Broadcast Communication in Vehicular Ad-Hoc Network Safety Applications

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***Abstract*—Contention-based protocols for Medium Access Control (MAC) in Vehicular Ad-Hoc Networks (VANET) are currently under development in several standardization organizations. The availability and maturity of the IEEE 802.11 technology makes it the first choice for the future vehicle-to-vehicle communications. At the same time, safety applications in a vehicular environment are expected to intensively use broadcast messages. However, the IEEE 802.11 standard has not been designed for broadcast communication and a number of problems arise from this. In this paper, we analyze the impact of the minimum Contention Window (CW) on the MAC layer performance in a realistic vehicular environment and we propose a simple solution for adapting CW to the network density in order to improve the reception probability of broadcast messages.**

I. Introduction

Inter-vehicle communication by the means of a Vehicular Ad-Hoc Wireless Network (VANET) is considered as the next step in traffic management and driver assistance. This technology is expected to seriously reduce the number of motor vehicle accidents and, consequently, the number of fatalities caused by them. A vehicle-to-vehicle (V2V) communication network would allow drivers to extend their knowledge about the current state of the transportation network and to receive precious information about their neighbour vehicles. In order to make this possible, the Medium Access Control (MAC) layer of a VANET must have the capacity to cope with the demands of the applications foreseen in the network.

With a few exceptions (e.g. Internet access, gaming, file sharing), VANET applications will use broadcast communication [1]. This is especially true for safety applications, which are practically the goal of an inter-vehicle network. Information manipulated by an intersection-control application, for example, is potentially interesting for all the surrounding vehicles and needs to be delivered to all of them.

Standardization of a MAC protocol for V2V networks is currently an ongoing work and several organizations (IEEE, ETSI, ISO) have already established dedicated working groups in order to study the problem. Both contention-based and contention-free solutions were taken into consideration, but the former seems to be the preferred choice. Indeed, Wi-Fi technology, built on the IEEE 802.11 standard, has reached an important level of maturity and its use in VANETs appears to be unavoidable, although it is important to note that the standard was not originally designed with multi-hop ad-hoc communication in mind [2]. An amendment to the IEEE 802.11a standard, developed by the IEEE 802.11 Task Group p, has already been finalized and will be integrated in the Wireless Access in Vehicular Environments (WAVE) architecture.

The standards from the IEEE 802.11 family provide medium sharing through the Distributed Coordination Function (DCF), an enhancement of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique. However, broadcast messages receive a special treatment in DCF and they do not benefit from these enhancements. The question that arises in this case is: does an access method built for single-hop communication and optimized for unicast messaging have the ability to deliver data reliably in a multi-hop broadcast-based system?

In this paper we focus on the performance achievable by one-hop broadcast communication, starting with an analysis of how broadcast is handled in IEEE 802.11. Next, we evaluate the impact of the minimum contention window on the MAC layer and we show that even a simple adaptive mechanism can bring important improvements. In section VII we conclude the article and provide an outline of our future work.

II. Broadcast in IEEE 802.11

The access method in IEEE 802.11 is built on a variant of CSMA, namely CSMA/CA. According to the standard, a node willing to send a message starts by listening the medium. If it senses that another transmission is taking place, the node has to back off from using the medium for a certain time period, T, calculated as follows:

$$T = Nb * SLOT\_TIME$$

where $SLOT\_TIME$ is a characteristic of the physical layer and Nb is an integer randomly chosen from a uniform distribution over the interval [0, CW].

The goal of this mechanism is to avoid that multiple nodes contending for the channel start transmitting at the same time once the channel becomes idle, hence the "Collision Avoidance" term.

In IEEE 802.11, every time the medium is sensed as idle for the duration of a $SLOT\_TIME$, T is decremented. If the medium becomes busy, the timer is paused and it restarts once the channel stays free for the period of a DCF Interframe Space (DIFS). The message is sent automatically when $T = 0$.

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The standard also describes the evolution of the contention window (CW), which is initially set to CW_{min}. In order to cope with high-load conditions, CW doubles every time the message experiences a collision, until it reaches CW_{max}. Every time a transmission succeeds, CW is reset to CW_{min}.

