Why 6Mbps is not (always) the Optimum Data Rate for Beaconing in Vehicular Networks

Miguel Sepulcre, Javier Gozalvez and Baldomero Coll-Perales

Abstract—The IEEE 802.11p standard has been created for vehicle to vehicle and vehicle to infrastructure communications. Vehicular networks require vehicles to periodically broadcast beacons in order to detect nearby vehicles or road infrastructure nodes and exchange critical information. The IEEE 802.11p standard defines different data rates that can be used for such transmissions, but 6Mbps has been generally assumed as the default data rate. Limited efforts have been conducted to date to demonstrate whether 6Mbps is the optimum data rate or not. This study addresses this issue, and demonstrates by means of simulations and field experiments that 6Mbps is not (always) the optimum data rate for beaconing in vehicular networks. The conclusions are validated in both urban and highway environments.

Index Terms— Vehicular networks, vehicular communications, connected vehicles, cooperative ITS, V2X, V2V, V2I, beaconing, broadcast, congestion control, awareness control, data rate, 802.11p, ITS G5.

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1 INTRODUCTION

Vehicular networks require vehicles to periodically exchange 1-hop broadcast messages in the control channel of the IEEE 802.11p standard in the 5.9GHz band. These messages are known as CAMs (Cooperative Awareness Messages) or BSMs (Basic Safety Messages), and are commonly referred to as beacons. They include positioning and basic status information of the transmitting vehicle or node. Beacons are used to support cooperative active safety and traffic management applications, and their correct reception is critical. It is generally assumed that beacons are always transmitted using the IEEE 802.11p 6Mbps data rate. In fact, 6Mbps was the data rate initially assumed in the standardization process, and since then it has been generally accepted as the default data rate. Using a default data rate simplifies the transmission process as vehicles only need to select the beacon's transmission frequency and power.

However, IEEE 802.11p defines different data rates between 3 and 27Mbps. Higher data rates make use of high order modulation schemes and coding rates, and therefore require higher transmission power levels to reach a target destination node or area. High data rates are hence generally more suitable for favorable channel quality conditions under which they can increase the transmission efficiency and throughput. High data rates also reduce the packets' duration and therefore the channel load and interference. On the other hand, low data rates reduce the required transmission power levels to reach a target node or area, and increase the throughput under unfavorable channel quality conditions. In contrast, they decrease the throughput under favorable conditions, and increase the packets' duration, channel load and interference.

The correct reception of beacons is critical for vehicular applications, and is highly conditioned by the channel load experienced on the control channel. Different congestion and awareness control protocols have been proposed to date to control the channel load and ensure the applications' effectiveness [1]. While congestion control protocols are aimed at controlling the channel load, awareness control protocols are aimed at adapting each vehicle's transmission parameters to satisfy its application requirements while reducing the channel load. Most of these protocols dynamically adapt the transmission frequency and/or power of beacons, but not the data rate that is generally set to 6Mbps. However, the data rate also has a significant influence on the channel load. In this context, this study analyses the impact of the data rate on the channel load and the applications' effectiveness. The study is based on simulations and field experiments in urban and highway environments. The study demonstrates that 6Mbps is not (always) the data rate that minimizes the beaconing channel load while ensuring the applications' effectiveness.

The paper is organized as follows. Section 2 reviews related studies. Section 3 illustrates the trade-offs between channel load and awareness range resulting from varying the data rate and transmission power. These trade-offs motivated the present study. Section 3 also describes the method proposed to identify the optimum data rate. Section 4 describes the metrics used in this study. Sections 5 and 6 present the results obtained by means of simulation and field experiments, respectively. Section 7 discusses the findings of this study, and Section 8 summarizes and concludes the paper.

Miguel Sepulcre, Javier Gozalvez and Baldomero Coll-Perales are with Universidad Miguel Hernandez de Elche (UMH), Avda. Universidad s/n (Edificio Innova), 03202, Elche, Alicante, Spain. E-mail: {msepulcre, j.gozalvez, bcoll}@umh.es.

2 RELATED WORK

The PHY layer of IEEE 802.11p defines 8 data rates (ranging from 3 to 27Mbps) that can be dynamically selected on a per packet basis. Previous studies have shown that the adequate selection of the data rate can have an impact on the capacity of IEEE 802.11-based wireless networks [2]. However, the 6Mbps data rate is generally assumed as the default data rate for beacons in vehicular networks. This was motivated by the standardization process that selected 6Mbps as the default data rate [3]. Jiang et al. further motivated the use of the 6Mbps data rate in [4]. The study in [4] proposed a method to identify the optimum data rate for beaconing in vehicular networks. The method considered three groups of vehicles intermixed in a highway: two reference groups and one study group. The reference groups were always configured to transmit beacons with the 6Mbps data rate, and represented 40% of the total channel load produced. The PDR (Packet Delivery Ratio) experienced by the study group when all vehicles transmitted at 6Mbps was used as a reference. The study then evaluated the PDR experienced by the study group when such group used each one of the available IEEE 802.11p data rates. For each data rate, the transmission power of the study group was adjusted so that the PDR achieved by the reference groups was equal to the reference PDR (i.e. the PDR experienced when all vehicles in both groups used the 6Mbps data rate). This was done so that vehicles in the study group produce the same level of interference to the reference groups irrespective of the data rate. Under these conditions, [4] showed that the 6Mbps data rate results in the highest PDR performance except when the channel is either slightly loaded or saturated[1]. To the authors' knowledge, [4] is the only study that has analyzed the optimum data rate for beaconing in vehicular networks. However, the authors believe that some of its assumptions should be revisited as the knowledge and development of vehicular networks has significantly progressed over the past years, and the channel load has been identified as a critical aspect to ensure an effective, stable and scalable deployment of IEEE 802.11p-based cooperative ITS systems.

