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Physical Carrier Sense in Vehicular Ad-Hoc Networks

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Abstract—Enhancing road safety using vehicle-to-vehicle communication has become an important goal for the automotive industry. A lot of effort has been put in the design of an efficient medium access control protocol, capable to function correctly even under heavy congestion. The solutions proposed so far focus on data rate or transmission power control. In this paper, we argue that the most important parameter for congestion control in vehicular ad hoc networks is the carrier sense threshold. We support this theory with analytical and simulation results and we demonstrate that the optimal threshold depends on the vehicular density. Furthermore, we propose an adaptive mechanism for physical carrier sense control and analyse its performance, showing an important increase in message reception probability.

I. INTRODUCTION

The remarkable development of the automotive and transportation industries over the last century has reshaped our society and our life. Nevertheless, the increase in the number of vehicles daily using the road infrastructure also triggered a growth in the number of car accidents. Over the last 50 years, the car manufacturers mainly focused on reducing the risks produced by these accidents, by introducing different safety solutions like airbags or anti-lock braking systems. The problem of this type of reactive approach is that it deals with the consequences of the accident rather than with its causes. Therefore, motor vehicle accidents remain the main cause of death for humans between 1 and 44 in the western society [1].

Direct vehicle-to-vehicle (V2V) communication is considered as one of the most promising proactive solutions for increasing road safety. Radio devices installed in cars would form a vehicular ad-hoc network (VANET), that would play a major role in increasing the drivers' awareness about potential road hazards.

Dedicated spectrum for traffic safety applications has already been reserved in both the United States and Europe, and a comprehensive list of future applications also exists [2]. Therefore, one of the last obstacles before VANETs become a reality seems to be the design of an efficient medium access control (MAC) technology.

A solution based on the highly successful and available IEEE 802.11 standard seems the best bet at the moment and, in July 2010, the IEEE 802.11p amendment, focused on wireless access in vehicular environments (WAVE), has been released. However, protocols using Time Division Multiple

Access (TDMA) are still considered in the technical groups of the regulatory bodies [4].

The ongoing debate is the direct consequence of the fact that none of the proposed protocols seems to be able to cope with the strict requirements of the vehicular environment [5]. The MAC layer is particularly challenged in high vehicular density scenarios, where the MAC protocol needs to accommodate a periodic access to a channel shared by several hundred nodes and, at the same time, try to reduce the effect of other hundreds of hidden terminals.

Decentralised congestion control becomes essential in this case, and several mechanisms designed for this purpose have been integrated in the ETSI Intelligent Transportation Systems (ITS) architecture [6]. This framework includes protocol agnostic solutions for transmission power and data rate control, while mechanisms for adaptive contention window (CW) have also been designed recently with the IEEE 802.11p protocol in mind [7].

However, in a case of repetitive history, these mechanisms proposed for congestion control also try to deal with the consequences of the hidden node problem instead of focusing on the problem itself. While a correctly chosen data rate or contention window can play an important role on alleviating this problem, the number of potential hidden interferers directly depends on four parameters: *i*) the distance between the sender and the receiver, *ii*) the node density, *iii*) the transmission power, and *iv*) the carrier sense threshold of all the involved nodes.

In the case of vehicular safety applications, the messages are always sent as MAC layer broadcast and they need to cover a predefined geographical area, therefore the sender-receiver distance does not allow an important margin for an adaptive mechanism. As the node density can not be placed under the control of the network, it appears that the number of hidden nodes can only be regulated using the carrier sense threshold (CS_{th}) or the transmission power. Despite its importance, CS_{th} has been ignored by the VANET research community and it is seldom mentioned in studies related to wireless local area networks (WLAN). In this context, this paper brings the following major contributions:

i) It provides an analysis of physical carrier sensing in a vehicular context. The requirements and characteristics of a safety VANET are substantially different from those of what is considered to be a classical multi-hop network and this

has important implications on the carrier sense threshold. We discuss some of these special properties, with a special focus on the safety beaconing that, among others, transforms the vehicular network in an exposed-node free network.

ii) It compares the efficiency of controlling the carrier sense threshold and the transmission power, showing that the former has a more deeper impact on the signal-to-interference ratio. Implementation issues for the two solutions are also discussed, attesting that carrier sense control is not only a more powerful tool, but also much more easier to include in real equipments.

iii) Using both analytical and simulation methods, we show that there exists an optimal carrier sense threshold that finds the right balance between the interference level and the probability to declare a busy channel. We prove that this threshold varies with the vehicular density and the size of the zone in which we wish to optimise the beaconing reception.

iv) We argue in favour of an adaptive mechanism for carrier sense control that could be included in a larger congestion control framework like the one proposed in the ETSI ITS architecture [6]. Based on the native ability of a VANET to measure local node density using safety beacons, the mechanism is simple to implement and very efficient.

The remainder of this article is organised as follows. We begin by discussing a number of previous articles related to our work in Section II. Section III presents the concept of carrier sense. We continue, in Section IV, with a point on the vehicular safety requirements and their implications on carrier sensing and we describe our system analytically in Section V. We examine results issued from a realistic simulation framework in Section VI and we draw our conclusions in Section VII.

II. RELATED WORK

Three main solutions have been conceived in the context of VANET congestion control and they are currently standardised by the ETSI ITS technical committee [6]. The first of these approaches is to adapt the beaconing frequency, practically reducing the network load. A detailed discussion on the different cross-layer mechanisms proposed in this context can be found in [8].

A second idea is to control the data rate at which messages are transmitted [9]. When the number of contending nodes would increase, the vehicles would choose a modulation with a higher data rate, hence reducing the duration they occupy the channel. This would also reduce the area covered by a safety message, but the number of transmission opportunities would grow. While theoretically interesting, this adaptive solution seems to be refuted by an experimental study by Bai et al. [10] which shows that QPSK is the only modulation with fair performance on the challenging V2V channel.

Finally, a lot of attention has been given to transmission power control in VANETs. Torrent-Moreno et al. [11] propose D-FPAV, a distributed algorithm which calculates an optimal common power level for all the nodes in a certain area, piggy-backing power information in the vehicular beacons. Artimy [12] describes a solution based on flow theory equations

which does not require the exchange of any messages between nodes. A mechanism relying on the channel occupancy status measured by the physical layer is studied by Huang et al. [13]. All these approaches improve the performance of the MAC layer but they do not discuss the importance of the physical carrier sense.

