Boquet, Guillem; Pisa, Ivan; López Vicario, José; [et al.]. «Adaptive beaconing for RSU-based intersection assistance systems : Protocols analysis and enhancement». Vehicular Communications, Vol. 14 (October 2018), p. 1-14. DOI 10.1016/j.vehcom.2018.08.003

Adaptive Beaconing for RSU-based Intersection Assistance Systems: Protocols Analysis and Enhancement

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Abstract

Current envisaged cooperative vehicular applications require moderate to severe requirements of reliability and latency according to their purpose. Dedicated Short Range Communications (DSRC)-based applications mainly rely on the periodic exchange of information that under certain circumstances may cause congestion problems on the communication channel obtaining unreliable and outdated information at application level. Adaptive beaconing protocols adapt transmission parameters to different criteria such as the channel load and application requirements to improve the overall performance of the vehicle network. Nevertheless, it has not been determined yet if the information disseminated by these protocols is suitable enough for the implementation of specific applications, e.g., Road Side Unit (RSU)-based Intersection Assistance Systems (IAS) like Intersection Collision Risk Warning (ICRW). In this context, we first analyze the network behavior in a realistic simulated intersection area where probability of packet reception becomes difficult to predict and models become highly complex. In that scenario, we present a critical analysis on the performance of current EU and US decentralized congestion control protocols while their performance is evaluated with respect to tracking accuracies required by Intelligent Transportation System (ITS) applications. Results obtained lead us to conclude that adaptation criteria of beaconing protocols is not able to support different safety applications at the same time, that is, there is a tradeoff in the selection of such criteria between enhancing applications supporting vehicles or infrastructure. In that sense, we discuss and provide novel adaptation criteria (Intersection Assistance State Machine, IASM) to improve the performance of beaconing protocols towards assisting safety RSU-based IAS. Finally, we propose and validate through simulations a novel beaconing protocol (Intersection Assistance Protocol, IAP) that improves performance over studied protocols.

Keywords: DSRC, Vehicular Networks, Adaptive Beaconing, RSU, Vehicle to Infrastructure, ITS applications, Intersection Assistance Systems, Intersection Collision Risk Warning
2010 MSC: 00-01, 99-00

1. Introduction

In the new envisaged paradigm of vehicular communications, vehicular safety applications that are to be implemented in the coming years have strict requirements in terms of reliability and latency due to the critical nature of their mission. In this context, information disseminated by vehicles within Vehicular Ad-hoc NETworks (VANETs) must be accurate, continuous and up-to-date to sustain those applications. To begin with, information exchange through latencies of the order of 100 ms is needed to facilitate the so-called *cooperative awareness* among vehicles and to be able to meet critical safety requirements. Under the current framework, Dedicated Short Range Communications (DSRC) enabled safety applications mainly rely on the periodic exchange of safety information between vehicles and infrastructure using Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Consequently, Cooperative Awareness

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Messages (CAM) are broadcasted on the standardized ETSI Intelligent Transport Systems (ITS)-G5 Control Channel (CCH) [1] in Europe while in the same way Basic Safety Messages (BSM) are used by US standardization bodies. *Adaptive beaconing protocols* are proposed by standardization bodies and researchers to improve the overall network performance, mainly adapting frequency and power transmission to different criteria such as channel load, traffic density, dynamics of vehicles or application requirements, to name a few. In that sense, several authors put an effort into summarize adaptive beaconing in three surveys found at [2], [3] and [4] while, e.g., the current European Decentralized Congestion Control (DCC) is standardized in [5] and U.S. standard in [6] (hereafter referred as USA DCC).

Intersections are one of the main scenarios mentioned in VANET literature where scalability is a major problem because of its unique and severe characteristics that critically affect packet reception. E.g., Intersection Collision Risk Warning (ICRW) application is considered as primary road safety application to detect possible vehicle collisions in road intersections relying on the processing of CAMs and Decentralized Environmental Notification Messages (DENM). Despite this, it has not been determined yet if information disseminated by the state-of-the-art beaconing protocols is suitable enough for the implementation of specific Road Side Unit (RSU)-based applications or to what extent they can sustain Intersection Assistance Systems (IAS) [7]. In that sense, some questions arise such as:

- Is designed criteria based on V2V metrics of state-of-the-art beaconing protocols diminishing or enhancing performance of RSUs?
- What is the optimal design criteria that maximizes performance for RSU-based applications?
- When and how adaptation criteria of beaconing protocols must be adapted to sustain different applications or scenarios?

In this context and to the best of our knowledge there is no study of the impact of the protocols on the position accuracy from the Point-Of-View (POV) of a RSU supporting IAS. Likewise, no adaptation criteria has been proposed to improve the performance of beaconing protocols towards IAS for different adaptation parameters besides beacon rate. Thus, in this paper we analyze VANET behavior in a high dense intersection area where probability of packet reception becomes difficult to predict and models become highly complex. Then, we evaluate the performance of current DCC protocols in a realistic simulation environment (Veins [8]) with respect to position accuracies required by ITS applications from a RSU's POV to see if information provided by the protocols is accurate enough to support IAS. Consequently, linking the analysis and the evaluation helps us to understand how the system and different approaches behave and to extract information on how to maximize position accuracy for RSU-based IAS from the information disseminated by the protocols on the shared channel. Finally, we propose and validate an enhanced intersection assistance protocol build on novel criteria based on vehicle dynamics and derived from the lessons learned. Summarizing, the main contributions of this paper are:

- a critical analysis of the position error behavior and current DCC protocols performance in an intersection area from the POV of a RSU,
- new adaptation criteria (named IASM) for communication parameters based on vehicle dynamics to enhance protocol's performance towards IAS
- and a novel beaconing protocol (named IAP) to enable safety RSU-based IAS.

The rest of the article is organized as follows: adaptive beaconing related work is discussed in Section 2. Then, the scenario considered is described under Section 3. The position error behavior analysis is derived in Section 4. Protocols studied are described and discussed under Section 5. Novel adaptation criteria is proposed, discussed and evaluated in Section 6. An intersection assistance protocol is presented and also evaluated in Section 7. Finally, conclusions are exposed in Section 8.

2. Related work

Adaptive beaconing protocols can be divided depending on their approach into message frequency control, transmit power control or hybrid based approaches. Also, depending on their aim, they can be divided into *congestion control protocols*, those aiming to control channel congestion, and *awareness control protocols*, those that aim to fulfill application requirements.

The most relevant trend being followed is to adapt beacon frequency as a function of channel load so as not to exceed a threshold considered optimal with respect to the throughput of the channel, which in turn leaves capacity to receive messages that promptly inform of specific events like DENM [9]. In addition, the vast majority of them are designed based on the fairness postulation, i.e., all vehicles must achieve the same performance and the same opportunities within the network. One of these examples is LIMERIC [10] that jointly with PULSAR [11] is currently considered by ETSI [12] to be included in the ITS-G5 vehicular standard together with their DCC mechanism [5] and CAM triggering conditions [1]. However, some challenges still remain unresolved, for instances [13] stated that moderately adaptive approaches like the ETSI's DCC do not perform well considering network dynamics caused by shadowing, so they proposed DynB which aims to be stable under heavy network congestion and to be able to quickly react to density changes. Besides, [14] pointed out that traditionally awareness control protocols have been designed and evaluated separately from congestion control protocols. Therefore, [14] proposed INTERN which integrates a congestion control process as a function of the channel load and an awareness control process which aims to adapt the power to the minimum necessary so that the messages are received with certain reliability at an individual warning distance. Also, [15] proposed an awareness control protocol that provides different levels of awareness-quality at different ranges while accounting for *correlated packet collisions*. Despite showing great performance in their function as demonstrated by their authors, none of these relevant protocols take into account the position accuracy at the application level, which is a relevant metric for most safety applications. In that sense, some protocols have been proposed which take into account tracking accuracies using a trajectory prediction approach, e.g., [16, 17, 18, 19]. Being [18] the one recently adopted as the official USA DCC in [6] which correlates communication behavior with tracking error stochastically sending packets when the suspected error of neighbors grows above a defined threshold. [19] used a trajectory prediction approach and a RSU to allocate channel resources according to tracking requirements from vehicles. Authors of [20] provided a congestion control method for road intersections using feedback from a RSU about optimal beacon rate and backoff slots previously computed offline. On another hand, authors of [21] proposed a situation-based rate adaptation scheme that allows temporary exceptions for endangered vehicles to use more than the equal fair share of the channel. Also, same authors proposed in [7] another beacon rate adaptation algorithm relying on their Intersection Collision Probability metric while stating that current state-of-the-art congestion control mechanisms are not able to support IAS adequately. Nevertheless, neither of the aforementioned approaches take into account V2I application metrics and some are not optimal at application level since each vehicle has different needs to meet application's requirements at each instant of time [22]. Also, they do not take into account interference levels from other channels which is an important metric in beacon reception as pointed out in [23, 24]. In that sense, taking advantage of the multi-channel environment defined in the standard, [24] proposed an adaptive relay selection scheme in which the V2V and V2I links switch transmission mode either to improve the transmission rate or to reduce their interference with other links when their QoS requirements have been satisfied.