The study in [4] uses communication density as the channel load metric. The communication density is defined in [5] as the number of carrier sensible events per unit of time and distance. This metric does not take into account the packet duration that is highly influenced by the data rate. The packet duration is though taken into account when considering the CBR (Channel Busy Ratio) as channel load metric. The CBR is defined as the proportion of time that the channel is sensed as busy. Most of the congestion and awareness control protocols (e.g. LIMERIC [6], PULSAR [7] and INTERN [8]) proposed for vehicular networks adapt the transmission parameters based on the channel load levels measured by means of the CBR. The method proposed in [4] results in that the proportion of the channel load generated by the reference groups is much higher than 40% when the study group is configured to transmit with a data rate higher than 6Mbps. It can be arguable whether a fair comparison is possible if the performance achieved with each data rate is measured under different CBR levels.

The transmission power was adjusted in [4] so that "the same level of interference" was experienced by the reference groups. However, it is not clear whether the selected transmission power levels guaranteed the communications range required by the vehicular applications. The authors believe that the impact of the data rate on V2X communications should be investigated considering both the channel load/interference and the applications' effectiveness. The transmission power should hence be adjusted so that the application requirements are satisfied (in this study, the target communication range is reached) irrespective of the data rate utilized.

3 DATA RATE: RELEVANCE AND TRADE-OFFS

This study is motivated by the trade-offs existing when using different data rates between the channel load they generate and the transmission power they require to satisfy the application requirements. High data rates reduce the packet duration and the channel load generated, but require higher transmission power levels to satisfy the application requirements. It should also be noted that augmenting the transmission power also increases the interference range. The channel load generated by the transmission of a beacon is directly influenced by its time duration. Such duration is a function of the utilized data rate and the size of the payload (in bytes)[2]. In addition, packet headers are added at the transport, network, MAC and PHY layers. It should be noted that the PLCP Preamble and the SIGNAL field at the IEEE 802.11p PHY layer have fixed time durations. In this context, the total duration (in seconds) of a packet with L bytes (including all upper-layer headers) that is transmitted with data rate R can be expressed as:

$$T_{L,R} = T_H + \frac{8L}{R} \tag{1}$$

where $T_H = T_{PREAMBLE} + T_{SIGNAL} = 40\mu s$ for IEEE 802.11p. Fig. 1 plots the packet duration (estimated using eq. (1)) for different packet sizes and all IEEE 802.11p data rates. The

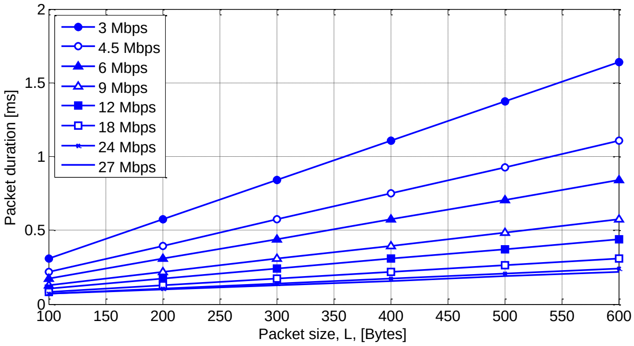

Fig. 1. Packet duration as a function of the packet size (including all headers). The duration is depicted for all IEEE 802.11p data rates.

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[1] In slightly loaded and saturated scenarios, the data rates that resulted in the highest PDR values were 4.5Mbps and 9Mbps, respectively [4].

[2] ETSI (ETSI EN 302 637-2 standard) and SAE (SAE J2735 DSRC Message Set Dictionary standard) have defined a variable packet size for beacons.

figure shows that the time duration of packets transmitted at 27Mbps is around 75% smaller than the time duration of packets transmitted at 6Mbps. This highlights the potential to reduce packet duration, and hence channel load, using higher data rates.

The time duration of beacons influences the maximum number of beacons that can be transmitted in a given area. Let's consider a simple scenario with all vehicles within a single hop. The maximum number of beacons that could be ideally transmitted (i.e. without collisions) can be estimated as the inverse of the packet duration plus the minimum waiting time between consecutive beacons (i.e., the AIFS - Arbitration InterFrame Space):

$$N_{L,R} = \frac{1}{AIFS + T_{L,R}} \tag{2}$$

Considering that beacons are transmitted using the AC_BE EDCA category [9], the AIFS has been set to 110µs. Fig. 2 depicts the ratio between the maximum number of packets transmitted with different IEEE 802.11p data rates ($N_{L,R}$) and with the default data rate of 6Mbps ($N_{L,6}$). The figure shows that the 27Mbps data rate could ideally increase the number of transmitted packets (and hence the capacity) by a factor between 1.5 and 3 compared to when using the 6Mbps data rate. This capacity gain is computed in an ideal scenario with no interference. The data rate can also have a varying effect in scenarios with interference. In particular, higher data rates reduce the packet duration and hence the probability of packet collisions for an equal number of packets transmitted into the control channel.

