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Razvan Stanica, Emmanuel Chaput, André-Luc Beylot

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Razvan Stanica, Emmanuel Chaput and André-Luc Beylot
Université de Toulouse
IRIT - ENSEEIHT
Toulouse, France
Email: {razvan.stanica, emmanuel.chaput, andre-luc.beylot}@enseeiht.fr

***Abstract*—The medium access control protocol of a future vehicular ad-hoc network is expected to cope with highly heterogeneous conditions. An essential parameter for protocols issued from the IEEE 802.11 family is the minimum contention window used by the backoff mechanism. While its impact has been thoroughly studied in the case of wireless local area networks, the importance of the contention window has been somehow neglected in the studies focusing on vehicle-to-vehicle communication. In this paper we show that the adjustment of the minimum contention window depending on the local node density can notably improve the performance of the IEEE 802.11 protocol. Moreover, we compare through simulation in a realistic framework five different methods for estimating the local density in a vehicular environment, presenting the advantages and the shortcomings of each of them.**

I. Introduction

Enhancing transportation safety and efficiency emerged as a major objective for the automotive industry in the last decade. One of the approaches with the most promising prospects in this area is the creation of a Vehicular Ad-Hoc Network (VANET) by installing communicating devices inside vehicles.

Motivated by the allocation of spectrum dedicated to intelligent transportation systems (ITS) in the 5.9GHz band, in both the United States and Europe, several standardisation bodies have consecrated special working groups to the topic. A common characteristic of all the proposals issued by these regulatory committees concerns the medium access control (MAC) layer of the vehicle-to-vehicle (V2V) communication architecture, where the IEEE 802.11 protocol is the widely accepted solution.

The commercial success of Wi-Fi products based on this standard and the maturity of the technology are incontestable arguments in favour of this decision. Therefore, the IEEE Task Group p recently brought an amendment to the original standard, specially conceived for wireless access in vehicular environments (WAVE) [1]. However, the protocols from the IEEE 802.11 family have been designed with a limited number of nodes in mind and they are well known for their inability to cope with increased network load. Despite this important issue, the IEEE 802.11p amendment does not propose any modification that could alleviate this scalability problem.

The ETSI Technical Committee on ITS has addressed this concern by proposing several mechanisms for distributed congestion control in a vehicular network [2]. Nevertheless, one of the most important parameters of the protocol, the minimum contention window (CW_{min}) used in the back-off mechanism, has not been taken into account in this optimisation framework. The dependence of the optimal CW_{min} value on the number of contending nodes is a thoroughly studied subject in the field of wireless local area networks (WLAN) [3]. Sadly, the solutions proposed in the WLAN context can not be directly applied in a VANET.

In this paper, we present five different approaches for CW_{min} adaptation which take into account the local density and we compare them through simulation in a realistic framework with the original IEEE 802.11p. We show that these mechanisms are simple to implement but efficient and we argue that an adaptive contention window should be at the basis of any congestion control solution.

The remainder of this article is organised as follows. Section II presents the IEEE 802.11p standard and the solutions proposed in the ETSI technical group with regard to distributed congestion control. We discuss next the influence of CW_{min} on the MAC layer in a vehicular environment and the suitability of previous proposals identified in the literature. Section IV details the different mechanisms we designed and analysed, while section V discusses the results we obtained.

II. The IEEE 802.11p Amendment

The IEEE 802.11 Task Group p (TGp) has been created in 2004 with the goal of integrating the standard in a wider architecture for wireless access in vehicular networks. In June 2010, the IEEE Standards Board approved the amendment proposed by TGp, which modifies the original IEEE 802.11 standard [1].

Although the WAVE architecture is expected to function on multiple physical channels, the IEEE 802.11p amendment only describes operations on a single channel. The other aspects of the system, including switching mechanism between channels and channel selection at a frame level, are addressed by the IEEE 1609.4 standard, currently in a trial phase [4]. Strangely, the solutions foreseen in the European ITS architecture [2] only include the IEEE 802.11p standard and not the entire WAVE system. The implementation of multi-channel operation remains therefore unclear in this case. However, an important characteristic in both IEEE and ETSI approaches is the existence of a dedicated control channel (CCH) that can be used solely for safety applications. As the information transmitted for safety purposes represents a potential interest for all the neighbouring drivers, safety applications exclusively use broadcast messages.