Adjusting the contention window of the backoff mechanism is IEEE 802.11 has also been investigated in [7] and [9] and it has shown promising results in congestion control. An adaptive contention window manages to optimise channel access for nodes that can sense each other's transmission, but it has no control over hidden nodes.

Schmidt et al. [14] propose to modify the receiver sensitivity, but without questioning the choice of a fixed threshold. With the exception of these initial results, we are not aware of any detailed analysis on hidden nodes or physical carrier sensing in VANETs and the studies closest to our work come from the field of IEEE 802.11 wireless local area networks.

Brodsky et al. [15] conduct an experimental study with an indoor IEEE 802.11 testbed and conclude that a fixed carrier sense threshold is sufficient in short range networks (under 100m wide) but it highly degrades MAC layer performance in long range networks, category that clearly includes VANETs. Kim et al. [16] find that the capacity of a multi-hop wireless network depends only on the ratio between transmission power and carrier sense threshold, while Yang et al. [17] propose a mechanism for joint transmission power and carrier sense control. However, as we shall discuss in Section IV, the vehicular environment presents unique characteristics and requirements that have not previously been taken into account.

III. PHYSICAL CARRIER SENSE

Physical carrier sense lays the foundation of an entire category of channel access methods, Carrier Sense Multiple Access (CSMA). The concept is well-known and it is used in both wired and wireless networks: before a transmission, a node has to first *sense* the channel to make sure that it is not already occupied by another station.

The carrier sense method described in the IEEE 802.11 standard is based on two functions: Clear Channel Assignment (CCA) and Network Allocation Vector (NAV). NAV is also known as *virtual carrier sense* and it is a MAC layer mechanism that uses special control messages - Request to Send (RTS) and Clear to Send (CTS) - in order to reserve the medium for data transmission.

CCA is a function of the Physical Layer Convergence Procedure (PLCP) and it is in charge of physical carrier sensing. In the case of the Orthogonal Frequency Division Multiplexing (OFDM) physical layer, CCA uses two mechanisms to assess the state of the channel: header detection and energy detection.

The PLCP header is always sent using the most robust combination of modulation and coding rate. It contains information on the data rate used for the rest of the message and a LENGTH field indicating the number of bytes to be transmitted. A node capable to decode the PLCP header calculates the time duration the channel will be occupied by

this transmission and declares the channel busy for this entire duration, even if the reception of the rest of the message fails. If no PLCP header is detected, the CCA function measures the energy level present on the channel and compares it with a predefined value, named Energy Detection threshold (ED_t). If the perceived energy level is larger than ED_t , CCA declares the channel busy and denies any MAC layer transmission.

This is translated in analytical and simulation studies on physical carrier sense [16] [17] by the use of two power thresholds. The first one, the Carrier Sense threshold (CS_t) represents the minimum power level needed for a node to sense a message. The second one is the Reception threshold (RX_t) and it gives the necessary power level in order to receive a message. Considering a given radio propagation model, these thresholds can also be presented as two areas surrounding the transmitter. In this case CS_r is the maximum range where the message is sensed, and RX_r designates the distance at which the message can be received.

IV. VANET CHARACTERISTICS

Dedicated spectrum has been reserved for road safety communications in both Europe and the United States in the 5.9GHz band. This spectrum is organised in multiple 10MHz channels, from which one, the control channel (CCH), is dedicated to safety applications, while non-safety applications can use the other service channels (SCH).

Road safety applications are based on two types of messages: periodic beacons, or Cooperative Awareness Messages (CAM), and messages triggered by the detection of a special, potentially hazardous, situation, named Decentralised Environment Notifications (DEN). As both CAMs and DENs are potentially interesting to all the other vehicles on the road, they are transmitted as MAC layer broadcast.

This strictly broadcast nature of the CCH has several intriguing implications. First of all, the RTS/CTS handshake used by the IEEE 802.11 Distributed Coordination Function (DCF) can not be used on the CCH because it does not work for broadcast messages. This deactivates the virtual carrier sense mechanism, the only solution proposed in the standard to solve the hidden nodes problem.

Second, because all the neighbouring nodes are also receivers of the safety message, the CCH is by definition an exposed-node free channel. Nevertheless, the carrier sense thresholds proposed in wireless multi-hop networks [16] try to find a balance between hidden and exposed stations and therefore they do not fit well with V2V safety communications. Moreover, the values currently proposed in the current IEEE 802.11 standard [3] are even more unrealistic, as they were optimised for the case of single-hop WLANs, with a central access point.

Another important property is the periodicity of the safety messages. This implies that if the MAC layer is not able to transmit a beacon before receiving the next CAM or DEN from the upper layers, the information in this beacon becomes outdated. The transmission of this message would waste bandwidth, increase delay for the message containing fresh

data and provide neighbouring vehicles with an inaccurate view of the sender's current state. Such expired beacons need to be dropped and therefore there is no queueing delay at the MAC layer on the CCH, the channel access time depending solely on the backoff mechanism [7].

Special performance metrics are also required when studying VANET MAC protocols. In a classical mobile ad hoc network (MANET) or WLAN, we are usually interested in applicative throughput and MAC layer delay. In a safety VANET context, the goal is not to exchange large files or stream video flows, but to disseminate information from on-board sensors to neighbouring vehicles in order to avoid dangerous situations. The delay is also limited by the beaconing period, as we discussed above. Consequently, it is more interesting to analyse metrics like beaconing reception probability at a certain distance from the sender, or the amount of time a vehicles is invisible to another one found in its proximity [5].

V. SYSTEM MODEL

In this section, we compare the efficiency of congestion control through adaptive transmission power and carrier sense threshold adjustment. We present the assumptions we make in our model and discuss implementation issues in the case of these two approaches.

A. Safety Range

We begin by defining a new area around every node, the safety range (SF_r). This area is included in CS_r , as it is shown in Figure 1a.

The reason behind this new threshold comes from the long range profile of the vehicular network. Actually, a full power transmission using the parameters proposed in the IEEE 802.11p amendment [3] could reach vehicles situated 1km away. This large coverage area is important because it allows an increase connectivity in sparse environments.