If all vehicles are not within one hop, the number of vehicles contributing to the channel load depends on their transmission range, and hence on their transmission power. The transmission power influences the distance at which beacons can be sensed and received. It would hence be unfair to compare the performance and efficiency of different data rates if they all utilize the same transmission power. This is the case because higher data rates make use of less robust modulation and coding schemes, and therefore require higher received (and therefore transmitted) signal power levels to correctly receive a packet. The standard [10] indicates the minimum sensitivity level required for each data rate. Such level is defined as the minimum absolute signal energy for which a reference 1000 bytes packet must be correctly received at least 90% of the time. Table I shows that there could be a 14dB difference between the minimum received signal level needed to decode a packet transmitted at 6Mbps and at 27Mbps. The sensitivity level requirements indicated in the standard are minimum performance requirements. The actual sensitivity level is implementation dependent, and can be improved by the chipset manufacturers. Table I also reports the minimum SINR (Signal to Interference/Noise Ratio) required for each data rate following the empirical tests reported in [4]. These results show again the very significant differences between data rates.

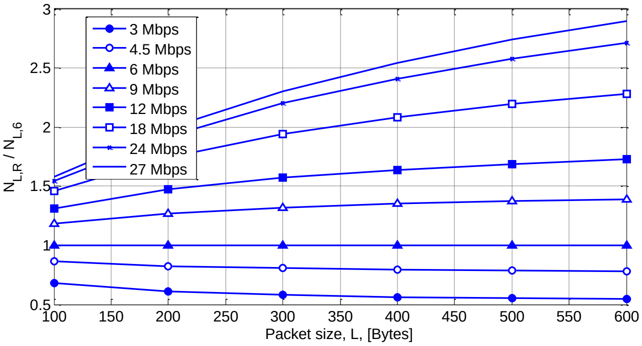

Fig. 2. Ideal capacity gain achieved with different IEEE 802.11p data rates compared to 6Mbps. The gains are shownas a function of the packet size.

TABLE I. IEEE 802.11P DATA RATES (10MHZ CHANNELS)

Data rate [Mbps]	Modulation	Coding rate	Minimum sensitivity [dBm] [10]	SINR threshold [dB] [4]
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 I and Fig. 2 clearly illustrate that the different data rates offer trade-offs between generated channel load and signal power requirements. This is particularly relevant for beacons broadcasted on the control channel. The critical nature of the control channel requires congestion and awareness control mechanisms to guarantee the network stability and scalability as well as the effectiveness of cooperative vehicular applications (e.g. guaranteeing a given communications range). In this context, the authors believe that the comparison and selection of data rates should be based on their capacity to reduce the channel load while guaranteeing the application requirements. To this aim, the transmission parameters of beacons should be configured first so that the application requirements of each vehicle are satisfied. In this study, the application requirements are defined in terms of communication range. This study compares the data rates when the transmission power of beacons is configured to the minimum level needed to guarantee the required communication range in absence of packet collisions[3]. The comparison is conducted considering that all vehicles in the scenario are configured with the same parameters (packet transmission frequency, transmission power and data rate).

4 METRICS

A key aspect when analyzing the relevance and impact of the data rate in vehicular networks is the channel load. This study computes the channel load generated by a vehicle using the channel occupancy *footprint* (or *footprint* in short) introduced in [11]. The footprint is defined as the

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[3] To ensure the same communication range, high data rates require higher transmission power levels than low data rates.

total channel resources consumed by the radio of a single vehicle in time and space. To calculate the footprint of a vehicle, it is first necessary to compute its contribution to the channel load. This contribution is calculated by multiplying the packet transmission frequency F, the packet duration $T_{L,R}$, and the packet sensing ratio (PSR). PSR is defined as the probability of sensing a packet at a given distance. This probability can be computed as the probability that a given packet transmission produces a received signal power (P_r) higher than the carrier sense threshold (CS_{Th}). CS_{Th} is the minimum received signal strength needed to detect a packet and therefore sense the channel as busy. The contribution to the channel load that a vehicle will generate at a distance d can be expressed as:

$$load(d) = F \cdot T_{L,R} \cdot PSR(d) = F \cdot T_{L,R} \cdot \mathrm{Prob}(P_r(d) > CS_{Th}) \tag{3}$$

The footprint of a vehicle can be expressed as the spatial integral of the load it generates [11]:

$$footprint = \int_d load(d) = F \cdot T_{L,R} \cdot \int_d PSR(d) \tag{4}$$

This study quantifies the channel load experienced by a vehicle using the CBR metric. The CBR represents the percentage of time that a vehicle senses the channel as busy. The CBR experienced at a given location can be obtained from the aggregation of the load contribution from all transmitters. The CBR experienced by a vehicle in a road segment with ρ vehicles/km can be related to the footprint as follows:

$$CBR = footprint \cdot \rho / 1000 \tag{5}$$

This relation considers that all vehicles have the same footprint. This relation is only valid if the vehicles are uniformly distributed and there are not packet collisions. As a result, the CBR expression in eq. (5) is particularly accurate for low channel load levels. In a practical scenario, the CBR estimated using equation (5) can be considered as an upper bound. This is the case because when packets collide the amount of time that the channel is sensed as busy is reduced compared to this upper bound. Such reduction is referred to as compression factor in [11], and can vary between 10% and 20% when the CBR varies between 0.3 and 0.6 ([11], [12]).