3. Scenario and system description

Intersection areas are characterized for unique and severe conditions where IAS are meant to detect hazardous situations and manage traffic in an intersection area to reduce vehicle related problems like road safety, pollution, traffic congestion and transport costs. Reliable awareness becomes of high relevance for IAS when trying to solve those problems efficiently and roadside ITS stations (IT-S) standardized by ISO [25] and ETSI [26] are designed to help in those severe situations. RSU-based intersection services considered by ETSI are many such as [27]: collision warning, wrong way driving, traffic condition warning, signal violation warning, traffic light management and optimal speed advisory, traffic information and recommended itinerary. Besides, ICRW is the most relevant application currently under standardization in [28]. In such a heterogeneous framework, applications' needs derive in very different required position accuracies that can be grouped into three scales: low (10-20 or even 30 m), medium (1 to 5 m), and high (a meter or submeter). [29] matches some ITS applications to the

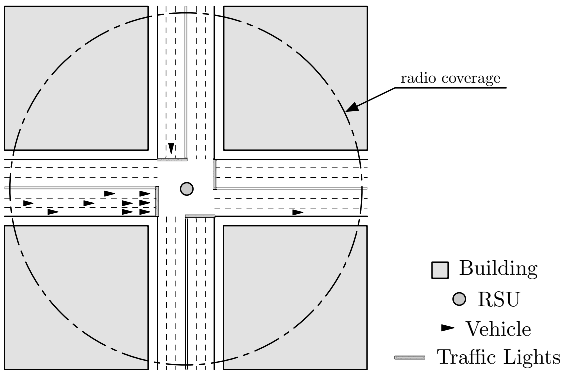

Figure 1: Urban traffic scenario in an intersection area obstructed by buildings (Scenario O).

aforementioned accuracy scales, hence, for the rest of this article results and figures would be compared to those.

3.1. Intersection model

An intersection simulation environment scenario has been designed and built in order to test the performance of protocols for IAS. The scenario used for the analysis and simulations is described below as it is necessary to understand the following sections.

Topology and network. The selected scenario is an intersection with a deployed RSU ITS-S running ICRW that requires real-time monitoring of all vehicles with a short end-to-end latency time in order to provide timely warning to drivers. Fig. 1 shows the topology of the scenario which consists of an intersection regulated by traffic lights of four 500 m long roads with six lanes each, three in each direction. Two scenarios have been considered to account for worst and best situations of vehicles sensing each other: (O) an intersection area fully obstructed by buildings (Fig. 1) and (Ø) the same unobstructed area where LOS conditions exist between vehicles of different roads. In a typical installation the RSU will be mounted in the intersection with one omni-directional antenna in the middle of the intersection [30]. The antenna has to cover all the approaching lanes, thus, the RSU is located in the middle of the intersection maximizing Line-Of-Sight (LOS) at a height of 5 m. We assume that all nodes in the network communicate according to the IEEE 802.11p and ITS-G5 standard. CAMs are periodically broadcasted by vehicles on the CCH with a Best Effort Access Category (AC_BE) [31], which results in the listening period (Arbitration Inter-Frame Space, AIFS) and Contention Window (CW) mentioned in Table 1 together with other relevant IEEE 802.11p PHY and MAC default parameters.

Table 1: IEEE 802.11p PHY & MAC parameters.

Parameter	Value
ITS-G5 Channel	CCH (5.9 GHz)
Bandwidth	10 MHz
Transmission Power (P_t)	23 dBm
Sensitivity (CCA_{th})	-95 dBm
Data Rate (R)	6 $Mbps$
Beacon Size (L)	300 B
$AIFS$, CW_{min}	110 μs, 15 $slots$

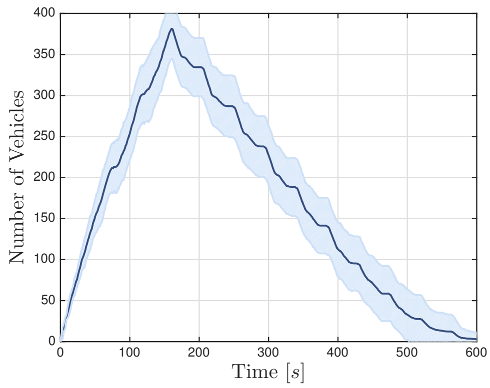

Figure 2: Average number of vehicles with two times standard deviation within the coverage area of the RSU.

Vehicle mobility. Three different vehicle classes were generated with different dynamics, lengths and probabilities of appearance because these values affect the behavior of vehicles. Vehicle speeds were normally distributed to achieve realistic car following behavior. Table 2 values result in a speed distribution where 95% of the vehicles drive between 80% and 120% of the maximum speed allowed. We focus only on high density traffic emulating realistic rush hours because similar densities where simulated in [32] under the same scenario showing unreliable position accuracies. Fig. 2 shows the evolution of the vehicle number across time in a road area of 19.5 km^2. Please note that vehicles stop appearing at $t = 160$ s. All vehicles move according to the default SUMO [33] *Krauss* driver model with a time step length of 0.01 s. Vehicle arrival process for each road was modeled using a $\mathcal{B}(160, 0.25)$ process with a trial every second which approximates a Poisson distribution.

Table 2: Percentage (ρ) of vehicle type together with their length (L), acceleration (a), deceleration (d), and max speed (v_{max}).

Class	ρ	L $[m]$	a $[m/s^2]$	d $[m/s^2]$	v_{max} $[m/s]$
A	0.29	4	2.6	4.6	$\sim \mathcal{N}(44, 0.1)$
B	0.7	5	2	4.2	$\sim \mathcal{N}(33, 0.1)$
C	0.01	15	1	3	$\sim \mathcal{N}(22, 0.1)$

Wireless channel. The radio signal attenuation is modeled as a function of path, shadowing and fading effects. The experimentally validated Two-Ray Interference model in [34] is used to capture radio signal attenuation over distance and ground reflection effects because transmissions experience either constructive or destructive interference with its own ground reflection. The small scale and the large-scale fading are both represented by the Nakagami model with $m = 3$ for distances between 0 and 50 m, approximating Rician distributed channel conditions where a LOS path exists. $m = 1.5$ from 50 to 150 m and $m = 1$ for distances above 150 m like in [35]. Also, as there is a substantial impact of shadowing on the performance of congestion control protocols, radio shadowing effects caused by other vehicles and by buildings are modeled using default [13] and [36] models, respectively.

4. VANETs in intersection areas

We critically evaluated the performance of static beaconing in the simulated environment of Section 3 as deriving an analytical model of the error is complex [37]. Nevertheless, we derived an approximation to understand which are the main contributions affecting the behavior of the system accounting for vehicle's dynamics as well as the state of the communication channel. This allows us to understand (i) why some protocols perform better than others and (ii) how to adjust the parameters or derive new protocols towards IAS.

Hereafter it is assumed that the positioning of the vehicle is error free because we are interested in the error contribution from the performance of the protocols not in the positioning of the node itself. A fix-period beaconing of 100 ms was selected for the analysis as was first suggested by ETSI and SAE for cooperative awareness applications. The main metric analyzed in this section is the position accuracy because safety applications have strict requirements in terms of awareness and latency. It is defined as the error between the current vehicle's physical position and the last reported position to the RSU which implicitly entails the requirement of latency.

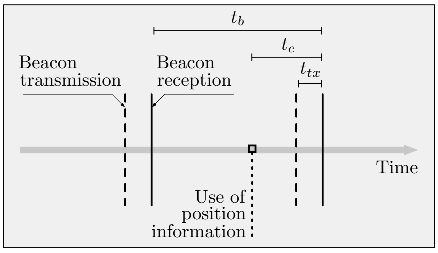

Figure 3: Relation of relevant time parameters that determine the position error of a vehicle at the RSU. The maximum position error would occur when $t_e \to 0$, i.e., when the position of the vehicle is used to compute the error right before receiving the next beacon.

4.1. Error behavior model

Firstly, assuming ideal channel conditions, a constant vehicle speed v and uniformly distributed events of looking up the position during a fix beaconing interval t_b, the average position error at the receiver can be expressed as half the minimum plus the maximum position errors as [22]:

$$\bar{e} = v\ t_{tx} + \frac{v(t_b - t_e)}{2}, \tag{1}$$

where t_{tx} is the transmission time of the beacon and t_e is the time between the position error computation at the RSU and the next beacon reception, as illustrated in Fig. 3. However, the reception of the next beacon depends on several factors as a packet may not be received due to low SINR (i.e., collision) or low SNR (i.e., reception power below receiver's sensitivity). This is illustrated in Fig. 4 where the average position error at the RSU increases as the average speed of vehicles drops while congestion occurs, contrary to (1). Hence, considering this and neglecting the error contribution of t_{tx} (cm-order), the maximum position error of a vehicle at time instant k can be estimated as:

$$\hat{e}_k = v_k E\{t_b{'}\}, \tag{2}$$

where t_b' is a random variable representing the actual time between two consecutive beacons. Its expectation can be expressed as the number of consecutive tries I needed to receive a beacon multiplied by the beacon interval, $E\{t_b'\} = E\{I\}t_b$. Now, assuming that packet loss is independent across time, the expected number of consecutive tries can be expressed as:

$$E\{I\} = \sum_{i=1}^{\infty} i\ P_{col}^{(i-1)}(1 - P_{col}) \approx \frac{1}{PDR}. \qquad (3)$$

Note that in the scenario the probability of a collision can be estimated as $P_{col} \approx 1 - PDR$ because packet loss due to SNR represent in average less than 0.6% of the total packet loss (Fig. 5).

Unfortunately, (3) is not valid in most complex vehicular situations because of the fast varying density of traffic and *correlated packet collisions* due to quasi-periodic transmissions of beaconing protocols and relative mobility of vehicles towards the RSU. Probability of reception is based on a plurality of factors, to mention a few, IEEE 802.11p MAC contentions, the *capturing effect* and the *hidden node problem* all effect message reception but are very difficult to express analytically [37]. Due to these qualities, the purely mathematical analysis of the position error becomes highly complex. Nevertheless, simulation results showed that (2) approximates the behavior of error, i.e., it clearly shows that error is a function of vehicle dynamics, which roughly depends on traffic conditions and scenario topology, and of probability of packet reception, which roughly depends on the number of vehicles and channel conditions. These allow us to divide the error analysis into two main parts:

- the error component due to vehicle dynamics
- and the error component due to packet loss,

Consequently, we empirically evaluate both contributions using the realistic Veins VANET simulation framework.

