Congestion Control in CSMA-based Vehicular Networks: Do Not Forget the Carrier Sensing

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***Abstract*—Inter-vehicular communications are considered to be an efficient proactive approach for reducing the number and the consequences of road accidents. After a series of remarkable standardisation efforts, one of the last points needing to be addressed in order for safety vehicular networks to become a reality is the scalability problem of the CSMA-based medium access control layer. With node densities that can range from very sparse to several hundred contending stations, the MAC protocol needs the capacity to adapt to the state of the vehicular network without compromising the performance of the safety applications. While previous studies focused on individual mechanisms for data rate selection or transmission power control from a global point of view, this paper proposes a complete congestion control framework aiming to increase the message reception probability in the immediate neighbourhood under heavy congestion conditions. We propose a new concept for physical carrier sensing, which takes into account the location of the transmitter, and we combine it with transmission power control and a recently proposed back-off mechanism to obtain an important improvement over the original protocol. Several implementation problems are discussed, showing the feasibility of the solution using existing hardware, and a simulation study confirms the performance of this enhanced channel access method.**

I. Introduction

Vehicle-to-vehicle (V2V) communications are emerging as an important element of a future Intelligent Transportation System (ITS), especially with regard to enhancing road safety. A vehicular ad-hoc network (VANET) would allow the rapid dissemination of safety messages, extending the drivers' knowledge about the traffic conditions beyond their line of sight. With spectrum already assigned for vehicular communications in the 5.9 GHz band in both US and Europe, and with an impressive list of use-cases formally described [1], one of the last milestones before the introduction of communication devices inside vehicles is the general consensus towards a wireless technology for channel access.

Building on the popularity and availability of IEEE 802.11-based products, the IEEE 802.11 task group p published in July 2010 an amendment specially designed to integrate the standard in an architecture for wireless access in vehicular environments (WAVE) [2]. While IEEE 802.11p considers important characteristics of a VANET, like the high relative speed between nodes and the short duration of the connectivity, other requirements have not been taken into account by the amendment. The most significant problem yet to be addressed concerns the protocol's scalability in a vehicular network with high mobility and density. The IEEE 802.11 Distributed Coordination Function (DCF) is already known for its inefficiency in handling a large number of contending stations, especially if hidden nodes are also present [3]. The broadcast nature of VANET safety communication does not help in this sense, practically stripping off the DCF from all the mechanisms designed to alleviate this problem. This results in a purely broadcast control channel (CCH), transporting valuable safety information using basic Carrier Sense Multiple Access (CSMA).

Congestion at the medium access control (MAC) layer became therefore a particularly important topic in the perspective of a future vehicular network. With the ETSI deciding to define a congestion control framework as a complement to IEEE 802.11p, a number of solutions were proposed in the research literature. However, these ideas ignore the mechanism situated at the core of any CSMA method, namely the physical carrier sensing.

In this paper, we propose a new channel access technique, Safety Range CSMA, that modifies the physical carrier sensing mechanism in order to take into account the characteristics of the vehicular network. More specifically, our goal is to increase the reception probability for safety messages in the immediate neighbourhood and to reduce the update delay between closely situated vehicles. Moreover, we integrate in this access method a new back-off mechanism and a solution for transmission power control, the result being a complete framework for MAC layer congestion control in safety VANETs.

To summarise, the major contributions of this paper are identified below:

i) We provide an analysis of the influence the physical carrier sense has on the beaconing reception probability in a vehicular network. We are particularly interested in the effect obtained on geographically close neighbours by adjusting the carrier sense threshold.

ii) Based on ideas issued from our analytical results, we present Safety Range CSMA, a channel access technique that takes into account the location of the node occupying the channel. By forcing collisions with far located vehicles, our solution is able to achieve a significant improvement over CSMA in the immediate neighbourhood, which is fundamental for road safety applications.

iii) We include other mechanisms for congestion control in Safety Range CSMA, obtaining a framework that controls three of the most important parameters of the MAC layer (physical carrier sense, transmission power, contention window). Our simulation study demonstrates that this protocol manages to alleviate the CSMA scalability problem, an essential property in a highly dense vehicular network.

This paper is organised as follows. Section II discusses related work from the area of VANET congestion control. In Section III, we describe the studied scenario and we determine the implications of physical carrier sense adaptation in a vehicular network. Section IV presents Safety Range CSMA and complementary mechanisms, and their performance is studied through extensive simulations in Section V. Finally, Section VI concludes this paper.

II. Related Work

Several ideas have been proposed in the context of MAC layer congestion control in vehicular networks. A first class of mechanisms is focused on data rate adaptation, but, while theoretically interesting, the efficiency of these solutions in a real VANET is challenged by a recent experimental study by Bai et al. [5] who show that, in the noisy vehicular channel, Quadrature Phase-Shift Keying (QPSK) is the only reliable modulation even without considering collisions that are inherent under high node density.

The impact of transmission power was extensively studied in the context of VANET congestion control [6]. An important number of adaptive mechanism have been proposed, the target being to use less power for message transmission in high density scenarios. This would reduce the area covered by a safety beacon, but it would increase the reception probability in the close neighbourhood, where the information is the most relevant. However, safety applications have precise coverage requirements, and transmission power cannot always solve the congestion problem, especially if a certain power margin is included as a weapon against the fluctuating channel conditions.