The previous section has emphasized the need to consider the application requirements when configuring the transmission of beacons. In particular, the transmission parameters should be set so that it is guaranteed that vehicles will receive the beacons at a certain communication range (CR) defined by the application. The communication range required by a cooperative vehicular application depends on the speed, the driver's reaction time [13] and the vehicular context [14]. For example, CR increases at high speeds since vehicles need more time to decelerate. Cooperative awareness metrics such as the inter-packet reception time or the packer reception frequency quantify the freshness of the received information. For a fixed beacon transmission frequency, these two metrics can be derived from the PDR. The PDR is hence considered in this study together with CR to analyze the applications' effectiveness. In particular, the applications' effectiveness is evaluated considering that an application requires a PDR equal or higher than a certain threshold at the required CR.

5 SIMULATION

The performance and efficiency of each data rate is first evaluated through simulations in urban and highway scenarios.

5.1 Simulation settings

The simulations have been conducted using the Network Simulator ns-2.35. Propagation in urban environments is modeled using the WINNER+ B1 model for urban environments and 10dB extra loss [15]. This model is recommended by the European research project METIS for V2V communications. The propagation model proposed in [16] for V2V communications is used for highway environments. Both scenarios simulate a straight street/road with 6 lanes and 3 different traffic densities (200, 300 and 400 vehicles/km). All vehicles are configured to transmit 10 beacons per second with the same data rate and transmission power during each simulation run. As previously explained, this study selects the transmission power for each data rate so that the target PDR level can be achieved at the required communication range in absence of interference. Table II summarizes the main communication and traffic parameters.

TABLE II. SIMULATION PARAMETERS

Parameter	Value(s)
Data rate [Mbps]	3, 4.5, 6, 9, 12, 18, 24, 27
SINR thresholds [dB] [4]	5, 6, 8, 11, 15, 20, 25, 30
Beacon transmission frequency [Hz]	10
Target PDR	0.95
Target CR [m] – Urban scenario	50, 100, 150
Target CR [m] – Highway scenario	100, 200, 300
Channel frequency [GHz]	5.9
Beacon size [Bytes]	250
Number of lanes	6
Traffic density [veh/km]	200, 300 and 400

5.2 Simulation results

Fig. 3 plots the PDR as a function of the distance for the different data rates and a transmission power of 20dBm in the urban scenario. As expected when using the same transmission power for each data rate, the figure shows that the PDR degrades when increasing the data rate. For example, increasing the data rate from 6Mbps to 27Mbps reduces the communication range at which the PDR is equal to 0.95 from approximately 210m to 50m.

The transmission power needed to satisfy the application requirements is different for each data rate. Fig. 4 plots for each data rate the transmission power required to obtain a PDR of 0.95 at different communication ranges. The power needed by the 27Mbps data rate is around 22dB higher than the power needed by the 6Mbps data

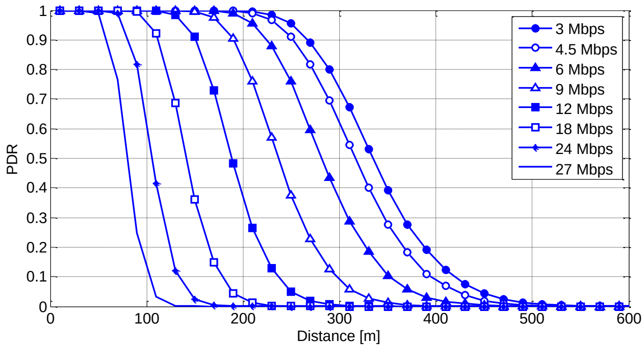
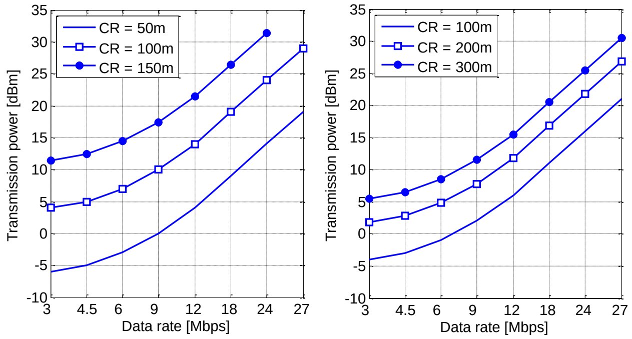
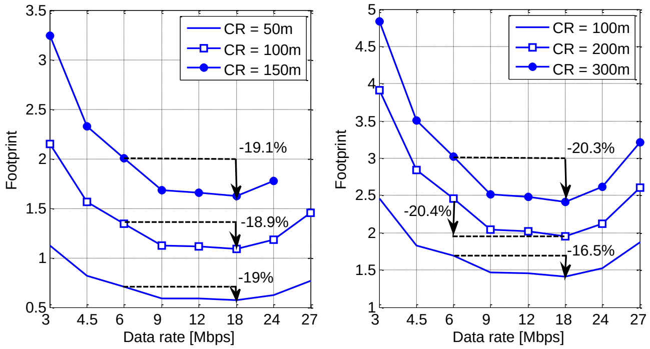


Fig. 3. PDR (Packet Delivery Ratio) as a function of the distance for different data rates. The results are obtained using a fixed transmission power of 20dBm in the urban scenario.



