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Cooperative Awareness in the Internet of Vehicles for Safety Enhancement

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Abstract

Connected vehicles will improve safety and enable new services to drivers and passengers. One of the main enabled services will be the cooperative awareness, that is the broadcast transmission of periodic messages containing updated information on status and movements. This continuos communication may help the drivers in critical situations and eventually enable vehicles to autonomously coordinate their actions. Being IEEE 802.11p still the de-facto standard for vehicle-to-vehicle (V2V) communications, in this paper we investigate its performance for cooperative awareness through large scale simulations involving hundred of nodes under various settings, and considering the combinations of different modulations and coding schemes. Results highlight the effect of traffic density, obstacles, and physical layer settings on both the reception reliability and the delay of information update, giving guidelines for the system design under realistic propagation and road traffic conditions.

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Part of this work have been presented in [1]

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1. Introduction

The interest in connected vehicles is radically increasing in the last few years, wishing for future new services and applications that may improve the market of the automotive sector. Wireless communications can, in fact, enable safety enhanced services, improve traffic efficiency and drivers' and passengers' comfort, and provide entertainment to passengers.

In this paper, we focus on safety applications, enabled by vehicle-to-vehicle (V2V) communications that allow vehicles to directly communicate with each other without the exploitation of an infrastructure [2, 3]. Independently on the final application, most services are enabled by the periodical exchange of single-hop broadcast short messages, typically called beacons, carrying information such as the vehicle identification, state, position and speed. The received beacons will be processed by several application modules enabling different services [4, 5].

The exchange of beacons allows to obtain a quite precise and up-to-date awareness of the neighborhood and of the dynamics of surrounding vehicles [6]. A more frequent transmission of beacons implies an improved awareness level, but also higher channel load and packet collision probability [7]. For this reason, the relationship between beaconing and some important aspects, such as, channel congestion and vehicles density has been recently investigated. To give some examples, beacon periodicity (BP) is investigated for channel congestion reduction for different radio access technologies in [8, 9]. The use of adaptive beaconing is proposed in [10], with the aim of investigating the impact of vehicle dynamics and channel load on the performance of safety applications. The effect of multi-hop propagation on the reliability of a forward collision warning application is studied in [11] with the objective to show that network-coding-based propagation yields an improvement of reliability with respect to a randomized forwarding strategy. The performance of beaconing in safety applications is investigated in [12] for highway scenarios under congested MAC

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conditions. Beacons reliability has been investigated in [13] as a function of different radio propagation models and different vehicular density for the cooperative collision warning application. Simulation of V2V communications in realistic large-scale urban area based on IEEE 802.11p standard are provided in [14], and the successful beacon delivery probability is investigated varying the vehicular density.

The impact of inter-vehicular distance has been recently investigated in [15], where the focus however is on a beacon transmission power control scheme in highway scenarios without realistic mobility models.

Differently from the recent literature, in this paper we focus on the impact of the the inter-vehicular distance on beaconing feasibility and reliability. In addition, we also evaluate as specific case study, what happens in the presence of obstacles on the roads or in the surrounding of intersections, where accidents are more probable and safety can be improved. Our evaluations are provided by simulation in realistic urban scenarios taking into account the real road maps and vehicular traffic, and representing the communication networks behavior from the lower physical layer and propagation to the MAC access and transport layers.

The paper is organized as follows: in Section 2, the potential wireless communication technologies to enable vehicular connectivity are presented; in Section 3, the requirements for safety applications provided by different standardization entities are described. In Section 4, the performance of beaconing in terms of delay, delivery distance, and delivery rate are presented. In Section 5 our conclusions are drawn.

2. Wireless Access for Connected Vehicles

The main wireless access technologies that can be considered for direct communications in vehicular networks are here summarized:

- The wireless access in vehicular environment (WAVE) with the IEEE 802.11p as the physical and MAC layer standard in the US and the first release of the ETSI cooperative-intelligent transport systems (C-ITS) called ETSI-ITS G5 in Europe;
- The long term evolution (LTE)-V2V;
- The visible light communication (VLC).

All these technologies have been already standardized, but a massive implementation toward a technological revolution that impact our daily lives while in motion, still remains an almost theoretic hot topic of computing and communication networks.