4.2. Influence of vehicle dynamics

Fig. 4 illustrates that error follows two different patterns as a function of time as shown by (2). On the one hand, there are periodic fluctuations in the error similar to the evolution in time of the average speed. These are due to the behavior of vehicle traffic at the intersection. For example, point A of Fig. 4, one of the time instants in which the error

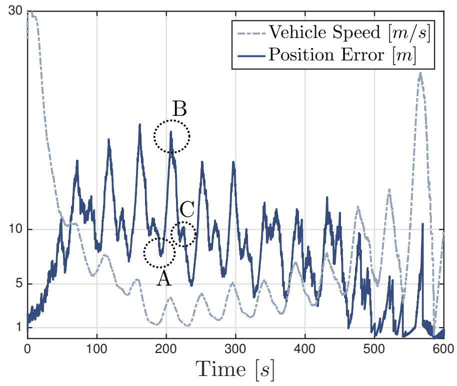

Figure 4: Average position error at the RSU compared to the average speed of vehicles across time in scenario Ø. Visual comparison of both parameters allows to understand dependencies of the error on the scenario topology and traffic density.

is minimal, corresponds to when immediately traffic lights turn green: vehicles in queue are stopped and those at the beginning start to accelerate, therefore the average speed of vehicles is much lower and the resulting error as well. Once the traffic light has turned green, the vehicles accelerate until reaching the maximum speed to leave the intersection, point B in Fig. 4. In addition, vehicles that previously stood in the queue move towards the traffic light. All of these increases the average speed and consequently decreases the position accuracy. Finally, the same phenomenon can be perceived at point C with vehicles that were on turn lane, although it is less scaled because the number of vehicles is smaller and the traffic light time is also shorter. The worst case scenario can be found at larger distances from the RSU where higher speeds are found. Also, the temporal analysis of lost packets showed that when vehicles stop appearing ($t = 160\ s$) packet loss due to SNR follow the same pattern as the speed. This is not due to the speed but to the distance in which vehicles are located because it coincides that they have the highest speed at further distances from the RSU.

Lesson 1. First study showed that intersections are characterized by high mobile traffic and that the error depends on the scenario topology and traffic characteristics. Also, that the fairness postulation is not optimal since each vehicle contributes differently to the error. Therefore, beacon frequency should be adapted to the dynamics of the vehicles, mainly because stopped vehicles near the RSU with low mobility capabilities saturate the channel with

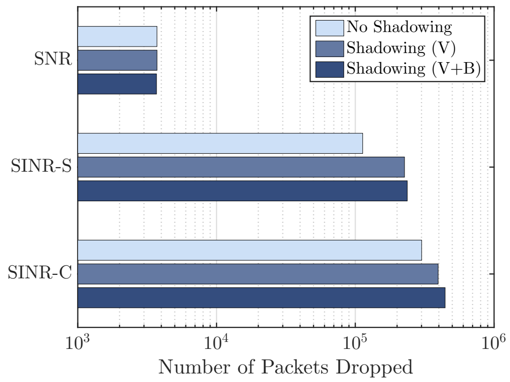

Figure 5: Average number of packets dropped at the RSU due to low SNR (SNR), simultaneous transmission (SINR-S) and concurrent transmission (SINR-C) for different simulated shadowing conditions.

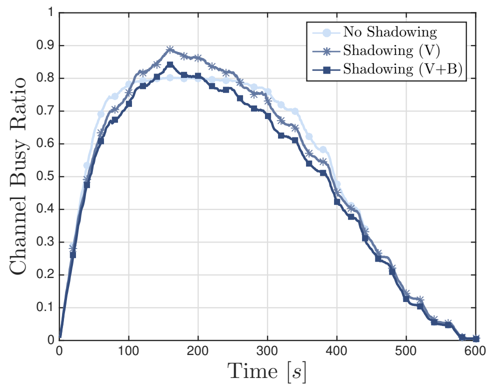

Figure 6: Impact of shadowing on the average CBR computed at the RSU. This figure illustrates the heavy influence of shadowing conditions on the behavior of CSMA/CA protocol.

redundant information that does not improve the accuracy, raise the probability of a collision and are the least likely to contribute to an accident.

4.3. Influence of packet loss

On the other hand, the error grows similar to the evolution of the number of vehicles but attenuated by the decrease in the average speed when traffic congestion occurs as illustrated in Fig. 4. This shows an inverse relationship between the influence of vehicle dynamics and channel congestion (which is proportional to traffic congestion) on the error. That is, when traffic congestion occurs the channel becomes more saturated increasing the error, however, at the same time, the average speed of vehicles decreases reducing the error. There are collisions in almost all instants of time due to the periodic transmission of beacons. The problem worsens as the number of vehicles increases coinciding in $t = 160\ s$ the greatest number of collisions with the maximum number of vehicles. Fig. 5 shows the number of packets dropped at the PHY and MAC layer of the RSU for different kind of simulated shadowing conditions accounting for no shadowing at all, shadowing dynamics of vehicles (V) (i.e., Scenario Ø) and the later one plus shadowing of buildings (V+B) (i.e., Scenario O). It is worth mention that packets can not be received because of: considered as noise due to low SNR, discarded as collision due to low SINR during preamble reception (i.e., simultaneous transmission) or discarded due to bit errors caused by low SINR at some point during reception (i.e., concurrent transmission). Fig. 5 illustrates the importance of shadowing on packet reception in an intersection which in the worst case translates to minimum PDR values of 10% corresponding to a 90% chance of collision. Also, number of vehicles increases the effect of radio signal shadowing dynamics increasing the probability that packets are not received due to a low SNR but, more importantly, increasing hidden nodes during which collision avoidance mechanism of CSMA is not involved. Thanks to shadowing of vehicles and buildings the range of distance at which vehicles sense each other is diminished increasing concurrent transmissions at the RSU.[1] Therefore, high density traffic infer a high collision probability arising the well-known scalability problem of the IEEE 802.11p MAC protocol which precisely congestion control protocols try to avoid [38].

Hidden node and collision problems can also be observed on the evolution of the Channel Busy Ratio (CBR) over time in Fig. 6. The CBR is computed at the RSU as the amount of time that the channel is sensed as busy during a second. The theoretical CBR limit in CSMA/CA without packet collisions can be computed as the total number of beacons that can be fitted in a second, N_l, multiplied by the duration of a beacon transmission, t_p. In addition, N_l can be deduced as the inverse of the packet duration plus the predetermined listening period (AIFS) as:

$$N_l = \frac{1}{AIFS + t_p}, \tag{4}$$

[1] At this point, an important distinction has to be made as [13] found out that shadowing diminishes collision probability from vehicles' POV, however, as found in this scenario, collisions are increased from the static RSU's POV which is located at intersection's center.

where t_p can be expressed as the duration of L bytes transmitted at a data rate R plus the duration of the predetermined 802.11p PHY header ($t_h = 40\ ms$) [39]:

$$t_p = t_h + \frac{8L}{R}. \quad (5)$$

Substituting first in (5) and then in (4) values mentioned in Table 1 and multiplying by t_p leads to a CBR theoretical limit of 0.8. However, as shown in Fig. 6, CBR is close to 0.9 exceeding the threshold of 0.8 because of shadowing attenuation. This result indicates that the behavior of the medium access protocol CSMA/CA converges to an ALOHA process where a node chooses a random transmission time without sensing the medium. At these densities, the network tends to behave like an ALOHA protocol even though a back-off mechanism is in place, which is aligned with the work in [38].

Lesson 2. Second study showed that high dense traffic and periodic beaconing increased *correlated packet collisions* resulting in catastrophic position accuracies as Fig. 7 illustrates. This indicates that congestion control protocols need to manage collisions. Furthermore, from this point of view, the fairness postulation is neither optimal since stopped vehicles with low contributions to the error interfere with further vehicles with higher speeds and prone to larger errors. Hence, adaptation to vehicles dynamics of all communications parameters (not only beacon frequency) is needed to allow vehicles contributing more to the error to overcome collisions and *capturing effect*.

5. Protocol evaluation for IAS

We considered three relevant state-of-the-art beaconing protocols currently considered by standardization bodies: LIMERIC [10], ETSI DCC [40] and USA DCC [18]. Discussion on the performance of the different protocols under this section aims to extract value information of how different adaptation approaches perform in the scenario, if current protocols are able to sustain IAS and to conclude how protocols' design criteria influence information reception for IAS. All parameters were adapted following the guidelines provided by the corresponding authors which the reader is referred to for specific details. In addition, default values of Table 1 were used for adaptation of specific parameters not considered by protocols.

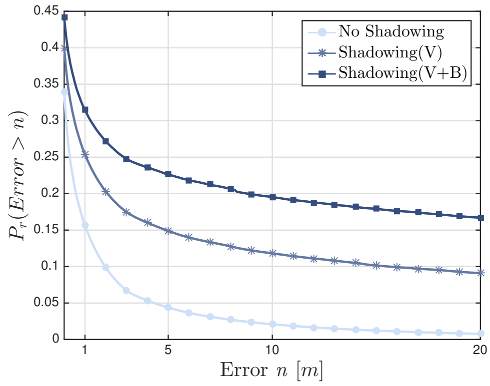

Figure 7: Impact of shadowing on the CCDF of the error computed at the RSU. A higher number of collisions translates into higher position errors and uncertainty which are not negligible for the implementation of IAS.

5.1. LIMERIC + PULSAR

Aim. Achieve desired channel load.

Beacon frequency is adapted at each time step k using equation (6) in combination with CBR information such that all vehicles converge to the same beacon rate and to a desired channel load level $CBR_{max} = 0.6$ that maximizes the throughput or number of successful messages exchanged per second. We added PULSAR [11] over LIMERIC, in this way CBR measured by vehicles does not differ much from that measured by the RSU. Thus, frequency is adapted to the global CBR which is the maximum CBR between the one locally sensed and the one reported by neighbors during two hops. The local CBR is computed using a low pass filter as in [11]. The CBR computing time window was set to 250 ms, hence rate adaptation occurs every 750 ms to account for the information dissemination delay. Then, each vehicle adapts its frequency r linearly as a function of the previous frequency plus the difference between CBR_{max} and the local CBR sensed by the vehicle as:

$$r_k = (1 - \alpha) r_{k-1} + \beta(CBR_{max} - CBR_k), \quad (6)$$

Constant variables of the linear model were set as $\alpha = 0.1$ and $\beta = 2000/150$ [10]. Besides, because vehicle number is not constant in the scenario, we implemented the gain saturation approach provided also by the authors in [10] in which rate update is limited by a threshold $X = 0.005$ to prevent instability. We considered the unsynchronized case, i.e., all vehicles do not check the CBR at same time. Finally, the minimum beacon rate was limited to $t_{b,min} = 0.1\ s$ to verify if LIMERIC's adaptation improves position accuracy w.r.t. the baseline when congestion occurs.