However, congestion control is mainly needed in scenarios with high vehicular density and, in these cases, a spatial reuse in the order of kilometers is not practical. While any received safety beacon is important because of the information it carries, the messages coming from vehicles in the close neighbourhood are clearly more interesting from this point of view. We therefore focus our analysis on this critical zone, covering a distance of SF_r around every transmitter.

Unlike the carrier sense range, whose value depends on the power level used by the transmitting vehicle and the carrier sense threshold of the other nodes, SF_r is the same regardless of the network state. We consider a value of 100-200m to be fairly realistic for the safety range.

In order to simplify the analysis, we propose an equivalent scenario, shown in Figure 1b. Instead of taking into account all the vehicles inside SF_r and CS_r , we only consider two vehicles: *i*) a receiver located at the limit of the safety range and *ii*) an interferer situated just outside the carrier sense range. This can be thought of as a worst case situation, but it is quite possible in a high density VANET.

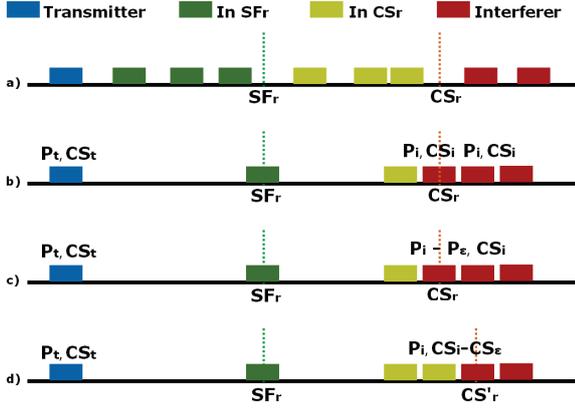


Fig. 1. System model. a) Safety range and carrier sense range in a vehicular scenario. b) Equivalent simplified model. c) Effect of power control. d) Effect of carrier sense threshold adjustment

B. Signal to Interference Ratio

Within this simplified scenario, we focus on the study of the signal-to-interference ratio (SIR) at the receiver:

$$SIR = P_{tr}/P_{ir}$$

where P_{tr} is the power sensed by the receiver coming from the transmitter, and P_{ir} is the perceived power level of the message sent by the worst-case interferer. Other potential interferers would have to be situated outside the carriers sense range of both the transmitter and interferer, therefore we consider their influence negligible.

If θ is the exponent of the path-loss radio propagation model, with an usual value between 2 and 4, we have:

$$P_{tr} = \frac{P_t}{SF_r^\theta}$$

with P_t being the power transmission level of the transmitter.

If P_i is the power used by the interferer, by using an analogous reasoning we obtain:

$$P_{ir} = \frac{P_i}{(CS_r - SF_r)^\theta}$$

We define the ratio of carrier sense range to safety range as

$$X = CS_r/SF_r$$

Therefore, we can write:

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

C. Power and Carrier Sense Control

Because every vehicle must reach at least all the other nodes inside SF_r , we consider there exists a minimum power level P_{min} needed to cover this area. This also translates into a maximum carrier sense threshold CS_{max} chosen in order to make sure that any transmission from a vehicle closer than SF_r can be received, regardless the transmission power used. The upper limit for the transmission power P_{max}

is given by the requirements of the regulatory bodies. The values of P_{max} are currently 44.8 dBm in the United States and 33 dBm in Europe [3]. Finally, the lower value of the carrier sense threshold CS_{min} depends on the quality of the receiver in distinguishing a transmission from ambient noise. The specifications of the OFDM receiver in the IEEE 802.11 standard set this minimum sensitivity limit at -85 dBm [3], while European regulations ask for a threshold of -104 dBm [6].

Assuming that $P_i > P_{min}$ and $CS_i > CS_{min}$, we now focus on the influence of transmission power control at the interferer.

Let us suppose that all the nodes outside the carrier sense range of the transmitter decrease their power level by P_ϵ . However, the worst-case interferer remains the same, because its position is determined solely by its carrier sense range and the power level of the transmitter. In this new scenario, shown in Figure 1c, we have:

$$P_{ir} = \frac{P_i - P_\epsilon}{(CS_r - SF_r)^\theta}$$

and consequently:

$$SIR_{P_\epsilon} = \frac{P_t}{P_i - P_\epsilon}(X - 1)^\theta$$

Things are slightly more complicated when we adjust the carrier sense range of the vehicles outside CS_r . All these vehicles were using a threshold of CS_i , that we now reduce with CS_ϵ . This means that the worst case interferer in the previous examples can now sense the transmitter and the message collision is avoided (see Figure 1d). The new carrier sense range becomes $CS'_r > CS_r$ and the new worst-case interferer is situated just outside of it.

Considering the positions of the interferer, the two thresholds are:

$$CS_i = \frac{P_t}{CS_r^\theta}$$

$$CS_i - CS_\epsilon = \frac{P_t}{CS'_r{}^\theta}$$

We therefore have:

$$CS'_r = CS_r \left(\frac{CS_i}{CS_i - CS_\epsilon} \right)^{\frac{1}{\theta}}$$

In this case the interference level is:

$$P_{ir} = \frac{P_i}{(CS'_r - SF_r)^\theta}$$

and we can calculate the new signal-to-interference ratio:

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

In Figure 2 we show the SIR gains in the case of transmission power (SIR_{P_ϵ}/SIR) and carrier sense (SIR_{CS_ϵ}/SIR) control. For the x-axis, we have considered $\Delta = P_\epsilon = CS_\epsilon$.

In the case of power control, the SIR gain is only influenced by P_ϵ . On the other hand, the results of carrier sense

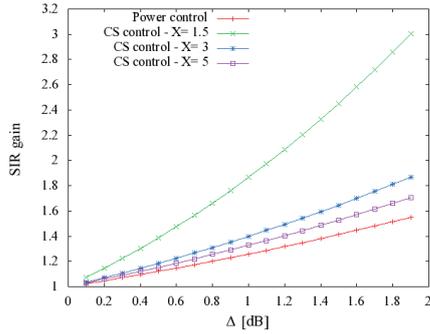


Fig. 2. SIR improvement following transmission power control and carrier sense threshold adjustment ($\theta = 2$)

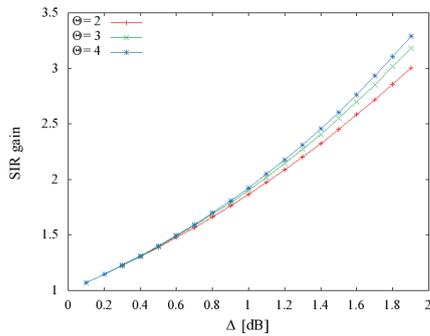


Fig. 3. SIR improvement following carrier sense threshold control with different values for the path-loss exponent

control are influenced by X , the ratio of the carrier sense threshold to the safety distance.