Trying to solve classical CSMA/CA problems like hidden and exposed nodes, IEEE 802.11 extends the physical carrier sense with a virtual one, by the means of 2 special messages: Request To Send (RTS) and Clear To Send (CTS), forming the well-known *IEEE RTS/CTS handshake*. In a network with symmetrical links and no mobility, this technique could practically eliminate any collision between data messages.

However, these special messages are never used for broadcast communication. The problem in this case is that multiple nodes would need to answer to the same RTS message and collisions would be imminent. Some solutions aiming at a reliable CSMA/CA broadcast were proposed (e.g. [3]), but they are very costly and difficult to implement.

Moreover, this multiple destination problem also appears in the case of ACK messages. Therefore, in a broadcast communication based on IEEE 802.11 protocols, not only we can not use the RTS/CTS handshake to eliminate hidden nodes, but the simple detection of a collision is impossible. This implies that a broadcast message will be transmitted only once, which makes broadcast a lot less reliable than unicast.

This might not be very important in an ordinary wireless network where broadcast corresponds to a small percentage of the network load, as it is the case in classical ad-hoc networks, where broadcast messages are usually just a tool for routing protocols. As a consequent, the MANET community mainly focused on developing techniques for intelligent multi-hop broadcast [4], but less attention was directed towards the impact of one-hop broadcast messages. A notable exception is a recent detailed analysis by Oliveira et al. [5], which shows that DCF performance significantly drops when the broadcast traffic represents more than 50% of the total traffic. However, the authors do not insist on this scenario, stating that a network with this kind of ratio of broadcast messages is not realistic. On the other hand, VANETs fall exactly into this category, as the foreseen applications mostly function in broadcast mode and, therefore, they are highly influenced by this problem. In addition, safety applications demand a high level of reliability, a totaly novel requirement for broadcast traffic.

The fact that collisions can not be detected implies that CW will never be increased for these messages and that they will always be transmitted using the minimum contention window, CW_{min}. This makes it very hard for a broadcast IEEE 802.11 MAC protocol to cope with high node density, an essential quality in a V2V network.

III. Minimum Contention Window

The influence of CW_{min} on the performance of the IEEE 802.11 DCF was extensively studied in the case of unicast messages in [6] and [7].

Even before the release of the first version of the standard in 1997, Bianchi et al. [6] showed that the network throughput varies with CW_{min} and they found that the optimum contention window could be calculated as:

$$CW = N * \sqrt{2 * \tau}$$

where N is the number of contending stations and τ is the total data transmission time (including the ACK message).

Cali et al. [7] propose an analytical model for a p-persistent IEEE 802.11 protocol and recommend an enhancement of the original MAC based on a local estimation of the number of contending nodes, N. A similar approach is presented in [8], where the impact of hidden nodes is also studied.

The idea of an adaptive CW_{min} is further developed in [9] and [10]. The premise of these papers is that a good estimation of N is very difficult to obtain, especially in wireless networks with high mobility. Therefore, they propose to calculate CW based on the proportion of idle time slots. In this case, the throughput is maximized when the average time the channel is idle equals the average time wasted in collisions.

All of these studies consider only the case of unicast traffic. Consequently, the proposed mechanisms presume the possibility of detecting a collision based on a missing ACK. However, a CW_{min} that maximizes the throughput for unicast messages is not necessarily equal to the CW_{min} which best fits the broadcast mode because unicast frames can be retransmitted in the case of a collision. Moreover, the goal of a VANET is not to maximize the throughput, but to make available at each node an accurate and similar description of the outside world.

One of the rare studies on the implications of the contention window in VANET broadcast is detailed in [11], where an adaptive algorithm is also presented. However, the proposed solution is still based on the packet error rate and the authors do not give any indication on how this quantity could be calculated or estimated in a broadcast environment.

In this paper we study the impact of the contention window in a realistic vehicular environment. In order to realize this, we use the Java in Simulation Time (JiST) general purpose simulation framework and the Scalable Wireless Ad hoc Network Simulator (SWANS), specifically designed for the study of MANETs [12]. Realistic node mobility is assured by a very accurate car following model, Street Random Waypoint (STRAW), which can use real world maps from the US Census Bureau's TIGER data files [13].