5.2. ETSI DCC

Aim. React to avoid channel congestion.

Beacon frequency is defined by CAM triggering conditions [1] combined with the periodic beacon interval T_GenCam_DCC (i.e., t_b) provided by DCC state machine. CAMs are triggered when the difference between absolute values of current heading, position and speed compared to information disseminated in previous CAM exceeds 4 °, 4 m or 0,5 m/s, respectively. On the other hand, transmission power, data rate and the Clear Channel Assessment threshold (CCA_{th}) are adapted using Table 3 state machine with the corresponding parameters listed that are consistent with those under consideration for trials and deployment [12]. Therefore, parameter adaptation is the consequence of the reaction to local CBR measures. The state machine interval check was set to 100 ms and DCC's $timeUp$ and $timeDown$ constants were set to 1 and 5 seconds respectively [12]. Finally, all vehicles are unsynchronized like in the LIMERIC case which in fact performs better as was reported in [12] under setup DccReactive-3.

5.3. USA DCC

Aim. Achieve reliable tracking accuracy.

Here, it is assumed that each vehicle will try to estimate the position of other vehicles using a predictor based on received information from the shared channel. Accordingly, on the RSU runs the same prediction model, a constant velocity model, as for every vehicle on the scenario. If position information of vehicles being tracked is received, the receiver uses this information to reset the estimated positions. Otherwise, if no information regarding tracked vehicles is received, receiver uses the prediction model to carry on and estimate the positions. Then, assuming no packet loss, the suspected tracking error of neighbors is computed as the difference between the predicted position (computed by the model only with information disseminated in the channel) and the actual position of the vehicle in an Euclidean sense.

On the one hand, beacon frequency is stochastically determined at each time step k by each vehicle calculating the transmission probability p based on suspected tracking error $\tilde{e}$ on neighboring vehicles towards its own position:

$$p_k = \begin{cases} 0 & \tilde{e}_k < e_{th} \\ 1 - exp(-\alpha|\tilde{e}_k - e_{th}|^2) & otherwise \end{cases} \quad (7)$$

where $\alpha = 2$ is the sensitivity to the suspected tracking error and $e_{th} = 0.2$ m the error threshold [18]. After each transmission, it is stochastically decided based on the Packet Erasure Rate (PER) whether suspected error $\tilde{e}$ is reset or continues to accumulate: $\tilde{e}_k^+ = (1-\zeta)\tilde{e}_k$ where $\zeta \sim Bern(1 - PER)$. PER is estimated on the fly by checking the inconsistency in sequence numbers of received packets from all corresponding senders (with at least two messages received) within a 1 s history log and then averaged over all senders. On the other hand, the transmission range L equals L_{min} if $CBR > CBR_{max}$, L_{max} if $CBR < CBR_{min}$ and

$$L_{min} + \frac{CBR_{max} - CBR}{CBR_{max} - CBR_{min}}(L_{max} - L_{min}) \quad (8)$$

otherwise. (8) is a function of the CBR measured within 1 s time window where $L_{min} = 50$ m, $L_{max} = 250$ m, $CBR_{min} = 0.4$ and $CBR_{max} = 0.8$. Finally, L is mapped to transmission power based on the empirical channel model reported in [41] with a granularity of 0.5 dBm.

5.4. Evaluation metrics

The following metrics have been used to study the performance of the beaconing protocols.

- **Position error** (PE) defined as the Euclidean error between the current vehicle's position and the last reported position to the RSU. It is computed at the RSU for each vehicle every 10 ms. This metric is used to evaluate the implementability of the protocols as security applications are sustained on accurate and updated position information.

- **Channel footprint** (CF) defined as the total channel resources consumed at the RSU in time and space [42]. This metric provides information on the amount of channel bandwidth used and can be compared against tracking error reliability. In addition, a high channel footprint indicates worse conditions for dissemination of other types of messages on the same channel.

Table 3: Parameter configuration of the ETSI DCC state machine.

State	CBR	t_b $[ms]$	P_t $[dBm]$	R $[Mbps]$	CCA_{th} $[dBm]$
Relaxed	< 0.3	100	33	3	-95
Active1	$0.3 - 0.4$	200	23	6	-85
Active2	$0.4 - 0.5$	300	23	6	-85
Active3	$0.5 - 0.6$	400	23	6	-85
Restrictive	> 0.6	500	-10	12	-65

The Complementary Cumulative Distribution Function (CCDF) defined as $CCDF = 1 - CDF$ provides the probability $P_r(Error > n)$ of the position error to be greater than n at the RSU. It was used to evaluate PE reliability for safety applications as against other approaches (e.g., average values and confident intervals) the distribution keeps all measured information. PDR was discarded because it is not a good metric of tracking performance since does not reflect *correlated packet collisions*. Not receiving several consecutive beacons increases tracking error more than receiving packets alternatively, despite the ratio between the number of packets received and sent (i.e. PDR) could be the same.

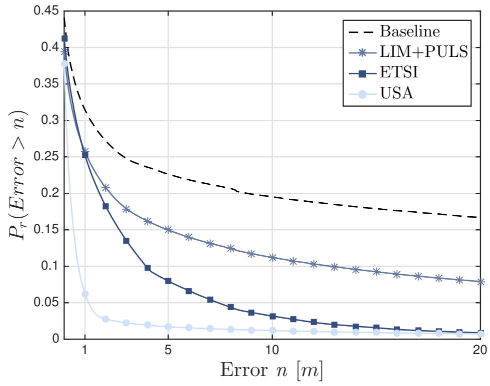

Figure 8: Comparison of the CCDF of PE of all protocols under Scenario O.

5.5. Simulation results

The performance of the described protocols was evaluated using Veins 4.6 for VANET simulation and SUMO 0.29 for vehicle mobility simulation on the scenario and parameters described in Section 3.1. The fix-period beaconing of Section 4 was considered as baseline for comparison. Table 4 summarizes the improvement of beaconing protocols w.r.t. the baseline for Scenarios Ø and O while Fig. 8 illustrates performance in Scenario O.

Both ETSI and USA DCCs are the ones performing better because of a reduced number of collisions. It is clear that USA DCC performs better in overall despite still providing not negligible maximum values. Contrary, ETSI DCC improves maximum PE values because of relaxed periodic transmissions but does not achieve high accuracy because of *correlated packet collisions* are still present. There is a notable difference between the two scenarios in PE of baseline and LIMERIC protocols because the high number of transmissions and shadowing effect, as predicted in Section 4.3. There is no such difference while using LIMERIC jointly with PULSAR, ETSI DCC and USA DCC different approaches that control channel load, the latter being almost independent of the scenario achieving similar PE values for both. Regarding CF, all the protocols decrease CF where USA DCC stands out for the almost null use of the channel. Nevertheless, high values of CBR above CBR_{max} are still measured by the RSU meaning that there is a discrepancy between vehicle and RSU measures.

The spatial distribution of the error shown in Fig. 11 should be taken into account at the time of implementing an application based on a RSU which needs position information of vehicles approaching the intersection. In that sense, considering an average vehicle width of about 2 m, an overall accuracy of 1 m is needed in order to locate a vehicle in a particular driving lane. Therefore, considering values from Table 4 (or observing Fig. 11 of Section 6.2), it can be concluded that maximum errors and standard deviations are too large to consider implementing a critical safety application relying only on the information proportioned by all three protocols to the RSU. This points out that further improvement of these protocols is needed to be able to sustain critical safety applications. However, regarding non-safety applications, 95% of error values would be under medium accuracy scale from up to

Table 4: Summary of statistical performance of studied protocols w.r.t. position error and channel footprint for unobstructed (Ø) and obstructed (O) scenarios. All results shown were obtained from 10 simulation runs. *mean* values are computed averaging all values measured in the same time step for each vehicle and then averaging over all simulation time steps. 95% percentiles shown are the average of all percentiles computed in each time step. $max(d)$ are the maximum PE values calculated within d m from the RSU. $max(CBR)$ are the maximum CBR values measured at the RSU.

		Baseline		LIM+PULS		ETSI DCC		USA DCC	
		Ø	O	Ø	O	Ø	O	Ø	O
PE [m]	mean	7.01	15.93	2.88	7.48	1.02	1.42	**0.44**	**0.65**
	95%	36.55	104.93	10.43	43.46	3.96	5.87	**1.09**	**1.17**
	max(50)	436.9	561.8	266.2	410.9	**26.44**	**32.33**	295.2	403.4
	max(100)	427.1	565.1	295.3	430.6	**40.9**	**154**	206.1	524.5
	max(400)	466.5	565.1	446.4	432.9	**167.3**	**218.8**	542.6	742.6
CF	mean	0.53	0.5	0.49	0.49	0.25	0.26	**0.02**	**0.02**
	95%	0.55	0.52	0.51	0.52	0.27	0.28	**0.02**	**0.02**
	max(CBR)	0.9	0.87	0.82	0.84	0.51	0.58	**0.06**	**0.06**

100 m using ETSI DCC as Fig. 11 illustrates. A similar performance would be obtained using USA DCC from distances up to 175 m enabling, e.g., an efficient traffic light management from the RSU.