These two solutions are currently standardised by the ETSI, the plan being to integrate them in a single architecture for decentralised congestion control, as described in [7]. Nevertheless, the ETSI framework does not address the influence of two of the most important parameters in IEEE 802.11, namely the minimum contention window (CW_{min}) and the physical carrier sense mechanism that make the object of this study. The impact of the contention window on the efficiency of safety V2V communications was analysed in [8], the conclusion being that the value of CW_{min}, and even the back-off mechanism currently defined in the standard, should be modified in order to increase the reliability of safety beaconing. On the other hand, physical carrier sensing has been studied mostly in a wireless local area network (WLAN) context [9], while being neglected by the VANET research community. However, the differences between the two types of networks are significant and the observations made in a WLAN scenario are not necessarily true for safety V2V communications. For example, Yang et al. [9] show that the optimal carrier sense range needs to find a trade-off between the number of hidden and exposed terminals. Nevertheless, on the VANET CCH all the messages are transmitted in a broadcast mode and they represent an interest for all the neighbours, therefore a terminal can not be *exposed* in the classical sense of the term.

In a previous work [4], we showed that the carrier sense threshold plays an important role on the CCH and its value should be adjusted depending on the local node density. However, proposed as an enhancement to IEEE 802.11p, the adaptive mechanism described in [4] is limited by the access method and is not aggressive enough in highly congested environments. Recently, Schmidt et al. [10] proposed to adapt the carrier sense by taking into account the time a message has spent in the MAC layer queue. This solution tries to minimise the number of expired safety beacons, but it does not consider the consequences of the mechanism on the number of collisions.

III. Network Model

In a vehicular network, every node periodically transmits a beacon, or Cooperative Awareness Message (CAM), sharing with the neighbouring vehicles its location, speed, and other relevant information from the on-board sensors. Important events that need to be announced outside this periodic framework use a second type of safety message, the Decentralised Environmental Notification (DEN). Both CAMs and DENs are relevant to all the surrounding nodes, therefore they are transmitted in broadcast mode, which does not allow the utilisation of acknowledgements or RTS and CTS control messages.

IEEE 802.11p is a relatively long-range technology, with a coverage area in the order of 1 km, and it is therefore clear that the safety messages are more precious in the close neighbourhood. As a consequence, instead of focusing on beaconing reliability over the entire coverage area, we concentrate on CAM reception inside a smaller region defined by a *safety range* (SF_r) around every vehicle. Moreover, because of the nature of safety applications, we are not interested in typical metrics like throughput or MAC layer delay, but we concentrate on the beaconing reception probability and the number of consecutive lost beacons between pairs of vehicles.

A. Signal-to-Interference Ratio

A transmission with initial power level P_t from node W reaches a vehicle V situated at a distance of SF_r with a power

$$P_{rt} = P_t / SF_r^{\theta}$$

where θ is the exponent of the path-loss radio propagation model, with an usual value between 2 and 4.

If we consider that every transmission is sensed by all the nodes situated inside the carrier sense range (CS_r) of the sender, the worst case interferer is situated exactly at CS_r from W and its transmission results in a signal with the following power level at V:

$$P_{ri} = P_i / (CS_r - SF_r)^{\theta}$$

Usually, when studying wireless networks, an accumulative interference model is used [9], taking into account simultaneous transmissions from nodes distributed over the entire 2-D space. However, the vehicular network generally presents a linear topology (this assumption is relaxed in the simulation study in Section V, where intersections are also considered) and, in this case, other interfering nodes must be positioned at more than CS_r from both the transmitter and the main interferer; therefore their influence can be neglected when calculating the signal-to-interference ratio:

$$SIR = \frac{P_t}{P_i}(X-1)^\theta$$

where $X = CS_r/SF_r$ is the ratio of carrier sense range to safety range. Taking advantage of the capture effect, the SIR must be larger than a certain threshold β in order to correctly decode a message.

As shown in [4], reducing the transmission power of the interferer with P_ϵ results in a SIR gain

$$G_{P_\epsilon} = P_i/(P_i - P_\epsilon)$$

On the other hand, decreasing the carrier sense threshold at the interferer with CS_ϵ from the original CS_i moves the main interferer farther away and translates in a different SIR gain

$$G_{CS_\epsilon} = \frac{\left[X\left(\frac{CS_i}{CS_i - CS_\epsilon}\right)^{\frac{1}{\theta}} - 1\right]^\theta}{(X-1)^\theta}$$

It can be easily verified that adjusting the carrier sense threshold has a more significant impact than modifying the transmission power. Increasing the carrier sense range reduces interference and it can eliminate hidden terminals, an essential feature considering that the concept of exposed terminal does not exist on the vehicular control channel (because of the broadcast nature of the communication) and therefore the well-known trade-off between hidden and exposed nodes does not need to be addressed.

B. Collision Probability

However, modifying P_i or CS_i also produces other outcomes than reducing the interference. We need to take into account the fact that the interferer in question is also a vehicle sending its own safety information. While reducing the transmission power can benefit other nodes using the channel at the same time, it is detrimental for the vehicle taking this action.

