Beaconing reception probability at less than $200m$ from the source as a function of CW (the 95% confidence interval is also shown)

IV. SIMULATION RESULTS

In order to establish wether the proposed back-off mechanism really has a positive impact and with the goal of setting the best value for certain parameters, we have turned to the Java in Simulation Time (JiST) environment and to its Scalable Wireless Ad hoc Network Simulator (SWANS) package [14].

For vehicle mobility, we have used the Street Random Waypoint (STRAW) model [15] on a 3km highway scenario. The vehicle entry headways follow an Erlang distribution with a mean value of either 60 cars/lane/km or 100 cars/lane/km. At the radio level, we have chosen a probabilistic shadowing propagation model and for the MAC layer we have set the parameters according to the values mentioned in the IEEE 802.11p amendment. Each simulation had a duration of 600 seconds and in our results we took into account only the messages exchanged in the last 300 seconds.

First, we study the effect of the minimum contention window on unsaturated beaconing, using a frequency of 10Hz for the CAMs (see Figure 2). Of course, such a high frequency will not be constantly required and, in a future VANET, the number of beacons will be controlled at the network layer.

Nevertheless, these conditions allow us to test the protocol in a harsh environment, which is very important when we think about the fact that the applications in this network can have a direct impact on human life.

The first thing we notice is that, even in an unsaturated system, the CW_{min} proposed in the current version of the standard (between 5 and 15, depending on the message priority) is far from optimal. However, when we compare the results with the ones obtained for saturated traffic we can see that, for the same node density, the best CW_{min} has a much lower value (the optimal CW_{min} in the saturated case for a density of 60 vehicles/lane/km is around 300) .

While this was expected, because the system is less loaded, another interesting fact can be observed. The linear relationship between the reception probability and the contention window does not hold for beaconing. For the two different densities shown in Figure 2, the optimal CW_{min} has a value between 50 and 70 and this is also true for several other densities we have tested. The difference from the saturated traffic scenario comes from the fact that, for beaconing, a too high value for the contention window results in an important number of expired beacons.

Our next objective is to find the best initial contention window for the proposed back-off algorithm. We have tested several values for CW in different density scenarios and we remarked that the best results are always obtained for an initial CW slightly superior to the optimal fixed CW_{min}.

As can be seen in Figure 3, the reception probability in the case of the decremental back-off strategy is similar with the one achieved by the best fixed contention window. However, when we compare the distribution of these losses, we notice that our proposal has an important impact on the number of consecutive beacons lost between two vehicles. For the same percentage of lost messages, the decremental back-off has a larger number of 1 and 2 beacons lost in a row, but it reduces the probability of a large number of consecutive losses.

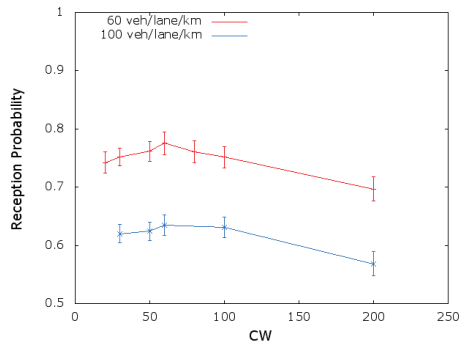To exemplify this, in Figure 4 we show a histogram repre-

Fig. 3. Beaconing reception probability at less than $200m$ from the source using the proposed mechanism (the 95% confidence interval is also shown)
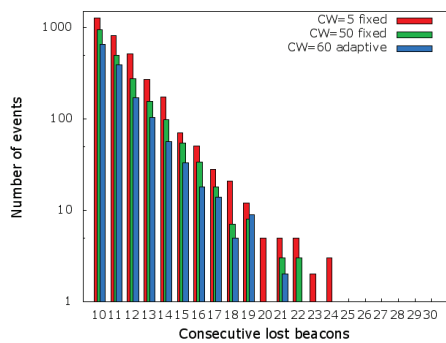

Fig. 4. Histogram representation of consecutive beacons lost between nodes situated at less than $100m$ for a density of 60 veh/lane/km (notice the log scale)

sentation of consecutive CAM messages lost between nodes situated at less than $100m$ from each other. We compare the results obtained by using the current value of the contention window ($CW_{min} = 5$) with those obtained by using the optimal fixed CW_{min} with a value of 50 and by the decremental back-off with initial $CW = 60$. What we notice is a significant improvement when using the proposed mechanism. For example, the number of times 15 consecutive beacons are lost is 55% lower in the case of the new back-off strategy than in the case when $CW_{min} = 5$ and 40% lower when compared with $CW_{min} = 50$.

Of course, the access method remains probabilistic and our mechanism does not set a threshold on the maximum number of consecutive losses and it is possible that in certain situations this number will be higher in the case of our mechanism. However, the results obtained from our simulations allow us to state that the probability of a "ghost node" is highly reduced by the decremental back-off.

V. CONCLUSION

Scalability is one of the most important properties for the MAC layer of a future VANET. This vehicular network will have as a main goal to improve transportation safety by the means of periodic CAMs transmitted by every vehicle.

In this paper we discuss the different approaches that could

be taken in order to improve the scalability of an IEEE 802.11p MAC layer. Our focus is on the back-off mechanism and on an adaptive contention window which seeks to find an equilibrium between collisions and expired beacons.

We propose a decremental back-off strategy, where every consecutive expired message results in a smaller contention window for the next message. The results we obtain through simulation indicate the proposed mechanism is significantly better than the one used in the current version of the protocol. Moreover, unlike other algorithms presented recently, it does not require the estimation of any parameter and it can be implemented with minor modifications of the standard.

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