The Distributed Coordination Function (DCF), which is at the core of the IEEE 802.11 standard, treats differently unicast and broadcast communication. The most important disparities come from the fact that broadcast messages are not acknowledged and the classical RTS/CTS handshake can not be used before broadcasting. Practically, the access method used on CCH is the basic CSMA/CA and none of the mechanisms designed for congestion control in unicast WLAN can be used.

With this problem in mind, the ETSI ITS Working Group proposed three methods for decentralised congestion control [2]. The first of these ideas is to adjust the packet rate through cross-layer mechanisms. Safety applications in VANETs are founded on the periodic emission of beacons, also named Cooperative Awareness Messages (CAM). The frequency of these messages is still an open research problem, but most studies anticipate a maximum value between 5Hz and 10Hz [4]. A CAM usually contains information about the vehicle's position, speed, trajectory and so on. In a very dense environment, vehicles usually have low speeds and the beaconing frequency could be reduced. However, it is still unclear if all the applications could deal with such a cutback.

Another solution could be to adapt the transmission power in order to limit the number of neighbours of a node [5]. However, this mechanism would require to control the transmitting radio unit at a very fine grained level which could prove to be very difficult and expensive taking into consideration the capabilities of the existing IEEE 802.11 devices. Moreover, safety applications usually impose very precise thresholds for information propagation and, if this threshold is not reachable using one-hop communication, multi-hop broadcast needs to be adopted, which would not only increase the delay, but also amplify the congestion problem. Therefore, transmission power control can be very efficient in some cases but it is by no means a general solution for V2V communications.

The third mechanism consists on adjusting the data rate in order to speed up the transmission of a beacon at high vehicular densities. This practically means to choose the modulation depending on the number of neighbours, trying to occupy the channel for less time in dense environments [6]. However, while a higher data rate decreases the channel busy time, it also requires a higher signal-to-noise (SNR) ratio at the receiver in order to be demodulated. In the case of the noisy vehicular channel, experimental data seems to indicate that a data rate higher than 6Mbps brings an important decrease in performance [7] and therefore data rate control does not seem to be a practical solution.

III. Minimum Contention Window

One of the features adopted in IEEE 802.11 to improve MAC performance is the binary exponential back-off (BEB) mechanism. However, as we explained, in the case of broadcast messages, a failed transmission is not recognisable and therefore a message is sent only once, using a contention window $CW = CW_{min}$.

The dependence of the optimal value for CW_{min} on the number of contending nodes (N_{cont}) in a saturated unicast WLAN cell has been analytically proven in [3]:

$$CW_{min\_opt} = N_{cont}\sqrt{2T_t} \quad (1)$$

where T_t is the time needed for transmitting the packet (acknowledgment included). Moreover, the study shows that the protocol's performance peaks when the time the channel is idle due to the back-off mechanism equals the time the channel is occupied by collisions ($T_{idle} = T_{col}$). Despite this well-known property, the IEEE 802.11 standard did not include any mechanism for the adjustment of CW_{min}. The main reason for this was that the protocol had been designed for WLANs, with a central access point and a limited number of stations in mind. A second argument came from the use of the RTS/CTS handshake. In this case, collisions are limited to the short RTS and CTS messages and therefore the time the channel is busy due to collisions is decreased. This implies that, for an optimal functioning, T_{idle} also needs to be reduced, which requires a lower contention window.

However, as we mentioned above, these assumptions are no longer valid in VANET broadcast communications. Moreover, the optimisation of CW_{min} for V2V communications should take into account the fact that a beacon is a special type of broadcast message, which can expire if it can not be transmitted during a beacon period. When a beacon containing updated information is formed, an expired beacon is removed from the MAC queue and it is considered as a lost beacon for all the neighbours. In [8], we have shown that, for a given vehicular density, the optimal contention window is able to keep a balance between the expired beacons and the collided ones. An adaptive CW_{min} becomes in this context one of the best solutions for congestion control. The question we address in this paper is what is the best mechanism that can realise this adjustment, taking into account VANET specificities.