On the other hand, a larger carrier sense range increases the number of contending neighbours and, with it, the collision probability and the probability to sense a busy channel. The latter can be at the origin of a raise in expired beacons, messages that cannot be transmitted during a beaconing period and need to be dropped when the next CAM, containing fresh information, arrives at the MAC layer for transmission.

Considering a beaconing period consisting of N_T slots, vehicle V will sense as busy N_b from these slots. The busy slot probability $P_b = N_b/N_T$ seen by vehicle V depends on

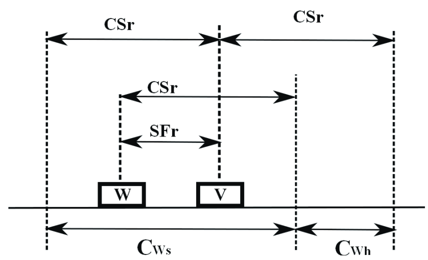

Fig. 1. Different zones around vehicle V

the number of sensed stations (n_c), on the probability of an expired beacon (P_{exp}) and on the collision probability (P_{col}). $E[N_b]$ can be expressed as follows:

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

where N_s is the duration of a beacon in slots, 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 capable of producing a collision at node V. In the first case, the collision is produced between two nodes that are in the carrier sense range of one another (with probability P_{cs}). This scenario, denoted in the following by a *type A collision*, can happen only if both vehicles transmit simultaneously. The duration of the collision in these circumstances is equal to the duration of a beacon, N_s. The second possibility, or *type B collision*, is that the colliding stations are hidden from each other, and the two CAMs can therefore superpose with probability P_{ch} at node V on a number of slots uniformly distributed between 1 and N_s. It is important to understand that, in our model, a collision does not necessarily imply a lost message, but only the simultaneous reception of more than one signals by node V. Using the capture effect or advanced decoding techniques, some of these messages might be correctly received. Nevertheless, the messages would use common slots and this should be considered in the computation of N_b.

If we assume that the number of nodes involved in a collision $n_i \approx 2$, which is a reasonable hypotheses, especially in the case of a one-dimensional network, we can write

$$E[N_b] \approx E[n_c]N_s(1 - P_{exp} - \frac{P_{cs}}{2} - \frac{P_{ch}}{4})$$

In order to start transmitting its CAM in a slot k of the beaconing period, node V must not experience an expired beacon phenomenon. If this prerequisite is accomplished, the first slot is uniformly chosen among the N_T slots of the beaconing period, and therefore the probability of node V beginning its transmission in slot k is:

$$P_k = (1 - P_{exp})/N_T$$

To help understand the significance of the two probabilities P_{cs} and P_{ch} we use the representation shown in Figure 1. Let us denote by C_V the set of nodes that can be sensed by V. A formal definition in this case is:

$$C_V = \{v_i | d(v_i, V) \leq CS_r\}$$

where $d(v_i, V)$ is the distance between nodes V and v_i. Using the same notation as above, we have $|C_V| = n_c$.

Choosing a vehicle $W \in C_V$, we define C_{Ws} as the set of nodes that can be sensed by both V and W ($C_{Ws} = C_V \cap C_W$), while C_{Wh} is formed by the stations that can be sensed by V, but not by W ($C_{Wh} = C_V \setminus C_W$).

Under the assumption of a unique carrier sense threshold, and using the notations $n_{cs} = |C_{Ws}|$ and $n_{ch} = |C_{Wh}|$, the probability that node W transmits a beacon without producing a type A collision at node V, knowing that W and V have j common neighbours, is

$$P_{noA|j} = (P_{noA} | n_{cs} = j) = \sum_{k=0}^{N_T-1} P_k (1 - P_k)^j \qquad (1)$$

A type A collision can only occur if two nodes start transmitting in the same slot. On the other hand, a type B collision takes place if any node belonging to C_{Wh} begins a transmission during one of the N_s slots occupied by W, or even in one of the $N_s - 1$ preceding slots. Therefore, we have

$$P_{noB|i} = (P_{noB} | n_{ch} = i) = \sum_{k=0}^{N_T-1} P_k (1 - P_k)^{i(2N_s-1)} \qquad (2)$$

If we consider that W is situated at distance r from node V, with $-CS_r < r < CS_r$, and that vehicles are uniformly distributed in the carrier sense range, the probability that a neighbour of V belongs to C_{Ws} is:

$$\tau_r = 1 - \frac{|r|}{2CS_r} \qquad (3)$$

and the probability of having $n_{cs} = j$ when we know r is:

$$P_{j|r} = P(n_{cs} = j | r) = \binom{n_c - 1}{j} \tau_r^j (1 - \tau_r)^{n_c - j - 1} \qquad (4)$$

Using (4) and (1), and for symmetry reasons, we can calculate

$$P_{noA} = \int_0^{CS_r} \sum_{j=0}^{n_c-1} \frac{1}{CS_r} P_{noA|j} P_{j|r} \, \mathrm{d}r$$

which, after replacing the terms from Equation (3) becomes

$$P_{noA} = \frac{N_T P_k}{CS_r} \int_0^{CS_r} \left(1 - P_k + \frac{r P_k}{2CS_r}\right)^{n_c - 1} \mathrm{d}r$$