WAVE/IEEE 802.11p (or its European version, C-ITS) represents the actual standard *de facto* for V2V communications: it was proposed to enable ad hoc short range communications also in high speed vehicular scenarios, with simplified signaling and low latency. This is made available by the *WAVE mode* that allows the transmission and reception of data frames with the wildcard basic service set (BSS) identity (ID) value and without the need of belonging to a particular BSS. This feature enables a fast exchange of contextual data, including position and speed. The access technology layer is based on CSMA/CA and operates in the 5.9 GHz frequency band. At the physical layer, IEEE 802.11p is based on orthogonal frequency division multiplexing (OFDM) modulation, with channels of 10 MHz and data rates between 3 and 27 Mb/s.

In early 2014, different working groups within 3GPP have also started studying V2X as an additional feature for LTE-Advanced [16–18]. All these standards specify a V2V feature to address road safety, so that cars can benefit from low latency by sending each other awareness beacons. Values of BP and tolerable latency for these messages are usually fixed for a given use case to guarantee the right level of safety for a specific scenario.

The use of cellular networks to enable vehicular communications is also one of the key features of 5G. This is made possible by the low end-to-end latency by existing LTE technology which also supports mobile speed of around 350 km/h [19]. One of the main advantages of LTE is the fact that the network has been already deployed. This aspect would cut the installation costs with respect to a large-scale deployment of IEEE 802.11p roadside units. On the other hand, the current implemented release of LTE lacks of a native V2V communication. A direct mode with emphasis on public safety (LTE- D2D, or Proximity Services - ProSe) has been specified within Rel. 12 and from Rel. 13 onward. Vehicular communications are explicitly introduced only from LTE Rel.14, whose standardization process is still ongoing, with the name of LTE-Vehicular (LTE-V2V) [16, 17].

Beside these developments, VLC is raising an increasing interest. The great development made by light emitting diodes (LEDs) allows, in fact, to provide vehicular communications through the head and rear lights and to integrate road side units (RSUs) in traffic lights [20]. The importance of this kind of communication is also shown by the development of the IEEE 802.15.7 standard, which defines the physical (PHY) and medium access control (MAC) layers to support multimedia services in mobile visible links [21].

VLC uses an unlicensed and uncongested bandwidth, located between 380 and 800 THz, but provides lower coverage and high directivity with respect to IEEE 802.11p or LTE.

Table 1. Safety applications and requirements for NHTSA, ETSI, and 3GPP.

Safety application	Beacon periodicity [Hz]	Communication range [m]	End-to-end latency [ms]
NHTSA			
Wrong way driver warning	10	500	100
Cooperative forward collision warning	10	150	100
Lane change warning	10	150	100
Blind spot warning	10	150	100
Highway merge assistant	10	250	100
Cooperative collision warning	10	150	100
Highway/rail collision warning	1	300	1000
Cooperative glare reduction	1	400	1000
ETSI			
Emergency electronic brake lights	10	N/A	100
Safety function out of normal condition warning	1	N/A	100
Emergency vehicle warning	10	N/A	100
Slow vehicle warning	2	N/A	100
Motorcycle warning	2	N/A	100
Vulnerable road user warning	1	N/A	100
Overtaking vehicle warning	10	N/A	100
Lane change assistance	10	N/A	100
Co-operative glare reduction	2	N/A	100
Across traffic turn collision risk warning	10	N/A	100
Merging traffic turn collision risk warning	10	N/A	100
Intersection collision warning	10	N/A	100
Co-operative forward collision warning	10	N/A	100
Collision risk warning from roadside units	10	N/A	100
3GPP			
Forward collision warning	10	N/A	100
Control loss warning	10	N/A	100
V2V use case for emergency vehicle warning	10	N/A	100
V2V emergency stop use case	10	N/A	100
V2I emergency stop use case	10	N/A	100
Queue warning	N/A	N/A	100
Warning to pedestrian against pedestrian collision	N/A	N/A	N/A
Vulnerable road user safety	1	N/A	100

The IEEE 802.15.7 specification defines three different PHY levels, with a number of possible modulations and coding schemes, that support data rate up to 96 Mb/s (but presently limited to a maximum of 266.6 kb/s in outdoor mobile conditions) and very low latency. At the MAC layer four options are foreseen: either beacon enabled slotted random access or non-beacon enabled unslotted random access, both with or without carrier sensing multiple access with collision avoidance (CSMA/CA).