From Figure 2, we notice that adjusting the physical carrier sense of an interferer has a much more important impact than reducing its transmission power. Moreover, the SIR gain increases for lower values of X , when the difference between SF_r and CS_r becomes smaller.

The path-loss exponent θ also has an influence on the performance of carrier sense control. However, as it can be seen from Figure 3, its impact is marginal, specially for low values of CS_c . These minor differences suggest that an adaptive carrier sense mechanism does not need an extremely accurate characterisation of the radio channel and it can be simply based on the value of X .

D. Implementation Issues

The above analysis demonstrates that a proper solution for carrier sense control can be more efficient than the other approaches considered for congestion control in a vehicular environment. Moreover, there are two other strong arguments that support our idea.

First of all, there is an important difference in the methods needed for adjusting transmission power and physical carrier sense. While the former is a hardware-based operation, where a fine grained control of the radio unit is needed, the latter can be realised using a purely software technique.

The ETSI ITS framework [6] requires a granularity of 0.5 dB for power control, a performance that remains difficult to achieve for currently available IEEE 802.11 products [18]. Meanwhile, setting the carrier sense threshold to any value between CS_{min} and CS_{max} is pretty straightforward.

Second, zooming out from our interferer-based analysis, the power is controlled at transmission time by a vehicle with the goal of increasing the reception probability for other vehicles inside its safety range. However, it is impossible for the transmitter to know the current state of the channel at all the receivers. On the contrary, carrier sense control is a receiver-based mechanism and it can benefit from the knowledge a node has on itself.

Of course, a sensible problem could come from the fact that any modification in the functioning of the CCA must make the object of a revision of the IEEE 802.11 standard, and history showed that the propagation of this type of adaptation into real products is difficult. However, there is a general consensus regarding the necessity of advanced mechanisms for congestion control in vehicular networks [4], and their integration in the standard is already under way. As discussed above, the physical carrier sense has a deeper impact than other parameters in this area, and its implementation on real hardware is less complex.

E. Beaconing expiration probability

As we have seen, increasing the carrier sense range leads to an important gain in SIR . Moreover, we argued in Section IV that the VANET CCH is by definition exposed-nodes free, which means that the physical carrier sense does not need to find the optimal balance between hidden and exposed vehicles, like in classical MANETs. Therefore, an obvious question needs to be addressed: *If reducing the carrier sense threshold brings all these benefits, why not always use CS_{min} ?*

The answer to this question comes from another property of the vehicular environment we mentioned in Section IV, namely the possibility to have an expired beacon.

As it has been discussed in [7], a small number of expired CAMs have a positive influence on the beaconing reception probability, helping reduce the number of collisions. However, because of the capture effect, a collision is restricted to only a fraction of the potential receivers, while a dropped beacon is lost for all the neighbouring vehicles. Therefore, when the number of expired beacons increases over a certain threshold, the gain it brings in reducing the collisions can no longer compensate the loss it produces by not transmitting the CAMs.

In [7], the impact of the contention window on the probability of expiration is studied. However, the carrier sense range also plays a role in this phenomenon. Increasing the carrier sense range produces an increase in the number of sensed nodes, and therefore on the probability for a vehicle contending for channel access to consider the medium as occupied. Because the IEEE 802.11 back-off timer is decremented only when the medium is idle, this means that the time spent backing-off depends on the number of sensed nodes, hence on the carrier sense threshold. Moreover, including more vehicles

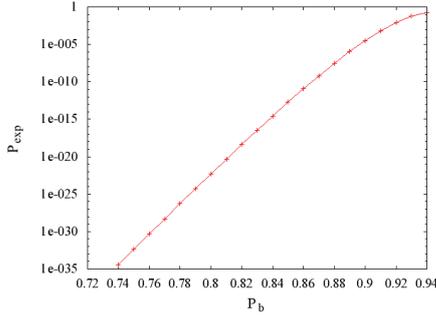


Fig. 4. Beaoning expiration probability for a contention window of 63 and a beaoning period of 1000 slots. Please notice the log-scale of the y-axis

on the carrier sense range does not only mean longer back-off, but it increases even the probability of having to enter the back-off mechanism.

A large CS_r can practically eliminate hidden nodes and, with it, the number of concurrent transmissions. However, by increasing the number of one-hop neighbours, it has the opposite effect on the number of simultaneous transmissions¹, as the probability of choosing the same transmission slot following a back-off period depends on the number of contending vehicles.

If we consider a beaoning period divided in T slots, a message expires if the following events occur simultaneously: *i*) the channel is busy when the beacon reaches the MAC layer and therefore the node randomly chooses a back-off b uniformly distributed between 0 and CW , and *ii*) the vehicle senses less than b idle slots in the following beaoning period.

Assuming that P_b is the probability that a node i , with a certain CS_r , senses the channel as busy during a slot, the probability $P_i(b)$ of having less than b idle slots in T consecutive slots is:

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

The expiration probability P_{exp} can be calculated as:

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

This dependency between P_{exp} and P_b can be observed in Figure 4. It is clear from this numerical example that even a minor modification of P_b triggers a significant reaction from P_{exp} . However, this dependence is circular, as the number of expired beacons also affects the probability of a busy slot. The analysis of the influence between CS_r , P_b and P_{exp} is very complex and in this paper we just use this theoretical ideas as a basis for the adaptive mechanism we describe next.