(a) Urban (b) Highway

Fig. 4. Transmission power needed to obtain a PDR equal to 0.95 at different communication ranges. The power levels are shown for all IEEE 802.11p data rates in urban and highway environments.



(a) Urban (b) Highway

Fig. 5. Footprint generated by a vehicle when configuring the transmission power to obtain a PDR equal to 0.95 at different communication ranges.

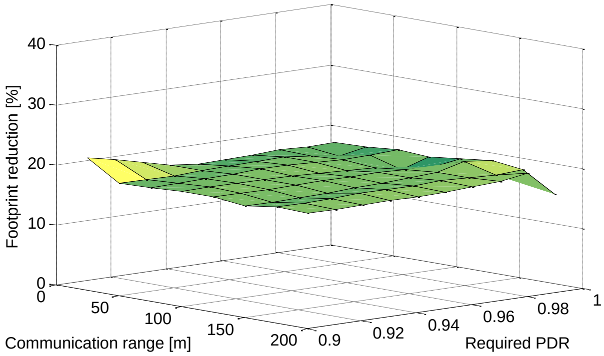


Fig. 6. Reduction of the footprint generated by a vehicle when using the data rate that minimizes the footprint compared to when using the default 6Mbps data rate (urban environment).

rate. This result matches the SINR difference shown in Table I. Fig. 4 shows that the propagation conditions result in that the transmission power levels required in highway environments are lower than in urban environments.

Fig. 5 depicts the footprint generated by one vehicle when the transmission power is configured with the transmission power levels shown in Fig. 4. Fig. 5 shows that the channel load generated by a vehicle can be reduced around 19-20% if higher data rates are used compared to 6Mbps. It is very important to emphasize that this reduction in channel load is achieved without sacrificing the awareness or application effectiveness since vehicles are configured for each data rate with the transmission power necessary to guarantee the same PDR at exactly the same communications range; this configuration results in that e.g. the 18Mbps data rate uses a higher transmission power level than the 6Mbps data rate. The data rate that minimizes the footprint is 18Mbps, but similar footprint levels are obtained for 9 and 12Mbps. Fig. 5 also shows that the footprint increases for 24Mbps and 27Mbps compared to 18Mbps. This is due to the very high transmission power levels needed by these data rates to reach the target ranges and PDR values (Table I. and Fig. 4). Fig. 5 shows that the increase in footprint resulting from these transmission power levels cannot be compensated by the reduction of footprint as a result of the shorter packet duration when transmitting at 24Mbps or 27Mbps.

The reduction of footprint experienced when using higher data rates is maintained for different communication ranges and target PDR values. This effect can actually be observed in Fig. 6 that plots the footprint reduction that could be achieved with the data rate that minimizes the footprint compared to the default 6Mbps data rate. Fig. 6 shows that the footprint can be reduced by approximately 19% independently of the application requirements (communications range and required PDR).

The previous results focused on the requirements and footprint of a single vehicle. Fig. 7 extends the analysis to a scenario where multiple vehicles transmit beacons simultaneously over the same channel. In particular, Fig. 7 plots the spatial distribution of the CBR experienced by vehicles when using each data rate in an urban scenario