Thinking to short term safety applications, although LTE-V2V may represent an interesting solution for connected vehicles in the long term and VLC may represent a complementary technology in specific conditions (such queues at a traffic light), WAVE/IEEE 802.11p (or its European version) has an a higher degree of maturation and remains the only consolidated solution to enable V2V communications. This is the reason why, in this paper we consider WAVE/IEEE 802.11p as the enabling technology for beaconing when safety is addressed.

3. Safety Requirements

In spite of the different names given by the various standards, safety applications are typically based on two types of messages: i) single-hop periodic messages, broadcasting by vehicles, and carrying information about speed, position, etc., and ii) event-driven messages, whose purpose is to disseminate safety information in a specific geographical region. In this work we focus on periodic messages, called cooperative awareness messages in ETSI [22] and basic safety messages in IEEE [23], that are hereafter denoted beacons.

The safety applications foreseen by three of the main international institutions and standardization bodies, NHTSA, ETSI, and 3GPP, are summarized in Table 1 by listing their requirements in terms of BP, communication range, and end-to-end latency. The applications considered are all characteized by the fact that their implementation requires the transmission of beacons. As a matter of fact, Table 1 refers to V2V communications with periodic transmission of beacons,

Table 2. Main simulation settings.

Parameter	Value
Carrier frequency	5.9 GHz
Bandwidth	10 MHz
Equivalent radiated power (P_t)	23 dBm
Receiver sensitivity ($\underline{P_r}$)	see Table 3
Receiver antenna gain (G_r)	3 dB
Minimum SINR ($\underline{\gamma}$)	see Table 3
Transmission range (LOS)	see Table 3
Sensing range (LOS)	740 m
Minimum beacon delivery rate ($\underline{BDR}$)	0.9
Packet length (B)	100 or 200 bytes
Beacon periodicity (f_B)	0.1 packets/s

whereas applications based on event-driven messages and vehicle-to-infrastructure (V2I) communications are not shown since out of the scope of the present work.

The numbers from NHTSA report the results of studies carried out during a project, in which 34 safety and 11 non-safety scenarios have been described. For each scenario, each application has been described by including the communication modalities and the requirements in terms of end-to-end latency, BP and transmission range [25]. Requirements from ETSI and 3GPP, through the working group SA1, can be found in [26] and [16].

As it can be observed, most safety applications are guaranteed by a BP of 10 Hz. Regarding the communication range, requirements are only provided by NHTSA, with values ranging from 150 to 500 m; however, such numbers are typicall of highway scenarios, and do not seem to be easily applicable to urban scenarios. Looking at the last column of Table 1, all institutions agree that a value of end-to-end latency of about 100 ms is suitable for most applications.

At the end, once the BP is fixed, the only requirement is the latency. However, it should be remarked that such latency is easily achievable by means of a reliable single hop communication, even in highly congested conditions. Indeed, even if no specific requirement has been provided for the reliability of beacon reception, such metric is what most studies focus on.

4. Beaconing performance in realistic urban scenarios

The performance of beaconing for safety enhancement is hereafter derived through simulations obtained with realistic urban traffic patterns and a detailed modeling of IEEE 802.11p. After the description of the simulation platform and the adopted settings in Section 4.1, results are discussed in Section 4.2.

4.1. Settings

Simulations are performed using the simulation platform for heterogeneous interworking networks (SHINE) that carefully reproduces the main aspects of IEEE 802.11p [27–30], with the position of vehicles provided by the road traffic simulator VISSIM [31]. The main settings are summarized in Table 2 and hereafter detailed.

Regarding the position of vehicles, they refer to a 2.88 km^2 central area of the Italian city of Bologna [32]. Two traffic conditions (i.e., vehicle densities) are considered, as summarized in Table 4 and represented in Figures 1(a) and 1(c): i) a fluent traffic scenario, with nearly 455 vehicles on average that correspond to slightly more than 150 vehicles per km^2, and ii) a congested traffic scenario, with nearly 670 vehicles on average that correspond to approximately 230 vehicles per km^2.