A number of modified back-off algorithms have been proposed in the literature with WLAN communication in mind. Nevertheless, most of them still require a fixed value for CW_{min} and only the BEB mechanism is changed. The few studies that focused on the impact of the contention window on V2V communications tried to apply these unicast solutions directly, therefore their results can not be extended to the broadcast CCH. Moreover, even those few exceptions that do consider broadcast safety messages ([6], [9]) still fail to take into account the fact that beacons can expire and prefer to concentrate on metrics like throughput or goodput, irrelevant in the case of a safety application. Nonetheless, the two mechanisms proposed in these papers are detailed in the next section, where three other ideas are also illustrated.

IV. Mechanisms for Local Density Estimation

In order to choose an optimal value for CW_{min}, a node needs to determine the local state of the network. This can be done either by estimating the number of contending nodes or by trying to retrieve this information by directly observing the wireless channel. We characterise below the properties and feasibility of five different solutions for contention window adaptation. It is important to note that local density information could also be useful for other purposes, like traffic information systems or transmission power control. While our study only measures the performance of these mechanisms in the case of a dynamic CW_{min}, the observations we make concerning feasibility and implementation are valid for any application based on density estimation.

A. Beacon-based neighbour estimation

Beaconing represents a native method for estimating the number of local neighbours. In [6], a node attempts to calculate the number of surrounding vehicles by counting the different sources from which at least a beacon has been received in the last T_{update} seconds. However, the number of neighbours, $\breve{N}$, determined this way can not be directly applied in (1), as proposed in [6], even though T_t would be very easy to calculate for CAMs. As a matter of fact, in an ad-hoc scenario, a node does not only contend with its direct neighbours, but also with its two-hop neighbours, which can not be detected by this mechanism. Moreover, equation (1) only holds when the network is saturated, and this is not the case on the VANET CCH. Therefore, we propose to calculate the contention window using a more general formula based on this linear dependency:

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

where λ is a parameter depending on the size of the beacon, and whose value we analysed through simulation.

The mechanism would be relatively simple to implement because the addresses of the neighbours will anyway be stored for routing purposes. Nevertheless, repeatedly changing the identifiers (pseudonyms) of a node for privacy purposes, as currently recommended in the ETSI architecture, could have a non-negligible impact on the performance of this solution.

B. Collided packets estimation

The second idea, described in [9], is to estimate the packet error ratio (PER) based on a sequence number added to each CAM. The contention window is initially set to a default value ($CW(0) = CW_{def}$) and, every T_{update} seconds, it is updated using the following algorithm:

$$CW(t) = \begin{cases} min(2 * CW(t-1), CW_{max}) \\ \quad if\ \ PER < PER_{min} \\ \\ max(CW(t-1)/2, CW_{min}) \\ \quad if\ \ PER > PER_{max} \end{cases}$$

The main advantage of this mechanism is that it tries to optimise directly the percentage of delivered beacons. It can also be rather straightforward to implement in a more general congestion control frame that would also include the other techniques discussed in section II.

However, the coexistence of a solution based on sequence numbers and a security protocol using changing pseudonyms appears to be extremely difficult. When a vehicle would change its identifiers, it would also need to reset its sequence counter and, therefore, tracking the lost beacons at the receiver level would become an important problem.

C. Idle time counting

The third mechanism we study aims at preserving the equality $T_{idle} = T_{col}$. In order to estimate T_{col} in a broadcast environment where collisions can not be detected, we take a similar approach as the one presented in the previous section, by counting the number of lost beacons (Nb_{lost}). We also draw advantage from the fact that these messages usually have a fixed size.

However, not all the missing beacons are lost because of a collision. A radio propagation problem on the channel or node mobility can produce a similar effect. Because of this, in order to achieve a better estimation of T_{col} we only take into consideration the beacons sent by vehicles situated at a distance of less than d_{col}, in the immediate neighbourhood. Missing messages sent from a geographically close node have a high probability to be lost due to a collision.

As in the previous algorithm, we begin with $CW(0) = CW_{def}$ and we compute a new value every T_{update} seconds:

$$CW(t) = \begin{cases} min(2 * CW(t-1), CW_{max}) \\ \quad if\ \ T_{col} > \alpha * T_{idle} \\ \\ max(CW(t-1)/2, CW_{min}) \\ \quad if\ \ T_{idle} > \alpha * T_{col} \end{cases}$$

where $\alpha > 1$ is a parameter whose value we will explore through simulation.

The simple idea behind this solution is that if there are too many colliding messages, the contention window should be increased, while CW should be decremented when the channel is idle for an important amount of time. This proposal presents the same advantages and drawbacks as the previous one. A supplementary implementation problem could come from the fact that the station requires the capacity to measure T_{idle}, a feature which is not currently available in all IEEE 802.11 devices.