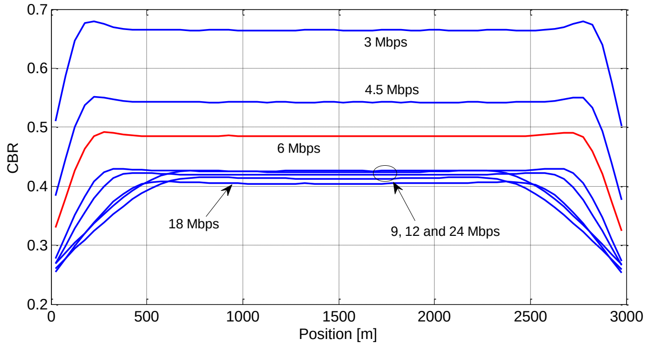
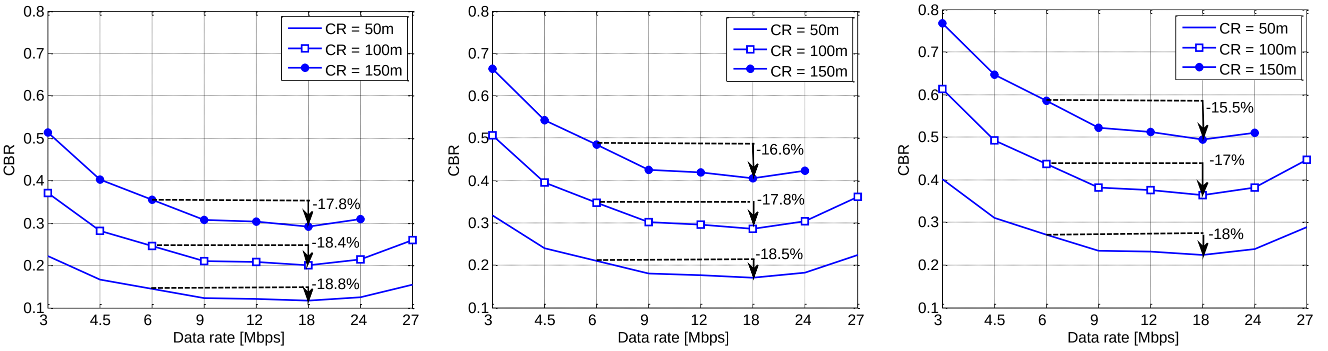
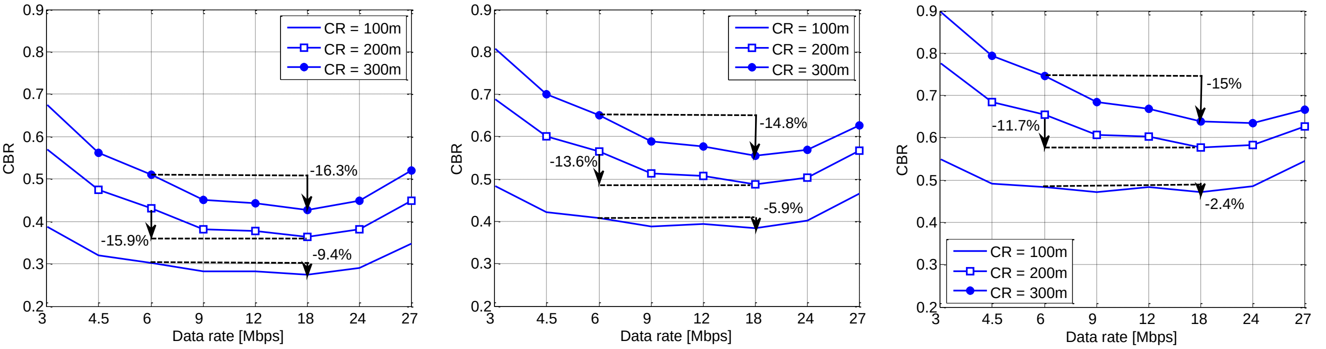


Fig. 7. Spatial distribution of the CBR (Channel Busy Ratio) experienced by vehicles when configuring the transmission power to obtain a PDR equal to 0.95 at a communication range of 150m in the urban scenario with a traffic density of 300 veh/km. The CBR is plotted as a function of the position of vehicles in an urban road with 6 lanes.



(a) 200 veh/km (b) 300 veh/km (c) 400 veh/km

Fig. 8. CBR experienced by the vehicle in the center of the scenario when configuring the transmission power to obtain a PDR equal to 0.95 at different communication ranges. These results correspond to the urban scenario and three different traffic densities.



(a) 200 veh/km (b) 300 veh/km (c) 400 veh/km

Fig. 9. CBR experienced by the vehicle in the center of the scenario when configuring the transmission power to obtain a PDR equal to 0.95 at different communication ranges. These results correspond to the highway scenario and three different traffic densities.

with a traffic density of 300 vehicles/km. The results depicted in Fig. 7 were obtained using the transmission power required to achieve a target PDR=0.95 at CR=150m in absence of interference (Fig. 4). Fig. 7 shows that the CBR or channel load is strongly influenced by the utilized data rate. The minimum CBR is experienced with the 18Mbps data rate. This data rate reduces the channel load by more than 16% compared to when using the 6Mbps without sacrificing the awareness or application effectiveness (all vehicles are configured for each data rate with the transmission power necessary to guarantee the same PDR at exactly the same CR). Fig. 8 and Fig. 9 confirm that the same trends are observed in urban and highway environments for three traffic densities that result in significantly different average CBR levels. Fig. 8 (urban environment) and Fig. 9 (highway environment) plot the CBR experienced by the vehicles in the center of the scenario when using different data rates and communication ranges. The channel load levels observed in the highway environment are higher than in the urban environment because the communication range required is higher (due to the higher speeds of vehicles) and therefore the transmission power is also higher. In any case, Fig. 8 and Fig. 9 confirm that the use of the 18Mbps data rate can reduce notably the channel load compared with the default 6Mbps data rate in both scenarios without sacrificing the awareness or applications effectiveness. The reduction of the CBR is higher for lower traffic densities. It reaches values up to 18.8% in the urban scenario and up to 16.3% in the highway scenario.