Focusing on IEEE 802.11p communications, the physical and MAC layer protocols are modeled in all details, including the sensing procedure, the random backoff, and collisions due to concurrent transmissions. The propagation is modeled by a path loss proportional to the distance raised to $\beta = 2.2$ in line of sight (LOS) conditions [33], with the addition of an attenuation when buildings impair the LOS [34]; specifically, we assume 9 dB loss per each external wall and 0.4 dB/m loss inside the buildings [34]. A packet is correctly received if both

$$P_r := \frac{P_t \cdot G_r}{\alpha_0 d^\beta} \geq \underline{P_r} \tag{1}$$

and

$$\gamma := \frac{P_r}{P_I + P_N} \geq \underline{\gamma} \tag{2}$$

where P_r is the the received power, P_t is the transmitted power, G_r is the antenna gain at the receiver, $\underline{P_r}$ is the receiver sensitivity, α_0 is the attenuation at 1 m, d is the transmitter-receiver distance, γ is the signal to noise and interference ratio (SINR), P_I is the average interference received (i.e., the sum of the contributions of all interferers, considering the same propagation model and taking into account the duration of each interference), P_N is the noise power, and $\underline{\gamma}$ is the minimum SINR. With the implemented model, hidden terminals, exposed terminals, and capture effects are taken into account.

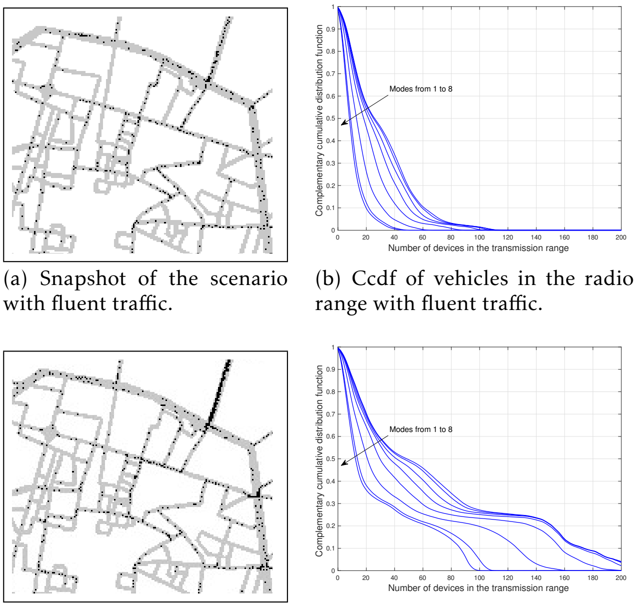
During the simulations, each on board unit (OBU) periodically transmits a beacon of B bytes in broadcast, with periodicity f_B set to 10 Hz in accordance to the value required by most applications (see Table 1). All transmissions are performed at constant power, adopting one of the eight combinations of modulation and coding scheme of IEEE 802.11p, hereafter called Modes and recalled in Table 3. The length of each transmission is thus also the same for all transmissions performed during one simulation, with a value that depends on the beacon size and the adopted Mode.

Table 3. IEEE 802.11p modulation and coding schemes.

Mode	Modulation & coding rate	Nominal data rate	Receiver sensitivity $\underline{P_r}$ [24]	Minimum SINR $\underline{\gamma}$	LOS range[1]	Duration of a 100 bytes beacon	Duration of a 200 bytes beacon
1	BPSK, 1/2	3 Mb/s	-85 dB	10 dB	740 m	320 μs	584 μs
2	BPSK, 3/4	4.5 Mb/s	-84 dB	11 dB	666 m	224 μs	408 μs
3	QPSK, 1/2	6 Mb/s	-82 dB	13 dB	541 m	184 μs	312 μs
4	QPSK, 3/4	9 Mb/s	-80 dB	15 dB	439 m	136 μs	224 μs
5	16-QAM, 1/2	12 Mb/s	-77 dB	18 dB	320 m	112 μs	176 μs
6	16-QAM, 3/4	18 Mb/s	-73 dB	22 dB	210 m	88 μs	136 μs
7	64-QAM, 2/3	24 Mb/s	-69 dB	26 dB	139 m	80 μs	112 μs
8	64-QAM, 3/4	27 Mb/s	-68 dB	27 dB	125 m	72 μs	104 μs

Table 4. Traffic scenarios in the 2.88 km^2 area of Bologna.

Traffic conditions	Average vehicles
Fluent traffic	455
Congested traffic	670



(a) Snapshot of the scenario with fluent traffic.

(b) Ccdf of vehicles in the radio range with fluent traffic.

(c) Snapshot of the scenario with congested traffic.

(d) Ccdf of vehicles in the radio range with congested traffic.

Figure 1. Example snapshots of the road network and simulated traffic under fluent and congested conditions and corresponding complementary cumulative distribution function (ccdf) of the number of vehicles in the radio range of the OBUs for the various Modes.