Finally, after solving the integral, we obtain

$$P_{noA} = \frac{2N_T}{n_c} \left[\left(1 - \frac{P_k}{2}\right)^{n_c} - (1 - P_k)^{n_c} \right] \qquad (5)$$

Similarly, the probability of avoiding a collision with a hidden node can be calculated as

$$P_{noB} = \frac{\frac{2N_T P_k}{n_c}}{1 - (1 - P_k)^{2N_s - 1}} \left[1 - \left(\frac{1 + (1 - P_k)^{2N_s - 1}}{2} \right)^{n_c} \right]$$

With $P_{cs} = 1 - P_{noA}$ and $P_{ch} = 1 - P_{noB}$, we still need to calculate the beaconing expiration probability P_{exp}. In order to experience an expired message, a station first needs to find the channel busy when the beacon is passed from the network layer. This triggers a back-off of b, and the condition for the CAM to expire is that the node senses less than b idle slots in the next beaconing period. The probability of this last event can be expressed as:

$$P_{idle}(b) = \sum_{j=0}^{b-1} \binom{N_T}{j} (1 - P_b)^j P_b^{N_T - j}$$

Finally, assuming the back-off is uniformly chosen between 0 and CW, we have

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

However, as discussed above, the collisions involving nodes from the safety range of a vehicle are much more important in our case. If we know that W is inside the safety range of node V, the same approach used in the computation of P_{noA} and P_{noB} can be used, with the difference that the upper limit of the integral is SF_r instead of CS_r. Using this, the probability of a type A collision (P_{SRs}) and that of a type B collision (P_{SRh}) involving at least one node from inside the safety range are

$$P_{SRs} = 1 - \frac{2N_T X}{n_c} \left[\left(1 - P_k + \frac{P_k}{2X}\right)^{n_c} - (1 - P_k)^{n_c} \right]$$

$$P_{SRh} = 1 - \frac{\frac{2N_T P_k X}{n_c}}{1 - (1 - P_k)^s} \left[1 - \left(\frac{2X - 1 + (1 - P_k)^s}{2X} \right)^{n_c} \right]$$

where $s = 2N_s - 1$.

C. Numerical Example

To better understand the impact of adjusting the carrier sense threshold, we solve the system of equations defined above for particular numerical values. Assuming a data rate of 6 Mb/s and a beacon size of 500 bytes, there is a maximum of 150 messages that can be transmitted during a beaconing period of 100 ms. We therefore took the example of a network with similar capacity, with a beaconing period measuring 1500 slots and a beacon size of 10 slots.

As our goal is to test the performance of the MAC protocol in medium and high density scenarios, we vary n_c between 50 and 250. While this final value might seem exaggerated, in a classical two-way highway with three lanes for each direction and a carrier sense range of 1 km, this results in a density of 42 veh/lane/km, or an inter-vehicular distance of 24 meters, not uncommon in most urban areas for rush hour traffic.

Using a contention window of 7 slots, the two probabilities, P_{cs} and P_{ch}, for a type A or a type B collision to appear at node V vary with the number of sensed vehicles as shown in Figure 2. We remind that one of the messages involved in the collision might still be decoded due to the capture effect. However, it can be observed that the probability of

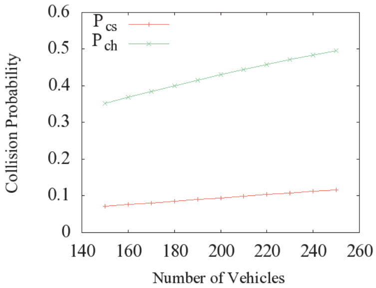

Fig. 2. Collision probability as a function of the number of sensed stations

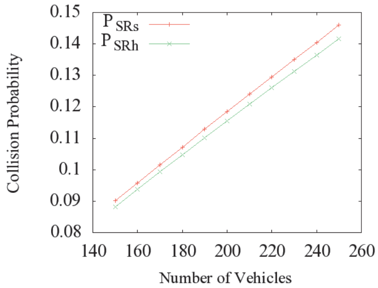

Fig. 3. Collision probability for the nodes inside the safety range as a function of the number of sensed stations for X=5

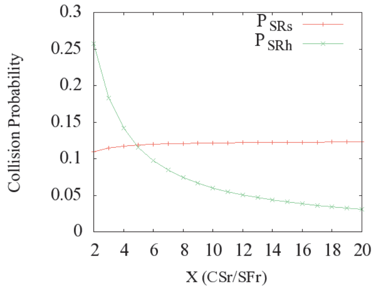

Fig. 4. Collision probability as a function of the ratio between the carrier sense range and the safety range for n_c= 200

simultaneous transmissions increases with the number of one-hop neighbours. Using a larger carrier sense range reduces therefore the interference level resulted from the spatial reuse, but produces more collisions at node V, especially between terminals hidden from one another.