¹Simultaneous transmissions occur when two or more stations sense the medium idle and begin their transmission in the same physical slot. Meanwhile, concurrent transmissions do not begin exactly at the same time, but they superpose themselves on at least a slot

F. Adaptive physical carrier sense

The importance of physical carrier sensing on the performance of safety oriented vehicular networks emerges from all the points we discussed in this section. Moreover, our analysis suggests (and the simulation results presented in Section VI confirm this) that the optimal carrier sense range depends on the vehicular density.

In a sparse network, a large CS_r allows the reception of messages from vehicles situated farther away and increases the connection time. At the same time, in this scenario, the beaoning expiration probability and simultaneous transmissions are kept under control by the small number of neighbours. Nevertheless, when the network becomes denser, a low detection threshold can not sustain an efficient safety message delivery as a result of a high number of expired beacons or simultaneous transmissions.

With this in mind, we propose a mechanism for carrier sense control and evaluate its performance by an extensive simulation study whose results are presented in Section VI. We believe that such a mechanism is fully compatible with other proposed solutions like transmission power control or adaptive contention window and it could be a powerful complement for them in a more general congestion control framework.

Our idea is based on the native capacity of a vehicular network to measure the local node density by the means of beacons. By counting the number of messages received in a beaoning period, a vehicle has a close estimation of the number of neighbours. Moreover, safety beacons include location information and therefore the node can easily determine the vehicular density in its surroundings. To further increase the accuracy of this estimation, when calculating this density we only take into consideration the beacons received from inside the safety range, where the reception probability is the highest.

We already defined the limits for the carrier sense threshold, CS_{min} and CS_{max} . We now set two boundaries on the vehicular density, λ_{min} and λ_{max} . When the density estimated by the node, $\tilde{\lambda}$, is under λ_{min} , the vehicles uses CS_{min} . Also, if $\tilde{\lambda} > \lambda_{max}$, the vehicle sets its carrier sense threshold at CS_{max} .

In the interesting case, when $\lambda_{min} < \tilde{\lambda} < \lambda_{max}$, we decided for a simple linear dependence and CS_t is calculated as follows:

$$CS_t = CS_{min} + \frac{\tilde{\lambda} - \lambda_{min}}{\lambda_{max} - \lambda_{min}} (CS_{max} - CS_{min}) \quad (1)$$

Other local density estimation techniques, based for example on traffic flow theory [12] or on the sequence numbers of safety messages [19] could be used instead of this beaoning-based approach. Nonetheless, mechanisms relying upon traffic flow theory show low performance when vehicles are in a free flow state. On the other hand, using the sequence numbers from the CAMs is not compatible with the VANET security architecture, where vehicles are supposed to periodically change all their identifiers in order to preserve drivers' privacy [2]. Our solution, although very simple to implement, does not present any of these weaknesses.

TABLE I
VALUES FOR DIFFERENT PARAMETERS USED IN THE SIMULATION

Slot duration	$13\mu s$
DCF Interframe Space	$48\mu s$
PLCP Header Duration	$8\mu s$
OFDM Preamble Duration	$32\mu s$
Minimum Contention Window	7
Transmission Power	$33dBm$
Noise Level	$-98dBm$
Beaconing Data Rate	$6Mb/s$
PLCP Header Data Rate	$3Mb/s$
SIR required to decode beacon	$10dB$

VI. SIMULATION RESULTS

A. Framework and Methodology

In order to study the influence of the physical carrier sense in VANETs and the efficiency of the proposed adaptive mechanism, we used the open-source Java in Simulation Time (JiST) framework and its Scalable Wireless Ad hoc Network Simulator (SWANS) package [20]. The JiST/SWANS simulator has been validated against equivalent models from other largely-used simulators in [21], a study that also points out its excellent computation performance.

In this discrete event simulator, each Java object represents an entity and it has the capacity to interact and synchronise with other objects. The IEEE 802.11 MAC entity used in this study is modelled using a state machine whose transitions are determined by the interactions with two other entities (Radio and Net). The MAC object is by default *idle* and, when a message is passed by the Net, the MAC entity verifies the state of the Radio. If the energy measured by the Radio object is under a certain threshold, the MAC moves in a *timer* state for the duration of an inter-frame space. If the Radio remains idle during this timing period, the MAC switches to a *transmitting* state and the message is delivered to other MACs using a Field entity. If the Radio object declares the channel busy whether at the initial verification or during the timer state, the MAC entity makes a transition to a *backoff* state where it remains until the Radio entity reports the corresponding number of idle slots. At this point, the MAC goes directly in the transmitting state and the message is passed to the Field entity. From any state except the transmitting one, the MAC object can switch to a *receiving* state if the Radio entity considers that a message can be correctly decoded based on the energy level of the signal. A received message is transmitted to the Net entity and the MAC returns in its initial state. Concerning the parameters of the MAC object, the values proposed in the IEEE 802.11p amendment [3] are used, with the exception of the receiver sensitivity (the equivalent of the carrier sense threshold) that makes the object of our study. Also, every vehicle sends safety beacons with a frequency of 10Hz and the CCH is monitored permanently by all the nodes. The most important values used in the simulation can be found in Table I.

A macroscopic car-following model, the Street Random

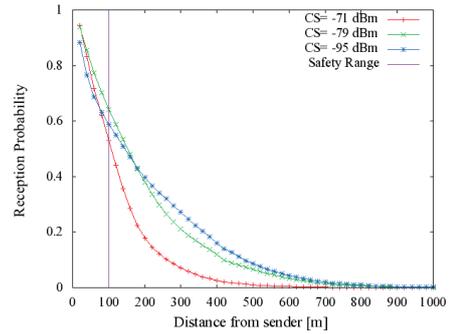


Fig. 5. Beaconing reception probability as a function of the distance from the sender for several carrier sense thresholds. The mean vehicular density in this case is 35 veh/lane/km and the safety range of 100m is also shown on the figure. The 95% confidence interval has about the same size as the symbols and has not been included for visibility purposes

Waypoint (STRAW) [22], produced realistic vehicular movement on real maps extracted from the U.S. Census Bureau's TIGER database. The STRAW vehicular mobility model is designed using a leader-follower logic. If the distance between a car and the next vehicle on the lane is larger than a certain threshold, the car movement is described only by its maximum speed and acceleration. When the distance to the vehicle in front decreases under the threshold, the follower starts decelerating until it matches the speed of the next car. When a car accelerates, its follower will do the same thing until it reaches its own maximum speed. In order to eliminate any bias introduced by a certain road topology, we repeated the simulations using three different maps. Every point in the figures discussed in this section is the result of a total of 90 runs, more exactly 30 runs on each road topology. We concentrate our study on medium and high vehicular density with a mean density between 25 and 50 vehicles/lane/km, but the local density in every scenario is very heterogeneous and it depends on road type and intersections.