With the settings detailed in Tables 2 and 3, the average radio range varies from approximately 740 m if Mode 1 is assumed, to nearly 125 m with Mode 8 (see Table 3. Independently from the adopted Mode, the sensing range is always set to the sensitivity of Mode 1, with a maximum range of approximately 740 m.

The distribution of the number of vehicles in the radio range of an OBU is represented in Figs. 1(b) and 1(d). More specifically, Figs. 1(b) and 1(d) show the complementary cumulative distribution function (ccdf) of the number of neighbors in the fluent and congested traffic, respectively. As observable, the neighbors are in most cases between 10 and 60 in fluent traffic conditions and between 10 and 100-140 in congested traffic conditions, with a peak of more than 200 neighbors in the worst cases (congested traffic, Modes 1-4).

The output is shown in terms of

- beacon delivery rate (BDR) BDR, calculated as

$$\mathrm{BDR} = \frac{n_{\mathrm{ok}}}{n_{\mathrm{tot}}} = \frac{n_{\mathrm{ok}}}{n_{\mathrm{ok}} + n_{\mathrm{err}}} \tag{3}$$

  where n_{ok} is the number of beacons correctly received, n_{tot} is the overall number of beacons that should have been received, n_{err} is the number of missed beacons;

- update delay Δt, calculated as

$$\Delta \mathrm{t} = t_{\mathrm{i}} - t_{\mathrm{i\text{-}1}} \tag{4}$$

  where t_{i} is the instant when the generic beacon is correctly decoded and $t_{\mathrm{i\text{-}1}}$ is the instant when the last beacon from the same transmitter was correctly decoded; Δt thus represents the freshness of the information about the generic vehicle;

- CAM range r_{CAM}

$$r_{\mathrm{CAM}} = \max\{d : \mathrm{BDR} \geq \underline{\mathrm{BDR}}\} \tag{5}$$

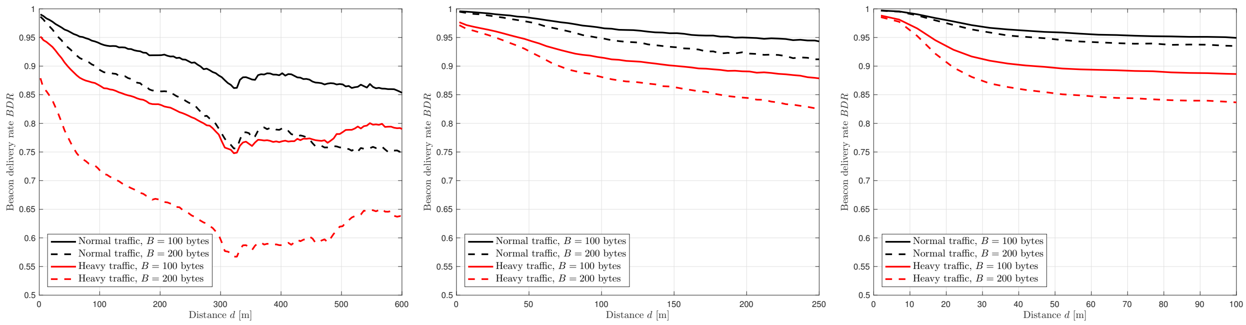
  where $\underline{\mathrm{BDR}}$ is the minimum acceptable BDR.

The end-to-end latency, meaning the time difference between when a generic packet is generated and when it is delivered, is instead not shown here, since it is always well below the 100 ms required by most applications (see Table 1).

4.2. Results

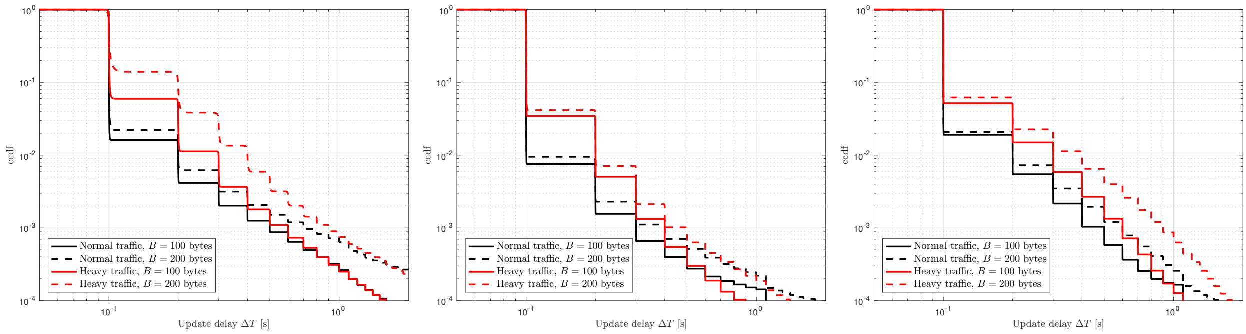
Impact of distance and obstacles. The BDR in LOS conditions varying the transmitter to receiver distance[2]