However, a different trend can be noticed in Figure 3 in the case of collisions involving nodes situated inside the safety range. In this situation, a collisions with a hidden node has a similar probability with a collision with a sensed node. An interesting observation can be made from Figure 4 where the influence of X, the CSr to SFr ratio, is depicted. When the difference between the carrier sense range and the safety range increases, the impact of hidden nodes becomes even less significant, especially if we consider that, even in the case of a collision, capturing the message transmitted from the safety range should still be possible in most of the cases because the hidden nodes are situated much farther, outside the safety range. This means that in a VANET where nodes have a carrier sense range of 1 km and a reasonable SF_r of 100 meters, the majority of the lost beacons coming from vehicles inside the safety range are the result of type A collisions, and not the consequence of hidden terminals.

IV. Safety Range Carrier Sense Multiple Access

Based on the observations made in Section III, we describe a new channel access technique, called *Safety Range Carrier Sense Multiple Access* (SR-CSMA), that tries to increase the reception probability for beacons coming from vehicles located within the safety range. The idea behind SR-CSMA is to take advantage of the capture effect and to force collisions with nodes situated farther away, while reducing the collision probability with close neighbours.

A. SR-CSMA Description

The functioning of SR-CSMA is based on the carrier sense mechanism, just like classical CSMA. When a message reaches the MAC layer for transmission, the state of the channel is checked. If the medium is idle, the message is sent with no delay. The difference from CSMA appears when another activity is detected on the channel. Normally this would automatically lead to a back-off, but SR-CSMA introduces an intermediary phase.

The contending node V first determines the location of station W currently occupying the channel. If the intersection of the safety ranges of the two nodes is not empty, meaning that there could exist stations that would consider both transmission as extremely valuable, the medium is declared busy. Otherwise, V estimates what level of interference would produce its transmission on a station S situated at the border of the safety range of the already transmitting W. Using this information, the signal-to-interference ratio at node S can be calculated. If the estimated SIR is larger than a certain threshold, V decides that the transmission can take place and declares an idle channel. The message is sent and the capture effect allows all the stations in the safety range of one of the transmitters to receive the most important of the two messages.

The same concept applies in the case of the back-off mechanism. When using CSMA, any sensed transmission blocks the timer and the countdown is restarted when the channel becomes idle again. In SR-CSMA, if the received message is not close enough to delay a transmission, then it is not considered strong enough to block the back-off timer.

In a vehicular network where the load can easily rise above the channel capacity, collisions are imminent and the goal of SR-CSMA is to control these undesired, but also unavoidable events. By forcing simultaneous transmissions from distant nodes, the channel is able to accommodate an increased number of nodes, and the probability of unwanted collisions is reduced, keeping a high beaconing delivery ratio in the immediate neighbourhood and preserving the efficiency of the safety applications.

B. Transmission Power Control

A transmission power control mechanism can be straightforwardly integrated in SR-CSMA. Assuming vehicle V can use any power level between P_{min} and P_{max}, when a message is sensed on the channel two power thresholds are calculated by V beginning from a target SIR, β_t. First of all, a maximum power is estimated in order to respect the SIR constraint in the safety range of the ongoing transmitter W. Knowing the signal power W achieves at the border of its safety range P_{SR_W}, this maximum threshold can be calculated as

$$T_{max} = P_{SR_W} / \beta_t$$

Second, a minimum threshold T_{min} is estimated to ensure that vehicles inside the safety range of node V can decode its message using the capture effect. A node situated at the border of this zone, between V and W, detects a power level P_{SR_V} coming from node W. Therefore, vehicle V needs to transmit using at least a signal power calculated as follows:

$$T_{min} = P_{SR_V}\beta_t$$

Of course, if $T_{min} > T_{max}$ or if $T_{min} > P_{max}$, a transmission that respects both constraints is impossible and the channel is declared as busy. Otherwise, any power level between the two thresholds can be chosen.

In order to reduce the interference, we propose to always use T_{min} in this case, or P_{min} if $T_{min} < P_{min}$. This latter situation can appear quite often, because a rather high value for P_{min} should be used to lower the probability for radio propagation errors.

C. Physical Carrier Sensing in IEEE 802.11

To estimate the different power levels needed in SR-CSMA, a station sensing a message on the channel requires information regarding the power level used by the transmitter. While this does not represent an issue if the transmission power is not controlled, the information is more difficult to obtain if several power levels can be used. To better understand how this problem can be solved, we take the example of the popular IEEE 802.11 protocol.

In IEEE 802.11 the Clear Channel Assignment (CCA) mechanism is in charge of physical carrier sensing. CCA is a function of the Physical Layer Convergence Protocol (PLCP), the upper part of the IEEE 802.11 PHY, and it relies on two mechanisms, namely header detection and energy detection.

The PLCP header is always transmitted using the most robust modulation, and it contains a 4-bits RATE field providing information about the modulation and coding rate used for the rest of the message. The length of the payload can also be retrieved from the PLCP header, and a station capable of decoding this information uses the CCA to declare the medium busy for the entire duration of the message, even if the reception fails at a certain point. If a PLCP header is not detected, CCA measures the energy level existing on the channel and compares it with an *energy detection threshold* (ED_t). If the perceived energy is larger than ED_t, CCA declares the medium busy. To give a numerical example, in the IEEE 802.11p OFDM PHY, the receiver must have the capacity to detect any PLCP header with a power level over -85 dBm and, if the PLCP header is missed, an ED_t of -65 dBm is used.