Because modelling radio propagation in an urban vehicular environment is still a matter of debate in the VANET community, we focused on highway scenarios, where propagation followed a probabilistic model with shadowing in which the fast fading component depends on the number of neighbouring vehicles [23].

B. Fixed Physical Carrier Sense

As we have discussed in Section V, an efficient physical carrier sense needs to find a trade-off between interference and transmission opportunities. We therefore begin our simulation study with an analysis of the impact of the carrier sense threshold on the beaconing reception probability. For three different mean vehicular densities (25 veh/lane/km, 35 veh/lane/km and 45 veh/lane/km) we measure the beaconing reception ratio as a function of the distance from the sender while varying CS_t between $-95dBm$ and $-55dBm$.

We would like to point out that the noise level in our simulations peaks at $-98dBm$, and we consider a signal-to-

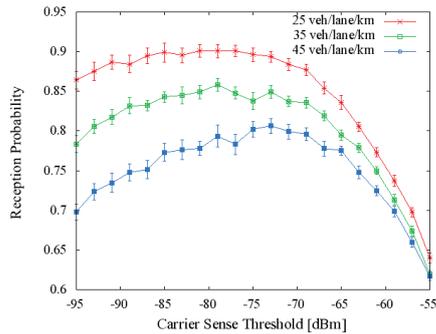


Fig. 6. Beacons reception probability as a function of the carrier sense threshold for different vehicular densities and using a safety range of 50m. The 95% confidence intervals are also shown

noise ratio of at least $3dB$ to be necessary for decoding the PLCP header, hence the minimal value of $-95dBm$ for CS_t . This noise level can be considered relatively high, and the VANET physical channel is indeed very noisy, as it has been confirmed by experimental studies [10].

In Figure 5 we show the results obtained for a vehicular density of 35 veh/lane/km and for three different carrier sense thresholds ($-95dBm$, $-79dBm$ and $-71dBm$). As expected, in all the cases the beacons reception probability decreases with the distance from the sender. However, if we compare what happens when CS_t is modified from $-95dBm$ to $-79dBm$, we observe that the reception ratio increases at a distance of less than 200m from the sender and it decreases beyond this distance.

The explanation of this behaviour can be found in the analysis we made in Section V. A higher CS_t reduces the number of sensed vehicles, and therefore the probability to consider the medium as busy. This allows more transmission opportunities to every node and reduces the number of simultaneous transmissions. However, on the negative side, because the carrier sense range is reduced, the degree of spatial reuse is increased and therefore concurrent transmission can occur from closer vehicles. This has little effect in the immediate neighbourhood due to the capture effect, but produces collisions at higher distances.

This phenomenon is exacerbated by further increasing CS_t (from $-79dBm$ to $-71dBm$ in Figure 5). As the physical carrier sense covers less and less space, the interferers get closer to the sender and the SIR increases, reducing the beacons reception probability even for closely situated vehicles.

In order to better understand the influence of the carrier sense threshold on the reception of safety messages, in Figure 6 we show the beacons reception ratio inside the safety range as a function of CS_t for different vehicular densities. We can notice that the number of received beacons slowly increases with CS_t , it reaches an optimal point and then drops quite sharply. Two other important observations need to be made at this point, challenging the current view of using the minimum receiver sensitivity as a carrier sense threshold [6] and arguing in favour of a more elaborate solution.

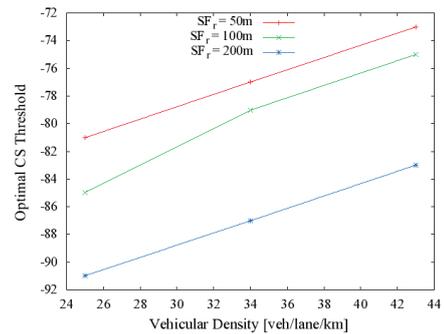


Fig. 7. Optimal carrier sense threshold as a function of the vehicular density for different values of the safety range

First of all, the difference between the peak value of the reception probability and the one obtained using the lowest possible value for CS_t ($-95 dBm$ in this case) can be significant, reaching almost 10% in the scenario with the highest density. Second, the optimal carrier sense threshold varies with the vehicular density, increasing when the number of neighbours becomes larger. This confirms the conclusions formulated in Section V and shows the necessity of an adaptive mechanism for physical carrier sense control.

However, before analysing the performance of such a mechanism, we need to address briefly the influence of the safety range in our model. The results from Figure 6 are obtained for $SF_r = 50m$ and, while the general trend remains the same for other values of SF_r , the optimal threshold varies with the size of the safety area. This was already suggested by the data presented in Figure 5, where we can notice the role of the safety range.

Therefore, in Figure 7 we show the best carrier sense threshold for different vehicular densities and safety ranges. We can notice that CS_t needs to be lowered if the goal is to have a large safety range. However, it is important to understand that, by doing this, the average reception probability inside this larger SF_r is increased but more beacons are missed by really close vehicles.

In the light of this conclusion, and based on similar observations on transmission power control [11], it is clear that the conception of a vehicular congestion control framework should begin with a precise definition of the safety area and its requirements on beacons reception ratio.

C. Adaptive Physical Carrier Sense

The simulations discussed above use the same carrier sense threshold for all the nodes in the network. However, as we mentioned, the local vehicular density in the studied scenarios is not at all uniform.

A direct consequence of this phenomenon is the slow increase in reception probability observed on the left side of the curves in Figure 6. Because some zones on the map actually present a much lower (higher) density than the average, the optimal value of CS_t is not as distinguishable as expected. However, we believe that in a homogeneous environment, the

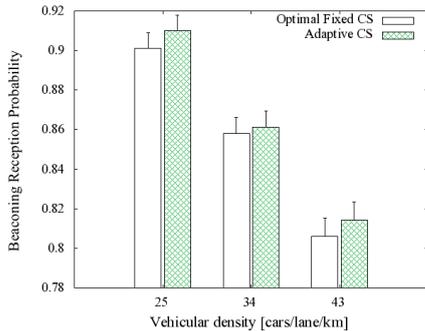


Fig. 8. Beacons reception probability for the best fixed carrier sense threshold and the proposed adaptive mechanism for three different vehicular densities. The 95% confidence intervals are also shown

optimal point would be more marked and the monotonicity more pronounced.