At the MAC layer we use the parameters from the IEEE 802.11p draft (see table I), an amendment to the original standard which is meant to be integrated in a larger architecture

TABLE I
802.11p KEY PARAMETERS

Preamble duration	32 μs
PLCP header duration	8 μs
Slot duration	13 μs
SIFS time	32 μs
Minimum contention window	3
Transmission rate	6 Mbit/s
Transmission power	33 dbm

for Wireless Access in a Vehicular Environment (WAVE) [14]. The IEEE 802.11p MAC uses one control channel and multiple service channels and it seems to be the preferred option for VANETs in both USA and Europe.

The control channel will only be used by safety applications and for beaconing. Beaconing is practically at the basis of all the other applications, as a car needs to be constantly informed about its surroundings [15]. Considering this, in our study we focused on the performance of beaconing but the same results would be obtained with any kind of CBR broadcast traffic.

IV. CW AND NODE DENSITY

We start by analyzing the influence of CW_{min} on broadcast traffic without taking into account specific problems like hidden nodes or node mobility. We randomly position N cars in an intersection and we disable node mobility, building an one-hop network of fixed nodes. We also consider a perfect physical channel, which leaves frame collision as the only possibility of a failed transmission.

Each one of the 4 roads that form the intersection has 2 lanes in each direction and a length of 250m. The transmission power of the nodes was carefully set in order to always have a completely connected network. Every simulation had a duration of 300 seconds and was repeated 10 times with different random positions for the cars. The beaconing rate was set at 10Hz, as recommended by both the U.S. Department of Transportation IntelliDrive program and the European Car2Car Communication Consortium [16].

We first analyze the collision probability for several values of CW_{min} when $N = 50$ (12,5 cars/lane/km). The results can be seen in figure 1.

As expected, the probability of a collision decreases when CW increases. The fact that the backoff is chosen from a larger interval decreases the probability that 2 nodes start transmitting in the same slot. We can notice that the collision probability is about 30% for $CW_{min} = 5$ and about 1% for $CW_{min} = 1500$.

The value of CW_{min} currently foreseen by the IEEE 802.11p draft is the same as the one used in the IEEE 802.11e standard and it varies between 3 and 15 depending on the message priority. For unicast messages, the binary exponential backoff can increase CW until it reaches the value $CW_{max} = 1023$, but broadcast traffic is always transmitted using CW_{min}.

The requirements imposed on the VANET MAC by the safety applications are different from what is expected in classical mobile ad-hoc networks. As an example, the delivery rate in the car's immediate neighbourhood is much more important than the total delivery rate as it is preferable to have an accurate description of a small geographical zone than a mediocre description of a large area. Considering this, we also show in figure 1 the collision probability for the nodes positioned at less than 50 meters from the source node. We can notice that there are fewer collisions in the close neighbourhood, mainly because of the capture effect which

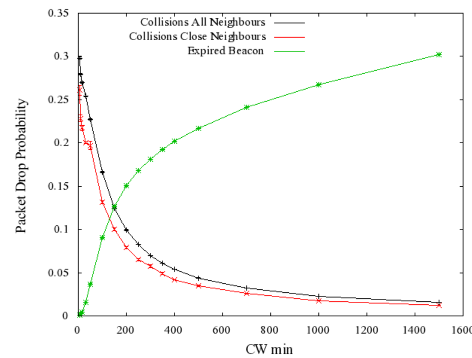

Fig. 1. Collision probability and expiration probability for beacon messages in an intersection for $N = 50$ (95% confidence intervals are shown)

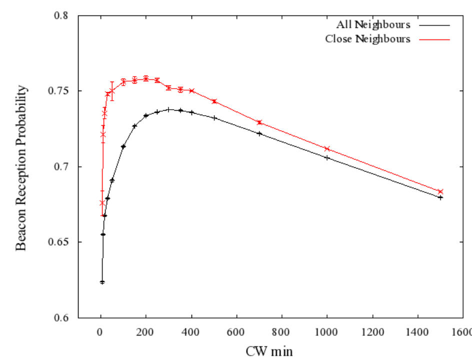

Fig. 2. Reception probability for beacon messages in an intersection for $N = 50$ (95% confidence intervals are shown)

was taken into consideration, but the influence of CW_{min} is the same as in the case when we consider the whole network.