[2]Per each transmission and per each receiver, the success or loss of the packet is stored with the related transmitter-receiver distance. At the



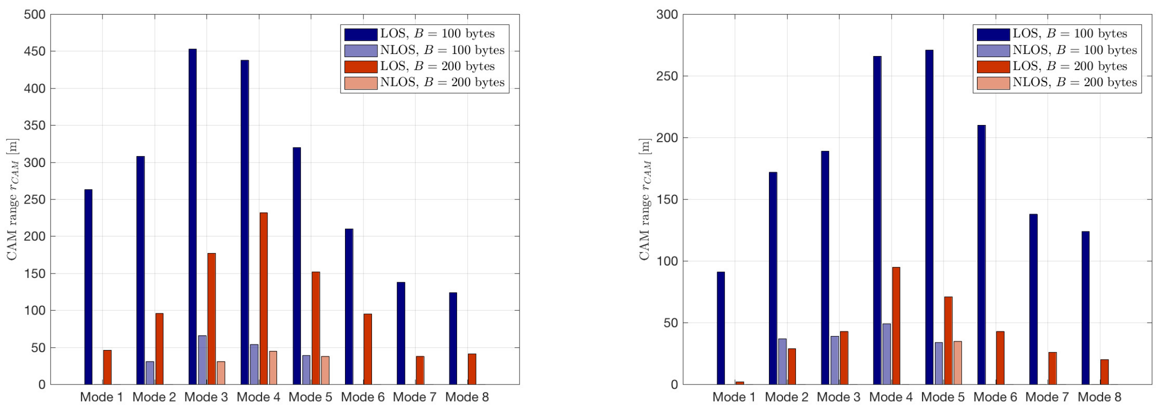
(a) Mode 1. (b) Mode 5. (c) Mode 8.

Figure 2. LOS beacon delivery rate vs. transmitter-receiver distance for selected Modes.



(a) Mode 1. (b) Mode 5. (c) Mode 8.

Figure 3. LOS ccdf of the update delay of the information from neighbors within a distance of 50 m for selected Modes.