This observation leads us to the necessity of an adaptive mechanism as the one described in Section V. If the optimal carrier sense threshold depends on the vehicular density and this density is highly variable in a VANET, only a mechanism capable of efficiently adjusting CS_t can cope with the requirements of safety applications. In this part of the paper, we focus on the study of the mechanism we described in the previous section. In a preliminary phase, we determine the parameters needed to calculate CS_t in Eq. 1.

As discussed above, the minimum value of the carrier sense threshold is $CS_{min} = -95dBm$ because of the ambient noise level. The superior limit CS_{max} depends on the safety range we intend to cover. The results provided below are issued from simulations with $SF_r = 100$, which led us to a value of $CS_{max} = -65dBm$. The vehicular density λ is estimated by using the beacons received from inside this safety range and the two thresholds were $\lambda_{min} = 10veh/km$ and $\lambda_{max} = 300veh/km$.

In Figure 8 we compare the beacons reception probability obtained for the optimal fixed value of CS_t with the reception ratio of the adaptive mechanism. We can notice that adjusting the carrier sense threshold gives slightly better results regardless of the vehicular density. However, the main strength of the mechanism does not come from this marginal improvement. The power of the adaptive approach becomes clear when we relate these results to those in Figure 7. What we notice is that the optimal values for CS_t are $-85dBm$, $-81dBm$, and $-75dBm$ respectively for the three studied vehicular densities, while on the other hand the carrier sense control mechanism is the same in all the scenarios.

A more detailed analysis is given in Table II, where the reception probability of the adaptive mechanism is compared with the one achieved using three fixed thresholds. We can notice that it always exists a fixed CS_t with a result close to the proposed solution. However, any CS_t achieves this performance only in a particular scenario and it can not compete with the adaptive mechanism under all these different vehicular densities.

TABLE II
BEACONING RECEPTION PROBABILITY FOR FIXED AND ADAPTIVE CS THRESHOLDS

Vehicular Density	Adaptive Mechanism	$CS_t = -95dBm$	$CS_t = -85dBm$	$CS_t = -75dBm$
25 veh/lane/km	91.02	86.42	89.88	88.64
35 veh/lane/km	86.12	78.38	84.27	81.81
45 veh/lane/km	81.41	69.76	76.32	80.20

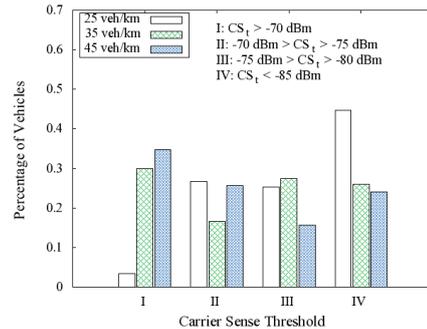


Fig. 9. Distribution of the carrier sense threshold determined by the adaptive mechanism under different average vehicular densities

We would also like to point out that, for $CS_t = -95dBm$, the reception ratio is considerably lower than the one obtained by adjusting the physical carrier sense, reaching more than 10% in the case of 45 vehicles/lane/km. This shows once again the limits of using the receiver sensitivity for carrier sensing in VANETs.

The behaviour of the adaptive carrier sense mechanism is further analysed in Figure 9, where we show the distribution of CS_t for different node densities. The heterogeneity of the local density is clearly demonstrated by these results, and we can see that the values of the carrier sense threshold are distributed over the entire interval. As expected, this local density increases when the average density increases and nodes switch from what we called *category III* or *IV* (CS_t under $-75dBm$) to the categories with the highest density. It is interesting to notice that the percentage of vehicles belonging to the lowest density category remains high, a sign that unsaturated roads exist even under heavy vehicular traffic.

This section has thoroughly studied the adaptive mechanism described in Section V in the case of VANET safety applications, showing that it leads to an increased performance of the MAC layer. More generally, we argue that the physical carrier sense is a critical parameter in a vehicular network and it plays an important role on the reception ratio of safety messages.

VII. CONCLUSION

Because of the long-range nature of V2V communications and the highly variable density of the vehicular environment, congestion control is an essential function of the MAC layer in VANETs. This problem becomes even more important in the case of safety applications as a consequence of the broadcast

nature of this type of messages.

The IEEE 802.11 standard appears to be the best solution for access control in a future vehicular network. Nevertheless, this protocol has been designed to function in WLANs and optimised for multimedia applications. It is more and more clear that its MAC layer mechanisms need to be adapted to the challenges of the harsh vehicular environment. The IEEE 802.11p amendment [3] was a first step in this direction, but sadly it concentrated mostly on physical layer issues, neglecting the influence of the MAC parameters.

In this paper, we investigate the impact of physical carrier sensing, the building block of CSMA techniques, on the reception probability of beacons in a safety area around the transmitter. First, we show that the carrier sense threshold has a higher influence on the interference level than the transmission power. We then discuss the antagonism between increasing the signal-to-interference ratio and reducing the expiration probability of a beacon. Our results show that the optimal carrier sense threshold depends on the vehicular density and therefore we propose a mechanism to control the physical carrier sense in VANETs. This solution proves to be both simple and efficient, bringing a significant improvement of the reception ratio for vehicles in the safety range. Moreover, we consider this mechanism to be fully compatible with other approaches for congestion control and its integration in a larger framework appears rather straightforward.

We would like to point out that this adaptive physical carrier sense mechanism has been designed with the requirements and properties of safety applications in mind and it might not be suitable for applications with different purposes (entertainment, comfort). However, we consider that the VANET MAC layer should be optimised with safety messages in mind, even if this reduces the quality of the non-safety applications. An interesting possibility in this case could be to use slightly modified versions of the IEEE 802.11 protocol on the CCH and SCH, creating ideal conditions for both safety and non-safety communications.