While a very large CW_{min} reduces drastically the probability of a collision, it also has an impact on the delivery delay because a larger CW means a larger average backoff time. Instead of measuring the delay of the messages, we have decided to use a property of the beaconing in order to study the consequences of an increased CW. As a matter of fact, a beacon that can not be sent before the arrival of the next beacon can be dropped because the information it contains is no longer valid and there is no point in wasting bandwidth with its transmission. Therefore, in figure 1 we also represent the probability to drop an expired beacon message from the MAC queue. We notice that this probability is 0 for low values of CW_{min} and it becomes important with the increase of the average backoff time (about 20% of the beacons are not sent for a $CW_{min} = 400$).

In order to establish the best compromise between losing a message after a collision and dropping it because it is outdated, in figure 2 we plot the reception probability for the beacons in function of CW_{min}. If we consider the entire network, the optimal contention window for $N = 50$ has a value between 250 and 350. The reception probability in this case sees a 12% improvement compared to the case $CW_{min} = 7$ currently proposed in the standard.

When we consider only the cars found at less than 50 meters

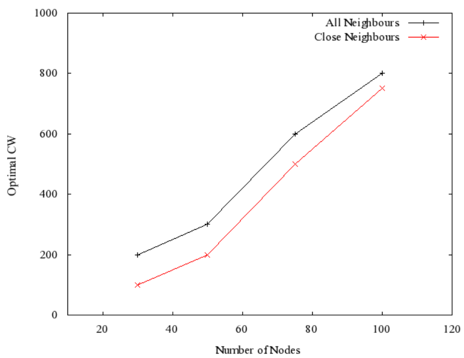

Fig. 3. Optimal value of CW_{min} as a function of node density

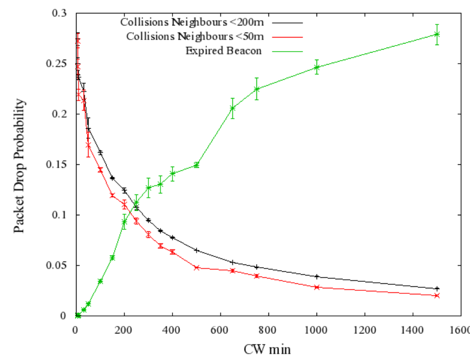

Fig. 4. Collision probability and expiration probability for beacon messages in an intersection for $N = 100$ considering hidden nodes (95% confidence intervals are shown)

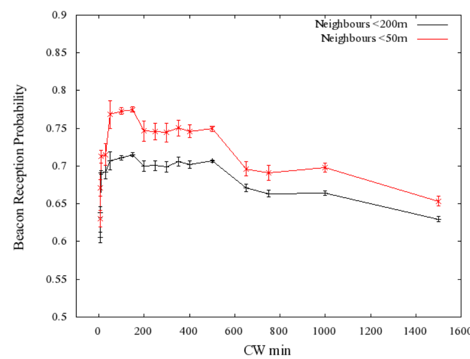

Fig. 5. Reception probability for beacon messages in an intersection for $N = 100$ considering hidden nodes (95% confidence intervals are shown)

from the source, the best results are obtained for CW_{min} between 150 and 250 but we still receive about 12% more messages than in the case of a small CW.

We repeated the simulations with several values for N. The shapes of the obtained curves are very similar with those presented for the case $N = 50$, but the optimal value of the contention window varies with N. This relation between the number of nodes and CW_{min} is shown in figure 3 and we can notice the linear dependence found in the case of unicast messages also holds for broadcast traffic.

V. CW and Hidden Nodes

In a wireless ad-hoc network, a source node contends for the channel with all its neighbours, but also with the neighbours of the destination node. If the concurrent access for neighbour nodes is controlled by the CS mechanism, the hidden node problem is more difficult to solve and it is usually handled with by the means of the RTS/CTS handshake. However, in the case of a broadcast message all the neighbours are also destinations for the frame and therefore the source node contends with all its one-hop and two-hop neighbours.

Willing to study the effect of hidden nodes on the relationship between CW_{min} and IEEE 802.11 performance, we zoom out from the previous scenario and we consider an area of 500 meters around the intersection. We also allow cars to move, using the StreetMobilityRandom model provided by STRAW [13] and we use a shadowed Nakagami fading radio propagation model. In order to keep the same vehicle density as in the previous case, we also double the number of cars ($N = 100$).