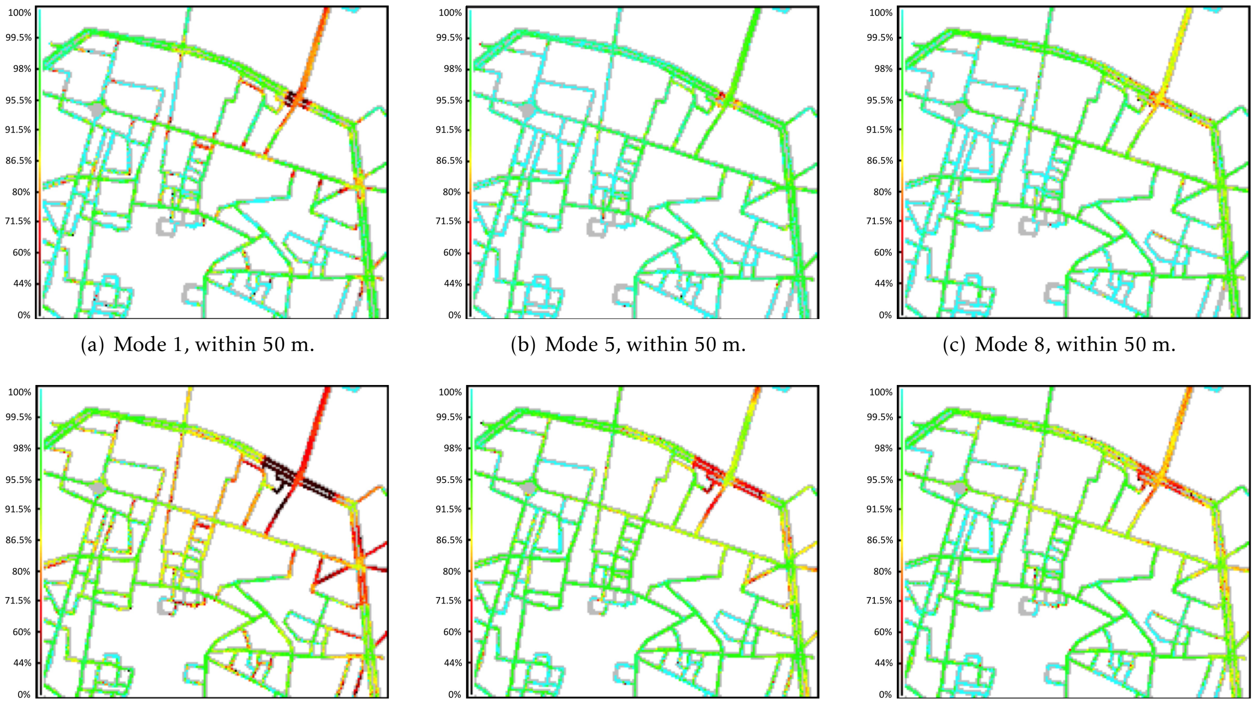


(a) Fluent traffic. (b) Congested traffic.

Figure 4. Maximum distance to have CAM delivery rate above 90% for the eight Modes.

is first shown in Fig. 2 with reference to Modes 1, 5, and 8. Results are shown for $B = 100$ and 200 bytes, with both fluent and congested traffic. As expected, the BDR worsens with an increasing distance due to heavier impact of interferers. Furthermore, a higher vehicle density and a larger size of beacons are shown to negatively affect BDR significantly. In contrast, an increase of the nominal data rate does not have a monotonical impact on the BDR. The BDR corresponding to Mode 5, in fact, appears in most cases

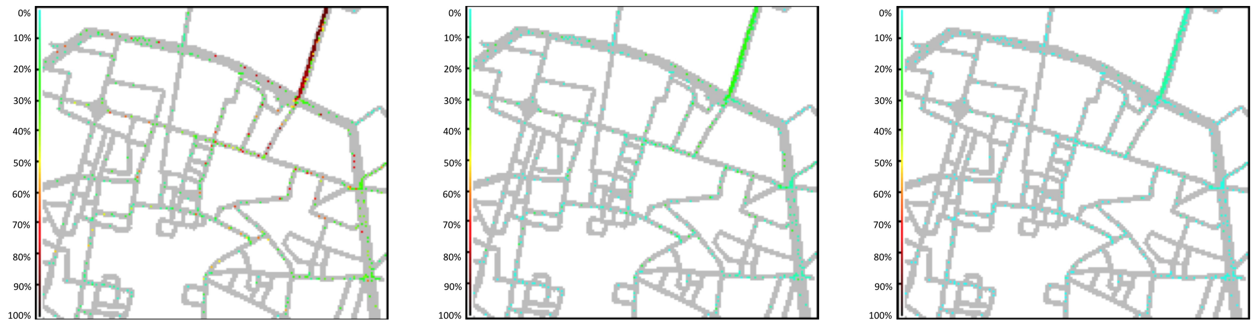
end of the simulation, the BDR is then averaged as a function of such distance.



(a) Mode 1, within 50 m. (b) Mode 5, within 50 m. (c) Mode 8, within 50 m.

(d) Mode 1, within 200 m. (e) Mode 5, within 200 m. (f) Mode 8, within 125 m (maximum range).

Figure 5. Congested traffic, beacons of 200 bytes. Beacon delivery rate as a function of the position of receiving OBUs.



(a) Mode 1, congestion level. (b) Mode 5, congestion level. (c) Mode 8, congestion level.

Figure 6. Beacon delivery rate as a function of the position of receiving OBUs.

higher than that obtainable with Mode 1 and Mode 8. This aspect, further highlighted later through Fig. 4, is caused by two opposite implications of a higher data rate: on the one side, it causes a lower robustness against interference and thus a lower reliability; on the other, however, it implies that transmissions have a shorter duration and thus less interference is produced to the other communications.