The previous results have shown that higher data rates can reduce the channel load without decreasing the application effectiveness compared to when using the default 6Mbps data rate. Another benefit derived from the use of higher data rates is the possibility to reduce the probability of packet collisions and interference (and hence improve the PDR) since packets require a shorter transmission time. Fig. 10 plots the PDR experienced as a function of the distance between transmitter and receiver when the transmission power is configured to obtain PDR=0.95 at CR=100m in absence of interference (Fig. 4). The results are depicted for the urban scenario when multiple vehicles transmit beacons simultaneously over the same channel (traffic density of 300 vehicles/km). Fig. 10 shows that packet collisions reduce the PDR, and the target PDR cannot be achieved at the target CR. The degradation of

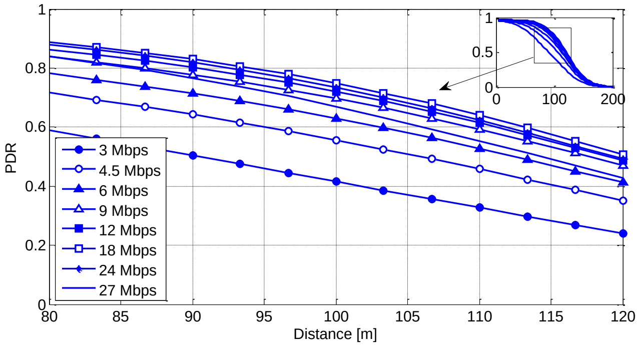
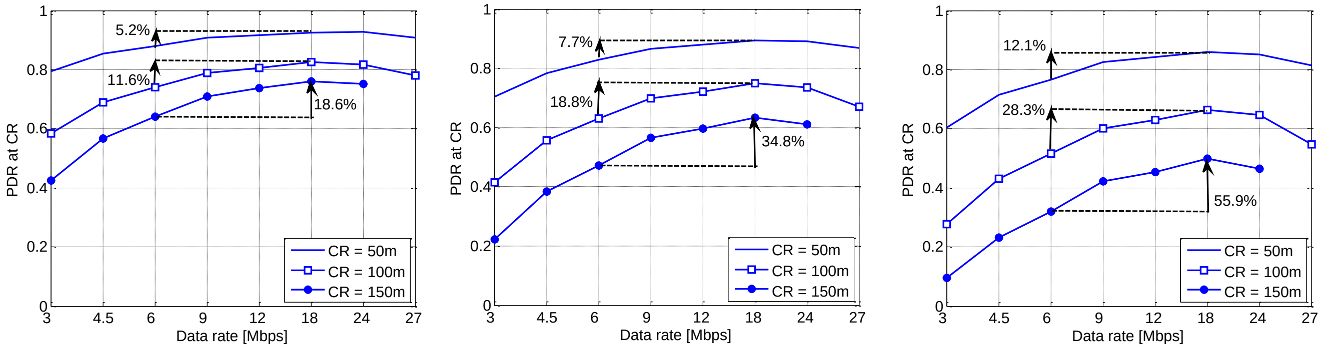
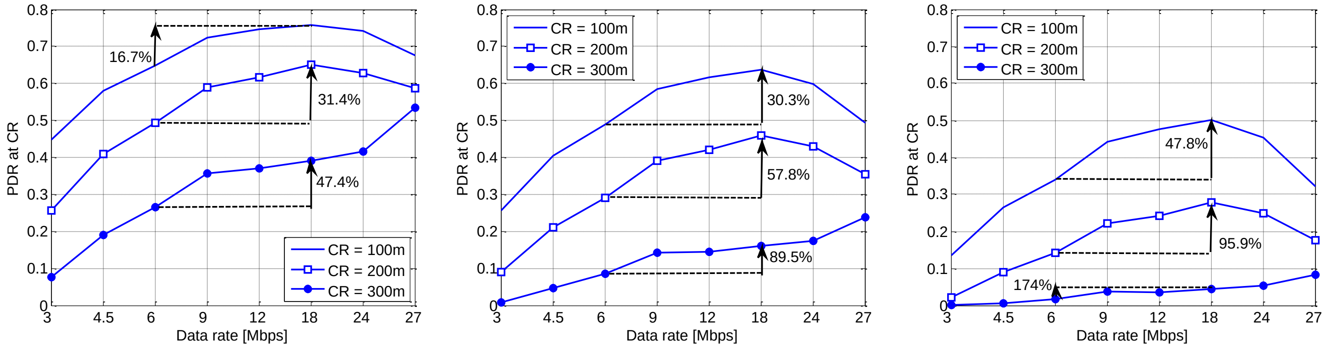


Fig. 10. PDR (Packet Delivery Ratio) experienced as a function of the distance between transmitter and receiver when configuring the transmission power to obtain a PDR equal to 0.95 at CR=100m in the urban scenario with a traffic density of 300 vehicles/km.



(a) 200 veh/km (b) 300 veh/km (c) 400 veh/km

Fig. 11. PDR experienced at the target communication range when configuring the transmission power to obtain a PDR equal to 0.95 (in absence of interference) in the urban environment with three different traffic densities.



(a) 200 veh/km (b) 300 veh/km (c) 400 veh/km

Fig. 12. PDR experienced at the target communication range when configuring the transmission power to obtain a PDR equal to 0.95 (in absence of interference) in the highway environment with three different traffic densities.

the PDR is higher for lower data rates since they produce higher channel load levels. Fig. 10 shows that the 18Mbps data rate results in the highest PDR. Fig. 11 and Fig. 12 show the PDR achieved at different target communication ranges in the urban and highway environments for different traffic densities. The results show that the use of higher data rates can increase the communication performance (and hence the awareness and applications' effectiveness) compared to the default 6Mbps data rate. The gains are particularly relevant at higher traffic densities and in the highway environment where higher channel load levels and packet collisions are experienced. The PDR obtained at the target CR is especially degraded for high CR values, but the use of higher data rates can reduce this degradation. Improving the PDR at the target CR improves the effectiveness of road safety applications that rely on the transmission and reception of beacons. These results demonstrate then that increasing the data rate would not only reduce the channel load and improve the network's scalability, but also improve the awareness range and the applications' effectiveness.