D. Stop time neighbour estimation

Although VANETs are built on top of the already existing transportation system, very few V2V communication solutions attempt to profit from ideas investigated in related vehicular research fields, as for example traffic flow theory.

The next algorithm is inspired by the approach taken in [10] for transmission power control, where the vehicular density is estimated based on the time the car is stopped in traffic. Therefore, the vehicle needs to measure the stop time (T_{stop}) in the last T_{update} time window. If $T_{stop} = 0$, the traffic is in a free-flow state and the contention window is set to CW_{min}. If $T_{stop} = T_{update}$, the vehicle is considered to be a part of a traffic jam and $CW = CW_{max}$. For intermediate values, the following formula is used:

$$CW = (T_{stop}/T_{update})(CW_{max} - CW_{min}) + CW_{min}$$

The mechanism could be implemented without any additional hardware, as the stop time can already be calculated using data from the speedometer. The problem could lie in the fact that a vehicle might be stopped for several other reasons than a traffic jam, specially in an urban scenario. However, the algorithm would only use a forged contention window in the first T_{update} period and the correct value would be quickly recovered.

E. Speed-based neighbour estimation

A more accurate estimation of local density based on traffic-flow theory is presented in [11], where vehicle speed and jerk (the derivative of acceleration with respect to time) are used to adjust the transmission power. We therefore propose to calculate the local density and the contention window as follows:

$$CW = \frac{|jerk|}{speed * D_{max}}(CW_{max} - CW_{min}) + CW_{min}$$

Although this approach uses more information than the previous one, it still lacks the ability to handle, without any delay, some situations common to city traffic, which result in a low speed without necessarily implying a high vehicular density (e.g. left-turn, stop sign). Moreover, jerk is not currently measured on a regular basis in vehicles.

V. Simulation Results

The mechanisms described in the previous section have been compared through extensive simulation using the Java in Simulation Time (JiST) framework and its Scalable Wireless Ad hoc Network Simulator (SWANS) package, extended with the Street Random Waypoint (STRAW) mobility model [12]. Four different real maps from the TIGER database have been used, in order to avoid any bias introduced by a particular road topology. As our study focused on MAC behaviour at medium and high vehicular densities, our traffic volume varied between 40 veh/km/lane and 80 veh/km/lane. The beaconing frequency has been set at 10Hz and each beacon had a size of 500 bytes. For radio propagation, a probabilistic model with shadowing, where the fast fading factor depends on the vehicular density, has been used.

The optimisation of the contention window in a WLAN context relies upon the idea of maximising throughput. In the case of safety applications, the data always fits in a single beacon, hence no fragmentation is required. This makes the study of throughput/goodput rather unsuitable and the metric of interest in this case is simply the reception probability of a beacon. Moreover, if a choice needs to be made, it is preferable to receive the CAMs sent by close neighbours than the beacons sent by more distant vehicles. Therefore, we focus our analysis on the beacon reception probability at a distance of less than 200 meters from the source vehicle.

TABLE I
Optimal values for the different parameters of the algorithms

T_{update}	λ	PER_{min}	PER_{max}	α	d_{col}	CW_{max}
5 s	0.5	5%	10%	1.1	200 m	50

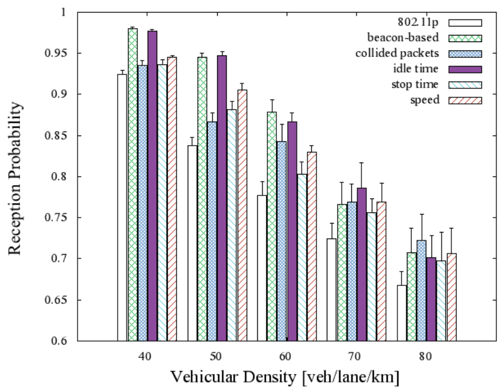

Fig. 1. Beaconing reception probability (including expired beacons) using IEEE 802.11p and the five mechanisms described in this paper for different vehicular densities (the 95% confidence interval is also shown)

We consider this metric to be particularly suitable because it includes in a single value both the probability of collision and the probability of an expired beacon. Moreover, because a beacon that can not be sent with the required time delay expires, all the received messages respect the imposed time constraints and therefore the analysis of the average delay becomes less important.