In our future work, we plan to investigate the relationship between physical carrier sense, transmission power and minimum contention window in order to merge all these solutions under the control of a single entity. We will also study the impact these mechanisms have on DENs, emergency messages with spatial and temporal requirements even more stringent than beacons.

REFERENCES

- [1] A. Minino, J. Xu, K. Kochanek, *Deaths: Preliminary Data for 2008*, U.S. National Vital Statistics Report, vol. 59, no. 2, December 2010
- [2] P. Papadimitratos, A. de la Fortelle, K. Evenssen, R. Brignolo, S. Cosenza, *Vehicular Communication Systems: Enabling Technologies, Applications, and Future Outlook on Intelligent Transportation*, IEEE Communications Magazine, vol.47, no.11, pp. 84-95, November 2009
- [3] The Institute of Electrical and Electronics Engineers, *IEEE Standard for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 6: Wireless Access in Vehicular Environments*, July 2010
- [4] A. Brakemeier, *WG4 Standardization Activities*, 2nd Annual Workshop of the ETSI Technical Committee on Intelligent Transportation Systems, Venice, February 2011
- [5] R. Stanica, E. Chaput, A.-L. Beylot, *Comparison of CSMA and TDMA for a Heartbeat VANET Application*, Proceedings of the 45th IEEE International Conference on Communications (ICC 2010), pp. 1-5, Cape Town, May 2010
- [6] The European Telecommunications Standards Institute, *ETSI ES 202 663 V1.1.0 - Intelligent Transport Systems (ITS) - European Profile Standard for the Physical and Medium Access Control Layer of Intelligent Transport Systems Operating in the 5 GHz Frequency Band*, January 2010
- [7] R. Stanica, E. Chaput, A.-L. Beylot, *Enhancements of IEEE 802.11p Protocol for Access Control on a VANET Control Channel*, Proceedings of the 46th IEEE International Conference on Communications (ICC 2011), pp. 1-5, Kyoto, June 2011
- [8] R. Schmidt, T. Leinmuller, E. Schoch, F. Kargl, G. Schafer, *Exploration of Adaptive Beaconing for Efficient Intervehicle Safety Communication*, IEEE Network, vol. 24, no. 1, pp. 14-19, January 2010
- [9] Y. Mertens, M. Wellens, P. Mahonen, *Simulation-based Performance Evaluation of Enhanced Broadcast Schemes for IEEE 802.11-based Vehicular Networks*, Proceedings of the 67th IEEE Vehicular Technology Conference (VTC Spring 2008), pp. 3042-3046, Singapore, May 2008
- [10] F. Bai, D. Stancil, H. Krishnan, *Toward Understanding Characteristics of Dedicated Short Range Communications (DSRC) from a Perspective of Vehicular Network Engineers*, Proceedings of the 16th Annual International Conference on Mobile Computing and Networking (MOBICOM 2010), pp. 329-340, Chicago, September 2010
- [11] M. Torrent-Moreno, J. Mittag, P. Santi, H. Hartenstein, *Vehicle-to-Vehicle Communication: Fair Transmit Power Control for Safety-Critical Information*, IEEE Transactions on Vehicular Technology, vol. 58, no. 7, pp. 3684-3703, September 2009
- [12] M. Artimy, *Local Density Estimation and Dynamic Transmission-Range Assignment in Vehicular Ad Hoc Networks*, IEEE Transactions on Intelligent Transportation Systems, vol. 8, no. 3, pp. 400-412, September 2007
- [13] C. Huang, Y. Fallah, R. Sengupta, H. Krishnan, *Adaptive Intervehicle Communication Control for Cooperative Safety Systems*, IEEE Network, vol. 24, no. 1, pp. 6-13, January 2010
- [14] R. Schmidt, T. Leinmuller, B. Boddeker, G. Schafer, *Adapting the Wireless Carrier Sensing for VANETs*, Proceedings of the 7th International Workshop on Intelligent Transportation (WIT 2010), pp. 1-6, Hamburg, March 2010
- [15] M. Brodsky, R. Morris, *In Defense of Wireless Carrier Sense*, Proceedings of the 24th ACM SIGCOMM Conference on Data Communication (SIGCOMM 2009), pp. 147-158, Barcelona, August 2009
- [16] T. Kim, H. Lim, J. Hou, *Understanding and Improving the Spatial Reuse in Multihop Wireless Networks*, IEEE Transactions on Mobile Computing, vol. 7, no. 10, pp. 1200-1212, October 2008
- [17] Y. Yang, J. Hou, L. Kung, *Modeling the Effect of Transmit Power and Physical Carrier Sense in Multi-Hop Wireless Networks*, Proceedings of the 26th IEEE International Conference on Computer Communications (INFOCOM 2007), pp. 2331-2335, Anchorage, May 2007
- [18] F. Ben Abdesslem, L. Iannone, M. Dias de Amorim, K. Kabassanov, S. Fdida, *On the Feasibility of Power Control in Current IEEE 802.11 Devices*, Proceedings of the 4th IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom 2006), pp. 1-5, Pisa, March 2006
- [19] L. Yang, J. Guo, Y. Wu, *Channel Adaptive One Hop Broadcasting for VANETs*, Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems (ITSC 2008), pp. 369-374, Beijing, October 2008
- [20] R. Barr, Z. Haas, R. van Renesse, *JiST: An Efficient Approach to Simulation using Virtual Machines*, Software - Practice & Experience, vol. 35, pp. 539-576, May 2005
- [21] E. Weingartner, H. vom Lehn, K. Wehrle, *A Performance Comparison of Recent Network Simulators*, Proceedings of the 44th IEEE International Conference on Communications (ICC 2009), pp. 1-5, Dresden, June 2009
- [22] D. Choffnes, E. Bustamante, *An Integrated Mobility and Traffic Model for Vehicular Wireless Networks*, Proceedings of the 2nd International Workshop on Vehicular Ad Hoc Networks (ACM VANET 2005), pp. 69-78, Cologne, September 2005
- [23] D. Dhoutaut, A. Regis, F. Spies, *Impact of Radio Propagation Models in Vehicular Ad Hoc Networks Simulations*, Proceedings of the 3rd International Workshop on Vehicular Ad Hoc Networks (ACM VANET 2006), pp. 40-49, Los Angeles, September 2006