In figure 4 we plot the probability that a beacon expires before being transmitted and the collision probability. Although the curves are very similar with those shown in section IV, these two cases should not be compared quantitatively, because in this second case the network is not fully connected anymore and we set a threshold of 200 meters for the neighbours that we consider in our analysis.

In the case of the reception probability, figure 5 shows an even more important improvement as in the case where no hidden nodes were taken into accounts, especially for the messages delivered in the close neighbourhood. About 15% more beacons were received for the optimal contention window value (between 100 and 200) than in the case $CW_{min} = 5$. The existence of hidden nodes and the node mobility appear to introduce an interesting effect, as the optimum point is harder to spot and the reception probability is similar for a large interval of CW. This seems to be particularly true in the case of nodes situated further away where the results obtained for CW_{min} between 150 and 500 are very close.

VI. Adaptive Contention Window

In the previous sections we established the fact that the reception probability of a beacon depends on both the number of contending neighbours and the value of CW_{min}. In a vehicular network, the node density can vary from almost 0 (rural areas, night time) to more than 100 cars/lane/km in cities at rush hour. Considering this, we propose to adapt the minimal contention window in function of node density.

This mechanism has already been proposed (e.g [9], [10]) in the case of unicast messages. In a classical wireless LAN the number of contending nodes is difficult to estimate, therefore the proposed solutions are based on measuring the time the channel is idle and the period the channel is busy because of a collision. If the first parameter is easy to obtain, collisions can not even be detected for broadcast traffic.

However, VANETs present a native method for estimating

TABLE II
BEACONING RECEPTION PROBABILITY

CW	P_{rec50}	P_{rec200}
7	67.07	63.85
150	77.47	71.53
$\lambda = 3$	74.65	70.25
$\lambda = 2$	79.89	73.05

the number of neighbours, by the means of beaconing. One of the objectives of a vehicular network is precisely to have an accurate description of the neighbouring environment. We propose to calculate the contention window as:

$$CW = \lambda * \breve{N}$$

where $\breve{N}$ is the number of nodes from which a beacon was received in the last t seconds and λ is a parameter we derive from our simulations.

In table II we compare the average reception probability of a beacon at 50 meters and at 200 meters for several values of CW_{min} in a similar scenario as the one presented in section V. First we show the results when the contention window is fixed, with a value of 7 (as used in the IEEE 802.11 standard) and with a value of 150 (the optimal value we found in our simulations). The results obtained using the proposed adaptive CW are also shown for 2 values of λ (we set t = 10 seconds for this experiment). We can notice that a correct value for λ can bring an improvement in beaconing reception even when we compare it with the peak obtained for a fixed CW. Moreover, when compared with the value currently described in the IEEE standard, we see a gain of almost 13%.

However, following the arguments presented in the case of unicast traffic [6], the best value for λ depends on the message size and the results we present here should be seen more as a proof of concept and not as an attempt to find the optimal λ.

VII. CONCLUSION

The impact of the minimum contention window on the performance of an IEEE 802.11 MAC was extensively studied in the literature for unicast messages. As far as we know, this is the first study analyzing the influence of CW_{min} in a network dedicated to broadcast traffic.

The contention window for broadcast messages, as it is described in the current standard, is fixed and has a small value (3 or 7 depending on the priority class of the message). Our results show that the lack of a mechanism which would adapt CW_{min} to the network density drastically reduces the capacity of an IEEE 802.11 MAC to cope with the requirements of a highly mobile vehicular network. We propose to use the innate capabilities of a VANET, brought by the beaconing based nature of the network and we show that an adaptive CW improves the performance of the MAC layer.

The proposal of an adaptive CW_{min} in IEEE 802.11 was first made even before the publication of the original standard in 1997. The fact that the standard was not initially designed for large, multi-hop ad-hoc networks meant that the effect of the CW_{min} was not seen as particularly important. However, considering recent evolutions in ad-hoc networking and in the wake of the proposal to use IEEE 802.11 in the future VANET, we believe that the idea of a contention window which takes into account the number of contending nodes should be reevaluated.

In our future work, we will focus on the study of an adaptive contention window for broadcast messages and we will also analyze the impact multi-hop communication has on the performance of the IEEE 802.11 MAC layer.

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