5.6. Protocol performance discussion

LIM+PULS. The study of the temporal position error behavior showed an improvement when congestion occured although no application requirements are considered. PE improves w.r.t. the baseline when channel becomes saturated. LIMERIC aims only to achieve a target CBR, hence, its performance is explained by the correct adaptation to CBR disseminated by PULSAR. As a reminder, LIMERIC was limited with a minimum beacon interval equal to the baseline's interval. PULSAR dissemination of 2-hop maximum CBR of neighbors allows vehicles to react to similar CBR values measured at the RSU and mitigate shadowing effects. However, CBR information is not accurate enough so does not reflect the actual situation at the RSU. Hence, CBR information disseminated by the RSU would solve this issue. Another drawback that limits improvement is the fairness postulation because vehicles differently contributing to the error transmit with same beacon rate. Error grows when dynamics are more relevant as no adaptation to these is used and correlated collisions still occur because of periodic transmissions. Also, on the other hand, vehicles transmitting with same constant power limit the performance because packets sent by low speed vehicles are received with greater signal strength than vehicles with higher speeds which are located far from the RSU. Linear parameters —which define the convergence stability, speed and time— were set to constant values but protocol performance would be improved if those were dynamically adapted to the number of vehicles because of the fast varying traffic density of the scenario.

ETSI DCC. ETSI's protocol reacts to CBR to avoid channel congestion decreasing power transmission and beacon frequency and increasing data rate and sensitivity. Adaptation is based on CBR measures of vehicles which differ significantly from the ones measured at the RSU. Thus, using PULSAR approach would improve performance like was tested in [31] and in LIMERIC's evaluation. However, contrary to LIMERIC, ETSI DCC does not only rely on the channel load to adapt beacon frequency. In fact, the periodic component of the beacon frequency is adapted to the CBR but the other frequency component is derived from vehicles dynamics (CAM triggering conditions). Thus, as the channel becomes more saturated, the protocol decreases the beacon frequency and the later component acquire more relevance improving the position accuracy. On the other hand, a high data rate lowers the probability of collision which enhances performance when congestion occurs. Decrease in power and increase in sensitivity objective are to avoid interfering with further vehicles and improve near communications, respectively. When congestion occurs, the carrier sense (CS) range is lowered thus further vehicles' signals are treated as noise enabling closer communications. This approach is not optimal in the specific scenario as seen in Section 4 because low speed vehicles are being prioritized as interferer vehicles get closer to the RSU.

In addition, tweaking state machine's reaction time to match the high mobility of the scenario would compromise its stability which is a current known problem of the protocol [13].

USA DCC. As stated in Section 4, vehicle dynamics and probability of collision are key components for tracking accuracy. USA DCC achieves high performance because of low collision probability conditions and fully adaptation to vehicles dynamics. Forcing all nodes to track vehicles has a computational cost disadvantage, however, it allows vehicles to estimate the error that others are having and to be able to react to it. Using the error threshold, despite not being a deterministic application requirement, it directly grants more priority to vehicles having more error. Besides, it reduces redundant information from the channel lowering collision which in turn leads to better opportunities to succeed for other kinds of messages. If a packet is lost, next one will be sent stochastically only when the predictor error exceeds the threshold, as there is no mechanism to avoid packet loss. This derives in large values of maximum error and uncertainty which do not cope with high accuracy position requirements. Another drawback —although this problem is alleviated as the RSU is the one regulating the intersection— is a significant reduction of awareness as new vehicles appearing inside the RSU range do not receive updated information about vehicles that already sent their beacon and that their model is predicting correctly.

6. Adaptation criteria for IAS

Results simulated and discussed in Section 5 showed that protocols designed using V2V metrics can barely support safety IAS despite being able to meet their requirements as demonstrated by their authors. This shows a tradeoff in the adaptation criteria between enhancing vehicle and RSU-based applications. Consequently, there is a need for new beaconing protocol criteria that yields to better performance on which RSU-based IAS can be sustained. Also, this shows the need to *adapt adaptation*, that is, to decide when and how to switch adaptations to comply with different kind of applications or scenarios, which is complementary with the work in [24, 43]. Since the latter is out of the scope of this paper, novel criteria for parameter adaptation to enhance beaconing performance towards IAS is proposed below.

Lesson 1 and 2 obtained in Section 4 and knowledge gained by Section 5 evaluation lead to the following adaptation criteria with the aim of maximizing position accuracy.

- C1 Vehicles prone to larger errors must have higher priority. Current fairness postulations are not derived from tracking accuracy and reliability.
- C2 All communication parameters must be adapted to the dynamics of the vehicles not only to the state of the channel.
- C3 Effect of packet collisions has to be mitigated. In other words, protocols must aim for low probability of collision conditions while in the event of a collision the most relevant packet must be decodable to avoid correlated collisions.

6.1. Parameter adaptation discussion

Parameter adaptation, limitations and their effects in an intersection area are discussed below. Please note that the discussion is from the POV of a RSU as a static node located in the middle of the intersection. Parameters selected are the most relevant in adaptive beaconing literature, aligned with ETSI's adaptation and limited by the current standardized MAC protocol.

Power *(P_t)*. Vehicle transmission power can be adapted taking into account that 33 dBm is the maximum power allowed at ITS-G5 CCH. P_t determines communication range (CR) and CS range. To obtain a lower collision probability (Criterion 3), it is interesting that the range in which vehicles are sensed is as large as possible to avoid the existence of hidden nodes. As power increases, so does CR and CS range. Therefore, in that sense, the higher the power in which vehicles transmit the better. In addition, a high power implies a greater robustness against channel attenuation. However, transmitting all with the same power does not solve the *capturing effect* (as seen in Section 5), nor does it to adapt the power to the distance towards the RSU because all packets will be received with similar power. Hence, following Criterion 1 and Criterion 2 we advocate that vehicles with higher speeds transmit with higher power than vehicles with slower speeds, so that in case of interference the former vehicles achieve better SINR values. The difference between transmission powers is then subjected to the modulation being used which imposes the minimum SINR to correctly receive a packet.

Data Rate *(R).* Available data rates in IEEE 802.11p with their corresponding modulation, coding rate, minimum sensitivity and SINR threshold needed to correctly decode are listed in Table 5. A recent discussion about optimum data rate for V2V beaconing can be found in [44]. The use of higher transmission speeds implies a decrease in packet duration and thus a decrease in channel congestion but, on the other hand, implies a less robust modulation and a lower CR. Higher SNR and SINR values are required at the receiver in order to be correctly decoded. Vehicles using a more robust modulation and coding scheme will contribute more to the channel load because of a longer packet duration which, in turn, increases the probability of collision. Therefore, in this context and following Criterion 1 and Criterion 2:

- Vehicles with higher speeds are prone to more error and usually found at larger distances from the RSU. So, a lower data rate is preferred to achieve a higher priority and better PDR values accounting for interference from low speed vehicles (SINR threshold reduction) or severe channel attenuation at further distances (sensitivity reduction).
- Low speed vehicles require less priority thus higher data rates are assigned to contribute less to CBR and to achieve lower P_{col} values (Criterion 3). Note that this also acts as a congestion control because vehicle speed is inversely proportional to the traffic density. The more traffic the lower the speed, thus the proportion of vehicles with low speed and high data rate will be higher. Unfortunately, packets colliding will not likely be decoded due to an increased SINR threshold required, nevertheless, lost packets will have less impact on the overall error.

Sensitivity *(CCA_{th}).* CCA_{th} defines the threshold from which the IEEE 802.11p preamble and header can be detected and decoded or contrary considered as noise, so that the medium is sensed as occupied or idle respectively. Obviously, CCA_{th} is limited by receiver's sensitivity but ETSI DCC considers as minimum and maximum values, -95 dBm and -65 dBm respectively. Lowering CCA_{th} (i.e., increasing CS range) of vehicles allows for the detection of transmissions from vehicles situated far away reducing the number of hidden nodes. However, more contending neighbors result in nodes sensing the channel as busy for a longer period and simultaneous transmissions, i.e., that two or more nodes choose the same backoff time, are more likely to occur. On the other hand, reducing the CS range allows for more transmission opportunities because of lower local CBR values and reduces the number of simultaneous transmissions at the cost of getting interferer closer (high SIR values) increasing concurrent transmission. Section 4 showed that in this scenario concurrent transmissions are more influential than simultaneous transmissions. Therefore, we advocate for the use of the minimum receiver sensitivity as CCA_{th} to minimize P_{col} at the RSU, that is, -95 dBm. Note that all the criteria can not be met at the same time: high speed vehicles can not be prioritized while P_{col} is minimized.

Priority *(AC).* IEEE 802.11p EDCA mechanism allows prioritizing between data traffic using four different queues with different AIFS listening periods and CW settings. Table 6 maps the ITS-G5 traffic classes onto the default parameters of the four AC of CCH. CW_{max} has been omitted as it is never used on broadcast mode. AC_BE category is intended to be used for CAMs which turns out to make use of the largest CW_{min} available. A large CW_{min} is preferred for both, high and low speed vehicles, to lower the probability of a simultaneous transmission (Criterion 3). Regarding Criterion 1 and Criterion 2, AC_BE is preferred for high speed vehicles and AC_BK for low speed vehicles. In that sense, vehicles with higher speeds will listen to the medium for shorter periods of time before transmitting, thus obtaining a higher priority. In this way, packets that have the most influence on the error are going to be transmitted first.

Rate *($1/t_b$).* Beacon frequency is the most influential and versatile parameter and the one where more effort has been put into by researchers. Adapting beacon rate following current fairness postulations does not cope with required position accuracies for IAS, neither it does aiming to achieve maximum throughput relying on CBR measurements of vehicles as shown in results of Section 5.5. With high accuracies in mind, beacon frequency must be adapted to vehicle dynamics while randomization is needed to avoid *correlated packet collisions*. The best approach that fits the criteria is the use of a prediction approach based on the position error. This approach decreases the uncertainty between

Table 5: IEEE 802.11p Data Rates (10 MHz Channel) [44].