Still focusing on the same Modes and considering both beacon sizes and traffic conditions, Fig. 3 shows the ccdf of the update delay of those vehicles that are within 50 m from the given receiver. Within such distance, the information could be of particular relevance for safety applications and the freshness of the information is of primary importance. The trends shown in Fig. 3 basically confirm the conclusions that have already been drawn: an increase of the beacon size or the vehicle density reduces the probability to receive an update within a target time interval, and Mode 3 allows in most cases lower delay than both Mode 1 and Mode 8. In addition, it is interesting to note that the probability to receive an update later than 1 s is not negligible, and goes from a minimum of $7 \cdot 10^{-5}$ to a maximum of $8 \cdot 10^{-4}$ in the considered cases. Such a late update implies that other techniques, like predicting the trajectory and future positions, or exploiting radar systems in addition to the V2V communication are mandatory to guarantee safe operations.

Going back to the BDR and focusing on the comparison of the various Modes, in Fig. 4 the CAM range is shown for all Modes, separating LOS from NLOS results, and considering both beacon sizes and traffic conditions. As already noted and here better highlighted, the Mode that allows to maximize the CAM range is not easily predictable, and varies between Modes 3 and 5, depending on the case. This conclusion is also in agreement to those in [35]. In addition to this aspect, Fig. 4 also allows to observe the effect of non line of sight (NLOS) on the effective CAM range. As expected, due to the high carrier frequency (5.9 GHz), NLOS conditions severely limit the CAM range. Whereas the CAM range exceeds 450 m in LOS in the best case, in fact, it reduces in NLOS to about 65 m and 35 m with 100 bytes and 200 bytes beacons, respectively; furthermore, the CAM range in NLOS falls down to few meters with most Modes. Although these results highlight the critical impact of buildings, especially relevant for intersection management, it must be remarked that few tens of meters could be enough for safe operations, as deeply discussed for example in [36]. Thus, if the possibly high update delay is handled and the adopted Mode is accurately chosen, the CAM range in NLOS conditions could be acceptable for safety purposes, even in congested traffic scenarios.

Impact of receiver position. The reliability of IEEE 802.11p based communications for cooperative awareness is further explored in Fig. 5, focusing on the effect of the position of the vehicles in the scenario. The worst case, i.e. 200 bytes beacons and congested traffic conditions, are assumed. More specifically, in Fig. 5 different colors express various levels of BDR perceived by the receivers located in each position, considering the transmissions received from neighbors within a parametric distance d^* equal to 50 m or 200 m.

If we focus to Mode 5, already shown to be preferable compared to Modes 1 and 8, and $d^* = 50$ m (Fig.5(b)), the BDR remains below 95% on most roads and junctions, but reduces to 70-80% in small critical areas near the main intersection of the scenario. The critical areas increase assuming $d^* = 200$ m (Fig.5(e)).

Looking at the results for various Modes, Fig. 5 again confirms the optimality of Mode 5 compared to Modes 1 and 8, in almost all the positions of the scenario and for both values of d^*. To deepen the causes of this effect, in Fig. 6 the average congestion level of the channel observed in each position of the scenario is shown. The congestion level is obtained as the average portion of time during which the channel is either sensed as busy or used to transmit or receive. As observable, with Mode 1 (Fig. 6(a)) the channel is heavily used, with a congestion level exceeding 70% in most positions. Such a high congestion implies a high interference to ongoing communications that results in a low BDR. In contrast, with Mode 8 (Fig. 6(c)) the congestion level remains always below 30%, and the low BDR is caused by the reduced reliability that follows the adoption of a higher order modulation and a higher coding rate.

5. Conclusions

In this paper, we investigated the performance of V2V beaconing using IEEE 802.11p for safety purposes under various settings and varying the adopted modulation and coding scheme (Mode). Through detailed simulations in realistic scenarios, it is shown that the Mode to adopt is a choice that significantly affects the system performance. Although such choice is shown to depend on the conditions and appears not predictable a priory, the best performance was obtained in all the investigated cases adopting either 4-QAM or 16-QAM modulation. If the optimal Mode is selected, the range achievable in LOS conditions with sufficient reliability reaches 100 m, even in a congested scenario with beacons of 200 bytes. The range reduces significantly with obstacles impairing the LOS, although it remains above 30 m for the optimal Mode in all the investigated cases. At the end, the more critical aspect appears thus the update delay caused by consecutive losses, which, in the worst case, exceeds 1 s in slightly less than one update every thousand.

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