SR-CSMA does not modify the energy detection mechanism, although the 20 dB difference between the minimum receiver sensitivity and the energy detection threshold has been defined in the context of the ISM band shared by multiple radio technologies and it might be exaggerated in the conditions of the dedicated DSRC spectrum. On the other hand, all the ideas described above can be put into practice with minor modifications of the PLCP header and the header detection function of the CCA. Inspired from the existence of the RATE field, we propose to add a POWER field to the PLCP header where the sender could share information about the power level used for transmitting the message. We believe that a 4 bits field would be adequate for this purpose and these bits could be obtained without increasing the size of the PLCP header, by a simple redesign of the various fields (a 12 bits LENGTH field is clearly disproportionate for the small safety messages).

D. Location and Power Estimation

However, knowing the power level used for transmission (P_t) is not enough for SR-CSMA. As discussed in Section IV-A, the location of the ongoing transmitter W and power levels at different distances from node V need to be estimated. A cross-layer mechanism using information from both PLCP and *facilities* layer is used for this purpose (the *facilities* layer is situated between the applications and the transport protocol and its goal is to recreate an accurate image of the vehicular environment inside every car [7]).

For a vehicular safety message, the location of the transmitter is already a part of the *facilities* message. A simple and accurate solution would be to move this information into the PLCP header. However, as we shall discuss, SR-CSMA does not need extremely accurate location information and this modification would introduce an undesired overhead because the rest of the message is usually transmitted at a higher data rate than the PLCP part.

We therefore propose to take a different approach for estimating the distance between nodes V and W. As discussed, when a safety message is correctly received with power level P_r and it reaches the *facilities* layer, the vehicle can determinate the distance d where the transmitter is situated. Any radio propagation model can be used at this point to estimate the channel conditions. As an example, in the following we will use the model already described in Section III-A, but a different representation can be easily integrated.

Assuming that $d^\theta = P_t/P_r$, the instantaneous path-loss exponent θ can be determined and an estimated value $\tilde{\theta}$ can be easily kept up to date by the *facilities* layer using the large number of received beacons. The PLCP can not directly fetch the location of node W from the message, but knowing the transmitted and received power levels and having access to the value of the estimated path-loss exponent, the distance between the receiver and the sender can be estimated as

$$\tilde{d} = \sqrt[\tilde{\theta}]{\frac{P_t}{P_r}}$$

A similar approach is used to estimate the various power levels described in Sections IV-A and IV-B (e.g. P_{SR_W}, P_{SR_V}). For example, to calculate the power of a signal transmitted by node W at a distance d_t from node V, the latter would estimate the distance between V and W, $\tilde{d_{WV}}$, and would calculate

$$\tilde{P_{d_t}} = \frac{P_t}{(\tilde{d_{WV}} - d_t)^{\tilde{\theta}}}$$

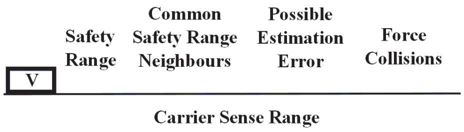

Fig. 5. Different zones in the carrier sense range of a node

Of course, in the quickly varying vehicular channel, these estimations might not be very accurate, and this reverse engineering approach might appear questionable. However, several arguments support the proposed solution. First of all, the use of OFDM signals for communication and radar purposes simultaneously is already considered and could highly facilitate the localisation task [11].

Second, we do not use directly the Received Signal Strength Indication (RSSI) for range estimation, as this leads to poor results [12], but a *continuous profiling* approach, where the received beacons are used to create an RSSI map of the area. RF profiling solutions are well-studied and they manage to achieve a positioning error between 3 and 10 meters [13]. The problem of these techniques is that they necessitate an important number of training messages to estimate the profile of an area, but this should not be an issue in a dense vehicular network where beacons are received from all the neighbours. Moreover, the road topology highly restricts the area where a neighbour could be situated, further facilitating this distance estimation task.

Finally, in order to take into account the impact of fast fading on the RSSI, SR-CSMA uses a value for the SIR target β_t that is much larger than the SIR level required by the capture effect. A high value for β_t can mask most estimation errors and, as shown in Figure 5, ensures that only transmissions from far vehicles are used for intentional collisions.

E. Reverse Back-off Mechanism

In order to describe a complete congestion control framework, we integrate a reverse back-off (RB) mechanism in SR-CSMA. This back-off mechanism has been initially proposed in [8] as a complement to the original IEEE 802.11p standard, and outperforms the classical binary exponential back-off (BEB). In BEB, the original contention window is small and it increases when a failed transmission is detected through a missing acknowledgement. As the broadcast nature of safety communications hinders feed-back reception, the BEB cannot be used in safety VANETs. The advantages of using a relatively high value for the contention window are well known in the case of WLANs [14], but using a large back-off time in vehicular networks results in expired beacons. In [8] it is shown that a small number of expirations is beneficial, but a trade-off between collisions and expired beacons must be maintained in order to approach optimal performance. Based on these results, and because recognising an expired beacon is straightforward, RB takes an opposite approach when compared with BEB, starting with a large contention window and decreasing it every time a beacon expires.