Data Rate [Mbps]	Modulation	Coding Rate	Minimum Sensitivity [dBm]	SINR Threshold [dB]
3	BPSK	1/2	-85	5
4.5	BPSK	3/4	-84	6
6	QPSK	1/2	-82	8
9	QPSK	3/4	-80	11
12	16-QAM	1/2	-77	15
18	16-QAM	3/4	-73	20
24	64-QAM	2/3	-69	25
27	64-QAM	3/4	-68	30

Table 6: Traffic Classes for ITS-G5 [31].

ITS-G5 Traffic Class	AC	CW_{min}	AIFS [μs]	Intended Use
0	AC_VO	3	58	High-priority DENM
1	AC_VI	7	71	DENM
2	AC_BE	15	110	CAM
3	AC_BK	15	149	Multihop DENM, other data traffic

beacon intervals allowing the opportunity to relax some adaptation criteria and improve the performance of the vehicle network. In this way, lower rates complying with maximum beacon intervals of standards can be achieved, generating low collision probability conditions (Criterion 3), while providing reliable awareness. Besides, position error threshold condition implicitly considers vehicle dynamics (Criterion 1 and Criterion 2). Therefore, using a predictor at the RSU can benefit all existing protocols with only a minimum computational cost disadvantage compared to force all vehicles to run a predictor. In fact, most intersection safety applications envisaged require monitoring position of vehicles. In that sense, previous evaluation of USA DCC revealed the potential of using a position predictor despite showing non implementable uncertainty error values. Hence, high reliability must be solved using randomized redundant transmissions and feedback provided by the RSU about channel metrics and position tracking information.

6.2. Criteria implementation

Under this section, we propose a slight modification of the studied protocols to validate criteria discussed in Section 6.1: Intersection Assistance State Machine (IASM). In that sense, we leave beacon frequency adaptation out so it can be implemented over existing protocols. Hence, discussion of Section 6.1 is synthesized in IASM state machine of Fig. 9 based on vehicles' dynamics. Two different states (LOOSE and RAISE) specify the corresponding parameters to be used and are selected according to the speed of the vehicle. LOOSE and RAISE states correspond to vehicles with low speed, which are intentionally prioritized less, and high speed, respectively.

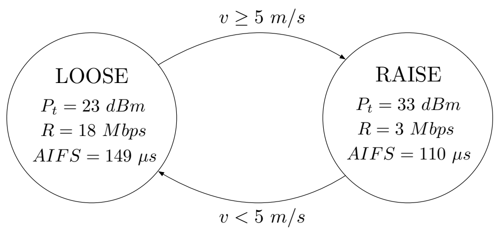

Figure 9: IASM's state machine adaptation of transmission power, data rate and listening period conditioned by vehicle speed and application requirements. Other parameters like the clear channel assessment threshold and the contention window remain constant.

As discussed, CCA_{th} and CW_{min} values always remain the same for each vehicle. The minimum data rate (3 Mbps) and the maximum transmission power (33 dBm) have been selected for vehicles in RAISE state. Contrary, a data rate of 18 Mbps has been chosen following the work in [44] for vehicles

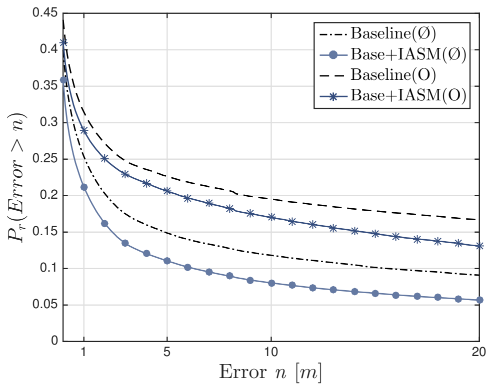

Figure 10: IASM improvement on the CCDF of PE using the baseline protocol for both scenarios.

in LOOSE. A P_t of 23 dBm has been chosen to meet the SINR threshold (5 dB) required to decode a packet sent in RAISE state in case of a collision, plus a margin to account for signal attenuation due to large distances and shadowing dynamics because most of the vehicles with higher speeds are located further. This translates in a 10 dB ratio between both transmission powers at the senders which is two times the SINR threshold. Finally, conditions to distinguish between both states (i.e., between high and low speed) are:

$$State := \begin{cases} LOOSE & v\ t_{b,min} < e_{th} \\ RAISE & otherwise \end{cases} \quad (9)$$

The rationale behind (9) is that high speeds are those whose contribution to the error is above the requirement imposed by the application during the period of time required by the minimum latency. E.g., in case of a required error threshold of 0.5 meters and a minimum delay information interval of 0.1 seconds, the LOOSE state is determined by the condition $v < 5m/s$ like in Fig. 9.

6.3. Criteria validation

To validate IASM we implemented it over the evaluated protocols using same simulation conditions and parameters of Section 5. Beacon frequency was adapted using the specific corresponding protocol's technique while all other communication parameters were adapted using IASM. Fig. 10 clearly illustrates improvement on the CCDF of PE for baseline protocol in both scenarios. Improvement on the CCDF is explained by IASM influence on the decrease in P_{col}, increased SINR values and MAC priority for high speed vehicles' packets.

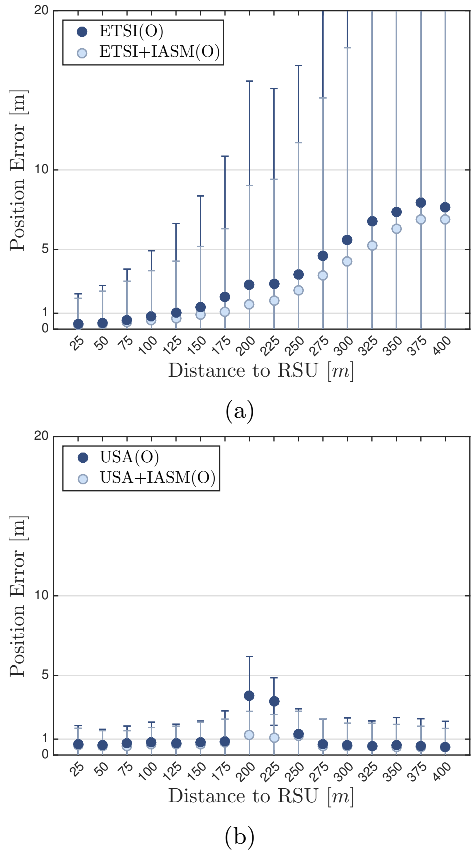

Figure 11: Comparison of the spatial distribution of PE using IASM on (a) ETSI DCC and (b) USA DCC in Scenario O. Mean values are represented by dots while 95% percentiles define the lengths of each bar. Only results obtained of two best performing protocols in worst case scenario conditions are shown.

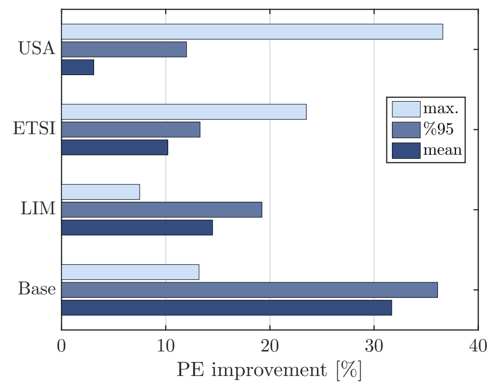

Figure 12: IASM improvement on PE over default studied protocols in Scenario O.

However, using baseline protocol the improvement is limited because of the over saturated channel. The protocol uses no adaptation of the beacon rate and the MAC protocol of the standard can not handle the large volume of beacons by itself. The improvement on maximum PE values is also limited because of the number of packets sent. There are more correlated collisions which cause PE values of specific vehicles to grow and thus high maximum PE values appear. Despite this, IASM improves the mean and 95% percentile of PE by over 30% which can be observed in Fig. 12.

Fig. 12 summarizes the improvement of IASM over all protocols sorted in ascending order of number of packets sent. One can clearly observe that error (PE mean and 95% percentile) improvement becomes larger when the number of packets is increased. This becomes clear for USA DCC in Fig. 11 and Fig. 12 where limited improvement on the average PE is due to the low number of collisions. Also, USA DCC approach limits IASM improvement as packets send at low speeds can become relevant in some circumstances. For instance, it only takes a few packets to predict a vehicle's trajectory traveling at constant low speed. Therefore, in this case, improving the reception of packets sent at high speeds over the aforementioned ones could not be optimal. However, IASM reduces uncertainty of USA DCC with a 10% improvement on the 95% percentile. On the other hand, changing adaptation criteria of ETSI DCC to IASM improves PE mean and 95% percentile over 10% while maximum values are improved over 23%. Besides, adding IASM criteria to LIMERIC improves the mean and 95% percentile by 14% and 20%, respectively.

Fig. 11 shows the improvement on the spatial distribution of PE compared to results obtained using the default protocols. Now, medium accuracies are found up to almost 150 m using ETSI+IASM which is a 50% range improvement w.r.t. default ETSI DCC. In Fig. 11, maximum PE values can be found above the low precision scale for each distance interval. Therefore, IASM can not provide high precision on its own despite decreasing the uncertainty and the average PE. This indicates that the adaptation of the beacon rate is the one that most influences PE. In this sense, the protocols studied need to address directly the problem of correlated collisions to be able to achieve acceptable levels of accuracy.

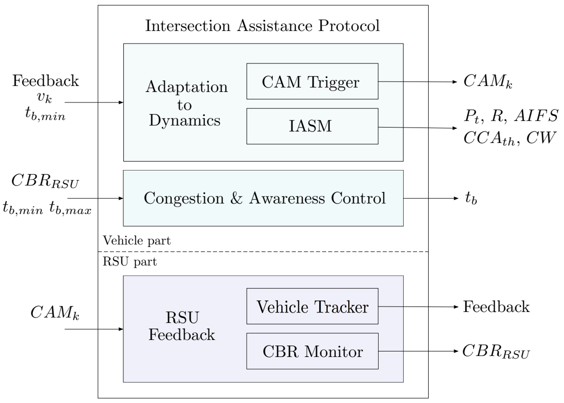

Figure 13: Design framework of the proposed IAP to enhance VANET performance towards RSU-based IAS requirements.