The first step of our study, which is not detailed here because of space constraints, was dedicated to optimising the different parameters involved in the five algorithms. After an important number of simulations, which examined a wide range of values, we have chosen those presented in Table I.

The beaconing reception probabilities for the studied solutions can be seen in Figure 1. In the case of IEEE 802.11p, a value of 7 has been used for CW_{min}. This is equivalent to the value mentioned in the standard for the access category with the second highest priority [1]. In order to better understand the behaviour of each mechanism, in Figure 2 we show the average contention window as a function of vehicular density.

The first thing we can notice from the data is that all the five solutions show better performance than the basic mechanism, with a difference that can reach more than 10%. Estimating the number of neighbours using the received beacons gives the best results for a vehicular density under 60 cars/lane/km. The idle time approach also gives similar results, showing that our estimation of T_{col} is quite accurate. However, even though the beacon-based and idle time algorithms show similar results concerning the CAM reception probability, they achieve this through different means, as it can be noticed from the dissimilar average values of the contention window. As expected, the beacon-based approach shows a linear increase of CW with the number of vehicles. Therefore, in high density, the

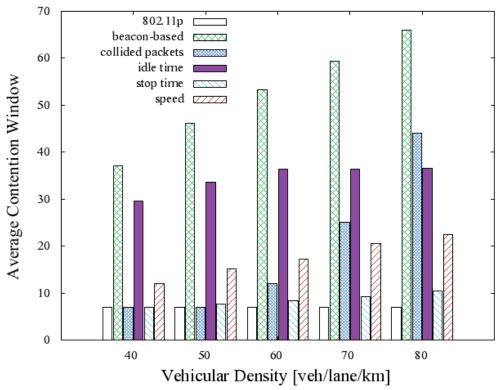

Fig. 2. Average contention window as a function of vehicular density for the analysed mechanisms

nodes back off for an important amount of time, which leads to an increased number of expired beacons. On the other hand, when using the idle time mechanism, the contention window converges to an average value of only 36. In this case, the majority of lost messages are due to collisions and the number of expired CAMs is much lower. These results come in support of the observation we made in [8], where we noticed that, in the case of beaconing, the reception probability is similar for a relatively large range of values of the contention window.

An interesting result is obtained when adjusting CW based on the number of lost packets. When the PER is below PER_{max} (10% in our case), the algorithm almost always uses the default value for CW ($CW_{average} = 7.5$) and its results are similar with those of the basic IEEE 802.11p. However, when the vehicular density increases and more beacons start colliding, the mechanism starts increasing the contention window and its performance drastically improves, showing the best results for a density of 80 vehicles/lane/km. Using a lower value for PER_{max} increases the efficiency of this solution in low density, but it also highly degrades its performance when the number of vehicles becomes more important. Dynamic thresholds would be an interesting approach in this case and we plan to study it in the future.

The two solutions inspired from traffic-flow theory also perform better than IEEE 802.11p. However, for the lower values of the vehicular density, their results are not as good as those of the beacon-based or idle sense mechanisms. This is because in these traffic conditions, vehicles are usually in a free-flow state and they rarely stop or modify their speed in order to increase their contention window. Nevertheless, when the number of cars increases, the mobility pattern is also altered and the two algorithms show similar results with the other strategies. It is also important to notice that the approach based on car's speed and jerk always achieves a better reception probability than the one based on stop time, because it uses a more detailed relationship between car movement and density. Moreover, a very significant property of these two mechanisms is that they can be used together with security solutions based on pseudonyms.

VI. Conclusion

In this paper, we have described five different mechanisms for contention window adaptation in a safety VANET. These mechanisms cover a wide range of approaches, from wireless channel observation to traffic-flow theory applications. Possible implementation issues and complementarity with other foreseen ITS solutions are also discussed. The five proposed algorithms have been optimised after a comprehensive set of simulations and their performance has been compared with the current version of the IEEE 802.11p protocol.

Although the results show that adjusting the contention window would bring an important enhancement at the MAC layer, we also notice that the simple fact of using an adaptive CW does not entirely solve the scalability problem of IEEE 802.11 in vehicular ad-hoc communication. However, our study underlines the efficiency and simplicity of such a mechanism and it recommends it as the main building block of any architecture for VANET congestion control.

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