As discussed in [8], the reverse back-off mechanism has two major advantages when compared to the classical BEB. First of all, using a larger value for CW_{min} reduces the collision probability, especially between nodes that can sense each other. Second, reducing the back-off time after an expired message distributes these losses in a much more uniform manner, and it manages to significantly lower the number of consecutive lost beacons between any two vehicles in the network. The only inconvenience could come from the fact that a larger back-off time increases the MAC layer delay, which could be problematic in the case of safety messages where short latency is essential. However, the lifetime of the beacon already sets a tight threshold for the delay and therefore the expiration probability takes into account the delay requirements.

Of course, a sensible problem could be that all these new mechanisms would require a revision of the standard, which is a laborious task and does not guarantee the modifications would also propagate in real products. However, there is a general consensus between automakers and hardware manufacturers regarding the necessity for a MAC layer congestion control framework and standardisation work in this area is already under way [7].

V. Simulation Results

To evaluate SR-CSMA, we used the JiST/SWANS simulation framework [15], together with the Street Random Waypoint car-following mobility model [16]. To remove any bias introduced by a certain road topology, three different real maps with similar road length extracted from the U.S. Census Bureau's TIGER database have been used. The results presented in this section are issued from 90 simulation runs, 30 for each road topology, with a duration of 300 seconds. Three different average vehicular densities have been tested: 25 veh/lane/km, 34 veh/lane/km and 43 veh/lane/km. However, because the simulated area is large (between $18km^2$ and $23km^2$), the local density varies significantly from the average value and, as discussed in [4], we can find both totally jammed streets and free flow area in all the studied topologies.

Because modelling radio propagation in an urban vehicular environment is still a matter of debate in the VANET community, we focused on highway an rural scenarios, where propagation followed a probabilistic model with shadowing for which the fast fading component depends on the number of neighbouring vehicles [17]. It must be pointed out that the propagation model used in the simulation is totally independent (and much more complex) from the one used by SR-CSMA for location estimation. As a matter of fact, as shown in Figure 6, this difference produces an important estimation error which, as explained in [12], grows with the distance to the transmitter. While the performance of the localisation algorithm could surely be improved by choosing an appropriate estimator [13], we decided to present the results obtained by SR-CSMA in this unfavourable scenario. We show

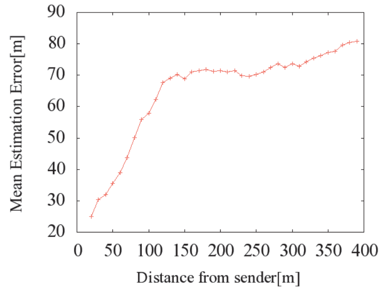

Fig. 6. Mean estimation error for transmissions coming from different distances for a vehicular density of 34 veh/lane/km.

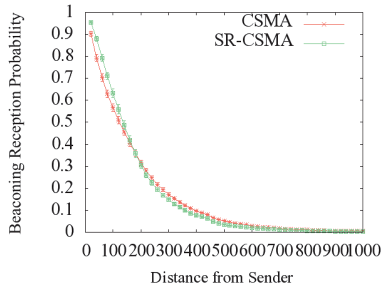

Fig. 7. Beaconing reception probability at different distances from the sender for CSMA and SR-CSMA for a number of 34 veh/lane/km. 95% confidence intervals are shown.

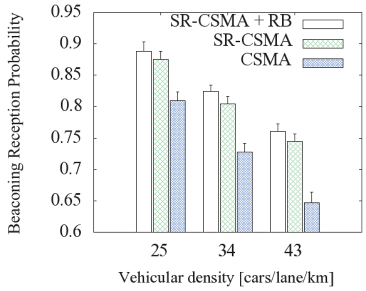

Fig. 8. Beaconing reception probability in the safety range for different vehicular densities. 95% confidence intervals are also shown.

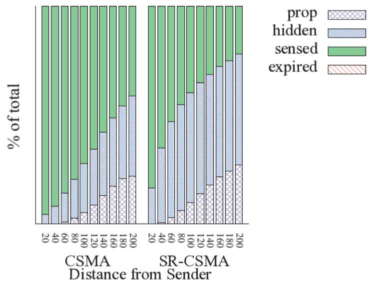

Fig. 9. Distribution of the reasons for a lost message at different distances from the sender for CSMA and SR-CSMA.

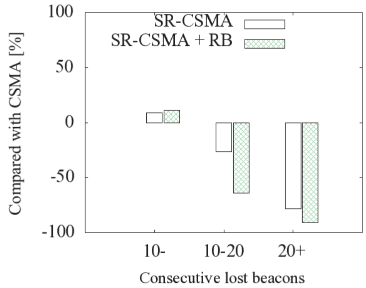

Fig. 10. Number of consecutive lost beacons between pairs of vehicles situated in the safety range of one another. The results are presented as a relative gain/loss with respect to CSMA

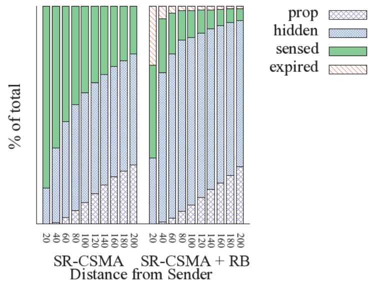

Fig. 11. Distribution of the reasons for a lost message at different distances from the sender for SR-CSMA with and without the reverse back-off mechanism.