7. Intersection Assistance Protocol

In Section 6.3 our results indicate that adapting other communication parameters using IASM rather than beacon rate improved the performance of studied protocols. Moreover, we discussed optimal beacon rate in Section 6. Hence, in this section we propose Intersection Assistance Protocol (IAP) with a full adaptation of all parameters based on learning from Section 4 and 5 and IASM's performance in Section 6. We present the following guidelines aligned with standardization bodies on which beaconing protocols must be based to enable RSU-based safety IAS.

7.1. Design framework

IAP is based on the following design approach derived from beacon rate discussion of Section 6.1 and IASM that can be divided into three main blocks illustrated in Fig. 13.

Adaptation to dynamics. This block uses IAS requirements of position accuracy and latency plus vehicle dynamics as input to: (i) set transmission power, data rate, sensitivity and beacon priority using IASM and (ii) send specific timed CAMs when needed using ETSI's CAM triggering conditions, a trajectory prediction approach like USA DCC, feedback provided by the RSU or an imminent vehicle collision.

Congestion & awareness control. Using CBR information disseminated by the RSU in combination with maximum latency requirements, this block controls congestion caused in the same intersection or by nearby interfering areas and provides up-to-date awareness required by applications and standards. This solves some of the situations where trajectory prediction approaches does not comply with ETSI's standard minimum CAM frequency requirements providing not enough awareness.

RSU feedback. This block is intended to be integrated with the specific IAS operating in the intersection area. It uses received beacons to track each vehicle under its coverage area and to compute CBR. It periodically disseminates CBR information (CBR_{RSU}) within ITS RSU standardized messages like, e.g., intersection traffic light status (SPATEM), road topology (MAPEM) and infrastructure to vehicle Information (IVIM) [45, 46]. In addition, provides feedback about vehicles position allowing vehicles to react to correlated or relevant packet loss. E.g., the following information included in periodic messages can be exploited to avoid correlated collisions and maximum error values: a vector containing vehicle Ids from which a message has been received between consecutive messages or the Id of the vehicle which information has not been updated for the longest period of time.

7.2. Implementation

A proof-of-concept implementation of IAP is implemented as follows based on all previous learning. Algorithms 1 and 2 shown in pseudo-code summarize the main procedures of the RSU and vehicles, respectively. Here, we are assuming that the only feedback provided by the RSU is CBR_{RSU} and $List_{RSU}$, 250 integers containing the Ids of vehicles whose packet has been received during last second. This information is encapsulated in a 1300B packet broadcasted in CCH every second using default values of Table 1.

1) Because of USA DCC approach proved a great potential: CAM triggering conditions are given by a deterministic trajectory prediction approach. In that sense, a beacon is sent only when the difference between the predicted position $\hat{\boldsymbol{p}}$ —computed using a constant velocity model and the last velocity information sent in a CAM $\boldsymbol{v}_j$— and the actual position known by the vehicle $\boldsymbol{p}$ exceeds $e_{th} = 0.5\ m$. On the other side, the RSU runs the same model to track each vehicle implementing the aforementioned *RSU Feedback: Vehicle Tracker* block. The use of a trajectory approach allows relaxing periodic beacon rate and aim for a controlled awareness under low probability of collision conditions.
2) Because LIMERIC proved a great adaptation to CBR and to overcome USA DCC approach limitations: a periodic beacon rate $1/t_b$ is derived from LIMERIC implementation of Section 5.1 using CBR_{RSU} and a relaxed $CBR_{max} = 0.25$ to meet Criterion III, which is approximating derived from a $P_{col} \leq 0.05$ in [13]. CBR_{RSU} is used to overcome discrepancy finding discussed in Section 5.6 between vehicle and RSU measures of CBR due to shadowing effects. Also, the beacon period is limited to $t_{b,min} = 0.1\ s$ and $t_{b,max} = 1\ s$ as defined in the standard [1].
3) Because protocols suffered from correlated packet loss causing not negligible maximum error values: if the vehicle Id is not present within two consecutive RSU packets, the next time scheduled beacon is randomized multiplying it by a uniform random variable in the range (0.001,1). Therefore, every vehicle increments an integer variable $notInListCounter$ every time a RSU messages is received and does not contain the vehicle's Id.
4) Finally, IASM was used to adapt other communication parameters rather than beacon rate because it was found to improve performance.

Algorithm 1 RSU

```
procedure FEEDBACK AND CBR MONITOR
every time step k ← 1 s
    CBR_RSU ← computeCBR()
    List_RSU ← createListOfVehicles()
    sendRSUMessage()
procedure VEHICLE TRACKER
every time step k ← 0.01 s
    trackVehicles()
```

7.3. Performance evaluation

To validate the proposed implementation, we used same simulation conditions and parameters of Section 5 despite the inclusion of the aforementioned RSU messages.

Simulation results are illustrated in Fig. 14 and Fig. 15 which clearly show a significant improvement on the CCDF and the spatial distribution of PE compared to Fig. 8 and Fig. 11 against all studied protocols. IAP grants a probability of 99.56% of the PE to be within medium accuracy scale for all its coverage area which enables safety IAS [29], contrary to the other protocols. Using IAP, 95% percentile PE values under one meter accuracy are found from distances within 250 meters from the

Algorithm 2 Vehicle

procedure ADAPTATION TO DYNAMICS
  every time step $k \leftarrow 0.1\ s$
  CAM trigger:
    $\hat{\boldsymbol{p}}_k \leftarrow \hat{\boldsymbol{p}}_{k-1} + \boldsymbol{v}_j \Delta t$
    if $\|\hat{\boldsymbol{p}}_k - \boldsymbol{p}_k\| \geq e_{th}$ **then**
      $sendCAM()$
      $\boldsymbol{v}_j \leftarrow \boldsymbol{v}_k$
      $\hat{\boldsymbol{p}}_k \leftarrow \boldsymbol{p}_k$
  IASM:
    if $v_k\ t_{b,min} < e_{th}$ **then**
      $P_t \leftarrow 23\ dBm$
      $R \leftarrow 18\ Mbps$
      $AIFS \leftarrow 149\ \mu s$
    else
      $P_t \leftarrow 33\ dBm$
      $R \leftarrow 3\ Mbps$
      $AIFS \leftarrow 110\ \mu s$
procedure CONGESTION AND AWARENESS CONTROL
  every time step $k \leftarrow t_b^k$
    $sendCAM()$
    $t_b^k \leftarrow LIM(t_b^{k-1}, t_{b,min}, t_{b,max}, CBR_{RSU}, CBR_{max})$
    if $notInListCounter > 1$ **then**
      $var \leftarrow getRandomVariable(0.001, 1)$
    else
      $var \leftarrow 1$
    $scheduleNextCAM()$ in $var * t_b$

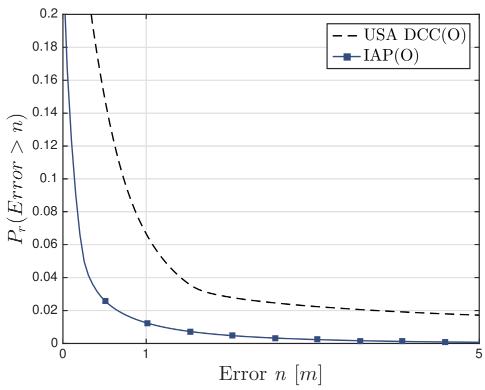

Figure 14: CCDF of PE of the proposed IAP in Scenario O compared to the best performing protocol of Section 5, USA DCC. Please note that axis scales changed to get more resolution when $P_r \rightarrow 0$.

Table 7: Summary of statistical performance of proposed IAP in scenario O. Improvement is calculated against best values of Table 4 among all protocols for scenario O.

		IAP [m]	Improvement [%]
PE	mean	0.08	87.7
	95%	0.28	76.1
	max.(50)	8.97	72.3
	max.(100)	20.35	86.8
	max.(400)	26	88.1

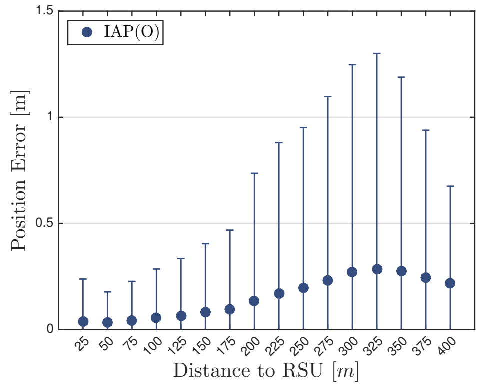

Figure 15: Spatial distribution of PE using IAP in Scenario O. Please note that y-axis scale changed compared to results of Fig. 11.

RSU. This is a great improvement on the PE uncertainty against the other protocols that were not able to provide sub-meter 95% percentile values at any distance. If the aim is to implement critical safety applications requiring high accuracies, high maximum values are still found despite obtaining the lowest values of all simulated protocols. A maximum PE value of 7.12 m is found for distances within 25 m. To solve this, a more aggressive feedback from the RSU or a more elaborated protocol is required. In that sense, no feedback of vehicles position was used on the proposed protocols as this would require a detailed study and modifications which is out of the scope of this paper. However, regarding non-safety applications, Fig. 15 and Table 7 show that IAP provides in average PE values within high accuracy scale and great uncertainty values for all its coverage area. Therefore, information disseminated by IAP is reliable enough to enable non-safety applications.