TABLE I
VALUES FOR DIFFERENT PARAMETERS USED IN THE SIMULATION

Beaconing Data Rate	$6Mb/s$
PLCP Header Data Rate	$3Mb/s$
SIR required to decode beacon	$10dB$
Beaconing Frequency	$10Hz$
P_{min}	$30dBm$
P_{max}	$40dBm$
β_t	$30dB$

below results for a safety range of 100 meters, but similar results were obtained for $SF_r = 50$ and $SF_r = 150$. The values used for the different CSMA and SR-CSMA parameters are summarised in Table I.

A. SR-CSMA

We first compare the beaconing reception probability for CSMA and SR-CSMA at different distances from the sender. Figure 7 shows the results in the case of a vehicular density of 34 veh/lane/km, and the trend remains similar in the rest of the tested scenarios. We can notice that, as expected, SR-CSMA manages to increase the reception probability in the safety range, balancing this with more losses at higher distances. For example, at $50m$ from the sender, SR-CSMA achieves an improvement of 9% for the beaconing reception ratio, while at $300m$, the reception probability is 7% lower than for the current version of IEEE 802.11. The improvement brought by SR-CSMA can be better observed in Figure 8, where the beaconing reception probability inside the safety range is presented for different vehicular densities. We can see that SR-CSMA can achieve a significant gain over CSMA, a gain that can reach 10% in the most challenging scenario.

To better understand how SR-CSMA works, in Figure 9 we show the distribution of the reasons that can lead to a lost safety message at different distances from the sender in the case of both CSMA and SR-CSMA. For example, at 20 meters from the sender, more than 90% of the messages lost using CSMA are the consequence of simultaneous transmissions with nodes located inside the carrier sense range, and less than 10% are due to collisions with hidden nodes. Two common characteristics can be identified for CSMA and SR-CSMA. First, because both approaches use a small contention window, there are no expired beacons. Second, both transmission techniques show a similar trend concerning the proportion of messages lost following a radio propagation error. However, as predicted by our model in Section III, for CSMA the losses inside the safety range are mostly a consequence of a type A collision. SR-CSMA modifies this distribution, using forced collisions with distant nodes that can still be recovered inside the safety range because of the capture effect. These results confirm that the gain noticed in Figure 8 is achieved by reducing the collision probability with close neighbours.

B. SR-CSMA with reverse back-off

We now analyse the effect of the reverse back-off mechanism on SR-CSMA. From Figure 8, we can notice that combining RB with SR-CSMA brings an even more significant improvement for the beaconing reception probability inside the safety range. However, the most important achievement of the new back-off mechanism can be seen in Figure 10, where we present the number of consecutive lost beacons between pairs of vehicles situated in the safety range of one another. The figure shows this number with respect to CSMA, and the results should be interpreted as follows. When using SR-CSMA instead of CSMA, there are 9% more cases of vehicles missing less than 10 consecutive messages from a neighbour inside its safety range. However, SR-CSMA reduces with 27% the probability of having between 10 and 20 consecutive lost beacons and with 79% the cases when more than 20 messages are lost in a row. Adding the RB mechanism, we further reduce the probability of having more than 10 consecutive losses (including the expired beacons that are not actually transmitted). This property is very important, because it alleviates the *ghost node* problem [8], where two vehicles, although situated in the safety range of one another, remain invisible for a long time period.

Figure 11 shows the impact of the reverse back-off on the events that result in a lost message. We can notice that, as expected, expired beacons appear when using RB and their importance is significant, especially for very close neighbours. The large contention window (127 in our simulations) manages to reduce even more the probability of colliding with a node inside the carrier sense range, and the hidden terminals become the main reason for the losses. We must point out that, in our simulation, a hidden terminal is not necessarily situated at a distance larger than a certain CS_r, but it can also be the result of bad channel conditions, as modelled by the radio propagation module. When the channel conditions are so poor that the header detection function of the CCA fails, SR-CSMA can not avoid the collision, even if the node affected by fast fading is located closely.

VI. Conclusion

This paper presents SR-CSMA, a new channel access technique for vehicular networks, specially designed with the requirements of safety applications in mind. SR-CSMA modifies the physical carrier sensing mechanism in order to force collisions with distant nodes in congested networks. By introducing this controlled collision concept, our solution reduces the probability of a simultaneous transmission with a closely located station, and, taking advantage of the capture effect, manages to increase the beaconing reception probability in the immediate neighbourhood. The concepts behind this congestion control framework are supported by an analytical study of the carrier sense mechanism in a vehicular environment, and their efficiency is confirmed by an extensive set of simulations showing a significant performance gain over classical CSMA.

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