Regarding CF, CBR values were found to oscillate near 0.25 with a maximum value found of 0.38 when congestion occurs and an overall average value of 0.2. This points out that IAP is able to keep the channel non-saturated increasing the probability of success of other messages with higher priority. Here, there is also room for improvement as LIMERIC linear parameters were set to constant values like in Section 5.6. Finally, Table 7 summarizes IAP performance and improvement over best results obtained in previous sections with significant 72.3 to 87.7% improvement values over the evaluated metrics of PE. In conclusion, loosely speaking, improvement comes from implementing a trajectory prediction approach with added redundant transmissions derived from reliable metrics —that are randomized to avoid correlated packet collisions— under acceptable channel usage and awareness values.

8. Conclusions

This article presented a critical analysis on the performance of EU and US current DCC protocols derived from a semi-analytic study through an RSU application's POV of the position error behavior in an intersection area. Its performance was evaluated and compared with different accuracy scales required by envisaged ITS applications. In that sense, it was deduced that none of the studied beaconing protocols were able to provide reliable information to enable RSU-based safety IAS. Position accuracy was found to be strongly influenced by vehicle dynamics, however, none of them provided adaptation to dynamics for other communication parameters rather than beacon rate. Neither accounted directly for the *hidden node problem* deriving in *correlated packet collisions* and *capturing effect* which was found to be of high relevance in the considered scenario to achieve low uncertainty. Therefore, we discussed and proposed IASM, a novel adaptation criteria of communication parameters to enhance performance of existing beaconing protocols towards RSU-based IAS. In addition, as a proof-of-concept, we proposed and evaluated a new beaconing protocol (IAP) that improved an 87.7% the mean position error over the studied protocols. IAP granted medium accuracy and acceptable maximum error values that enable the implementation of safety IAS. Nevertheless, some challenges still remain unsolved as, e.g., when to *adapt adaptation*, how the proposed criteria effects vehicles' applications or how to achieve very high accuracies with very low uncertainties on which critical safety IAS can be sustained.

Acknowledgment

This work is supported by the Spanish Government under Project TEC2017-84321-C4-4-R cofunded with European Union ERDF funds and also by the Catalan Government under Project 2017 SGR 1670.

References

[1] Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service (2014).

[2] M. Sepulcre, J. Mittag, P. Santi, H. Hartenstein, J. Gozalvez, Congestion and Awareness Control in Cooperative Vehicular Systems, Proceedings of the IEEE 99 (7) (2011) 1260–1279.

[3] K. Z. Ghafoor, J. Lloret, K. A. Bakar, A. S. Sadiq, S. A. B. Mussa, Beaconing approaches in vehicular ad hoc networks: a survey, Wireless personal communications 73 (3) (2013) 885–912.

[4] S. A. A. Shah, E. Ahmed, F. Xia, A. Karim, M. Shiraz, R. M. Noor, Adaptive beaconing approaches for vehicular ad hoc networks: a survey, IEEE Systems Journal.

[5] Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part (2011).

[6] SAE J2945: On-Board System Requirements for V2V Safety Communications (2016).

[7] S. Joerer, B. Bloessl, M. Segata, C. Sommer, R. L. Cigno, A. Jamalipour, F. Dressler, Enabling situation awareness at intersections for IVC congestion control mechanisms, IEEE Transactions on Mobile Computing 15 (7) (2016) 1674–1685.

[8] C. Sommer, R. German, F. Dressler, Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis, IEEE Transactions on Mobile Computing 10 (1) (2011) 3–15. doi:10.1109/TMC.2010.133.

[9] Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service (2010).

[10] J. B. Kenney, G. Bansal, C. E. Rohrs, LIMERIC: a linear message rate control algorithm for vehicular DSRC systems, in: Proceedings of the Eighth ACM international workshop on Vehicular inter-networking, ACM, 2011, pp. 21–30.

[11] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi, H. Hartenstein, Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications, in: Vehicular Networking Conference (VNC), 2011 IEEE, IEEE, 2011, pp. 116–123.

[12] Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium; Validation set-up and results (2015).

[13] C. Sommer, S. Joerer, M. Segata, O. K. Tonguz, R. L. Cigno, F. Dressler, How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help, IEEE Transactions on Mobile Computing 14 (7) (2015) 1411–1421.

[14] M. Sepulcre, J. Gozalvez, O. Altintas, H. Kremo, Integration of congestion and awareness control in vehicular networks, Ad Hoc Networks 37 (2016) 29–43.

[15] B. Kloiber, J. Härri, T. Strang, S. Sand, C. R. Garcia, Random transmit power control for dsrc and its application to cooperative safety, IEEE Transactions on Dependable and Secure Computing 13 (1) (2016) 18–31.

[16] G. Bansal, H. Lu, J. B. Kenney, C. Poellabauer, EMBARC: Error model based adaptive rate control for vehicle-to-vehicle communications, in: Proceeding of

the tenth ACM international workshop, ACM, 2013, pp. 41–50.

[17] H.-H. Nguyen, H.-Y. Jeong, Crosslayer beaconing design toward guaranteed cooperative awareness with contending traffic, in: Vehicular Networking Conference (VNC), 2015 IEEE, IEEE, 2015, pp. 131–134.

[18] C.-L. Huang, Y. P. Fallah, R. Sengupta, H. Krishnan, Adaptive intervehicle communication control for cooperative safety systems, IEEE network 24 (1).

[19] L. Sun, A. Huang, H. Shan, L. Cai, Adaptive beaconing for collision avoidance and tracking accuracy in vehicular networks, in: Wireless Communications and Networking Conference (WCNC), 2017 IEEE, IEEE, 2017, pp. 1–6.

[20] W. Guan, J. He, L. Bai, Z. Tang, Adaptive congestion control of dsrc vehicle networks for collaborative road safety applications, in: Local Computer Networks (LCN), 2011 IEEE 36th Conference on, IEEE, 2011, pp. 913–917.

[21] S. Joerer, B. Bloessl, M. Segata, C. Sommer, R. L. Cigno, F. Dressler, Fairness kills safety: A comparative study for intersection assistance applications, in: PIMRC IEEE International Symposium, IEEE, 2014, pp. 1442–1447.

[22] R. K. Schmidt, T. Leinmuller, E. Schoch, F. Kargl, G. Schafer, Exploration of adaptive beaconing for efficient intervehicle safety communication, IEEE network 24 (1).

[23] P. Fazio, F. De Rango, C. Sottile, A predictive crosslayered interference management in a multichannel MAC with reactive routing in VANET, IEEE Transactions on Mobile Computing 15 (8) (2016) 1850–1862.

[24] T. Yang, X. Cheng, X. Shen, S. Chen, L. Yang, QoS-aware interference management for vehicular D2D relay networks, Journal of Communications and Information Networks 2 (2) (2017) 75–90.

[25] ISO 21217:2014 - Intelligent transport systems – Communications access for land mobiles (CALM) – Architecture (2010).

[26] ETSI EN 302 665: Intelligent Transport Systems (ITS); Communications Architecture (2014).

[27] Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions (2009).

[28] (DRAFT) DTS/ITS-0010015 v1.1.4 (TS 101 539-2) Intersection Collision Risk Warning Specification (2018).

[29] F. A. Santos, A. T. Akabane, R. S. Yokoyama, A. A. Loureiro, L. A. Villas, A Roadside Unit-Based Localization Scheme to Improve Positioning for Vehicular Networks, in: Vehicular Technology Conference (VTC-Fall), 2016 IEEE 84th, IEEE, 2016, pp. 1–5.

[30] ETSI, TS, 102 724 V1.1.1-Intelligent Transport Systems (ITS); Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band, ETSI, Sept.

[31] Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4; Sub-part 2 (2013).

[32] G. Boquet, J. L. Vicario, A. Correa, A. Morell, I. Rashdan, E. M. Diaz, F. P. Muller, Trajectory Prediction to Avoid Channel Congestion in V2I Communications, in: PIMRC IEEE International Symposium, IEEE, 2017.

[33] D. Krajzewicz, J. Erdmann, M. Behrisch, L. Bieker, Recent Development and Applications of SUMO - Simulation of Urban MObility, International Journal On Advances in Systems and Measurements 5 (3&4) (2012) 128–138.

[34] C. Sommer, S. Joerer, F. Dressler, On the applicability of two-ray path loss models for vehicular network simulation, in: Vehicular Networking Conference (VNC), 2012 IEEE, IEEE, 2012, pp. 64–69.

[35] Intelligent Transport Systems (ITS); STDMA recommended parameters and settings for cooperative ITS; Access Layer Part (2012).

[36] C. Sommer, D. Eckhoff, R. German, F. Dressler, A Computationally Inexpensive Empirical Model of IEEE 802.11p Radio Shadowing in Urban Environments, in: 8th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2011), IEEE, Bardonecchia, Italy, 2011, pp. 84–90.

[37] M. Killat, H. Hartenstein, An empirical model for probability of packet reception in vehicular ad hoc networks, EURASIP Journal on Wireless Communications and Networking 2009 (1) (2009) 721301.

[38] T. V. Nguyen, F. Baccelli, K. Zhu, S. Subramanian, X. Wu, A performance analysis of CSMA based broadcast protocol in VANETs, in: INFOCOM, 2013 Proceedings IEEE, IEEE, 2013, pp. 2805–2813.

[39] Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band (2012).

[40] Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part (2011).

[41] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, P. Mudalige, Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 ghz dedicated short range communication (dsrc) frequency band, IEEE Journal on Selected Areas in Communications 25 (8).

[42] Q. Chen, D. Jiang, T. Tielert, L. Delgrossi, Mathematical modeling of channel load in vehicle safety communications, in: Vehicular Technology Conference (VTC Fall), 2011 IEEE, IEEE, 2011, pp. 1–5.

[43] M. Sepulcre, J. Gozalvez, Context-aware heterogeneous v2x communications for connected vehicles, Computer Networks.

[44] M. Sepulcre, J. Gozalvez, B. Coll-Perales, Why 6Mbps is not (always) the Optimum Data Rate for Beaconing in Vehicular Networks, IEEE Transactions on Mobile Computing.

[45] Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Facilities layer protocols and communication requirements for infrastructure services (2016).

[46] SAE J2735: Dedicated Short Range Communications (DSRC) Message Set Dictionary (2016).