6 FIELD EXPERIMENTS

An extensive field testing campaign has been conducted in urban and highway environments to verify with experiments and hardware nodes the conclusions reported in the previous section.

6.1 Set-up and methodology

Two OBUs (On Board Units) have been employed in the field experiments. Each OBU is equipped with an IEEE 802.11p DENSO WSU (Wireless Safety Unit) prototype and is mounted on a passenger car. Each OBU used a single Nippon omni-directional antenna with 0dBi gain. The antenna was placed on the roof of a vehicle and was connected to the DENSO WSU prototype with an LMR240 antenna cable of 3m length and approximately 3dB cable loss. Each OBU employed a Novatel SMART-V1-2US-PVT GPS receiver to accurately track the vehicle's position. This receiver presents a reference positioning accuracy of 1.8m (RMS) and 20Hz maximum update rate. All the experiments were performed in or near the city of Elche (Spain) in good weather conditions.

Multiple test-drives were conducted to obtain the PDR and PSR curves for different transmission power levels (P_t=5, 10, 15 and 20dBm) and all IEEE 802.11p data rates. In each test-drive, one OBU moved away while the other one was static. The PDR curves are used to estimate for each data rate the transmission power required to achieve the target PDR level at the target communication range. Since measurements were conducted with a limited set of transmission power levels, the transmission power required has been estimated by interpolation. Once this transmission power is estimated, the PSR curves are needed to estimate the footprint.

One of the main challenges was to obtain the PSR curves since the radio interface of the DENSO WSU prototype does not log sensed packets. To solve this limitation, the CBR was logged instead. Since the DENSO WSU device logs the CBR in integer units, the beacon transmission frequency was set to 500Hz. Using a high beacon transmission frequency allowed measuring the CBR without significant resolution loss. Despite the high beacon transmission frequency, there were no packet collisions since there was only one transmitting vehicle in each test drive. The measured CBR curves were normalized by the CBR experienced at short distances to obtain the PSR curves. At such short distances, all beacons are sensed and therefore contribute to the CBR. The most important configuration parameters used in the field experiments are summarized in Table III. For the interested readers, the complete set of PDR and PSR models derived from the field experiments are available in [16]. These models have been produced for all IEEE 802.11p data rates.

TABLE III. CONFIGURATION PARAMETERS

Parameter	Value
Transmission power [dBm]	5, 10, 15, 20
Beacon transmission frequency [Hz]	500
Data rate [Mbps]	3, 4.5, 6, 9, 12, 18, 24, 27
Antenna gain [dBi]	0
Channel frequency [GHz]	5.9
Beacon size [Bytes]	250

6.2 Experimental results

The urban measurements were conducted in Mariano Benlliure street, an 800m long single-lane straight street in the city center of Elche with parked cars at both sides (Fig. 13). The measurements reproducing highway conditions were conducted in the industrial area of Elche, in a two-lane straight street without parked cars and limited vegetation (Fig. 14). In both scenarios, the static vehicle was located with LOS (Line-of-Sight) conditions to the moving vehicle.

Fig. 13. Mariano Benlliure street in Elche (Spain) where urban field tests were conducted.

Fig. 14. Street on the Industrial area of Elche, Spain, where the measurement campaign for the highway-like environment was conducted.

Fig. 15a shows the PDR curves obtained in 4 consecutive drive-tests in the urban environment using a transmission power *Pt* equal to 15dBm and the 6Mbps data rate. Each PDR value was calculated as the ratio between the number of beacons correctly received and the total number of beacons transmitted. As it can be observed, the PDR became especially unstable for medium and high distances. This effect can be produced by the presence of multiple reflecting objects (e.g. parked vehicles and buildings) that create a strong multipath effect. Fig. 15b shows the average PDR values obtained from the different drive-tests. There are several mathematical functions with a symmetric *S* shape that can be adjusted to model and derive the PDR curve from these PDR values. These functions can be grouped into three broad categories: exponential, piecewise-defined, and sigmoid functions [17]. The functions proposed in [17] have been evaluated, and the sigmoid function is the one that minimizes the mean squared error of the average PDR curve for all conducted drive tests.

A similar process has been followed to model the PSR for each transmission power level and data rate. The main difference is that the PSR curves were derived from the measured CBR levels as explained in Section 6.1. Fig. 16 shows the CBR levels measured in the same four consecutive drive tests used to derive the PDR values reported in Fig. 15 (i.e. P_t=15dBm and 6Mbps data rate). The average CBR is then computed for each distance, and a CBR model is derived using the sigmoid function. The PSR model shown in Fig. 17 is then obtained by normalizing the CBR model by its maximum value (i.e. the CBR level experienced at short distances to the transmitting vehicle).

The PDR models are used to estimate the transmission power level needed to obtain a PDR equal to 0.95 at different communication range (Fig. 18). Measurements were conducted with a limited set of transmission power levels (P_t=5, 10, 15 and 20dBm). As a result, the values shown in Fig. 18 have been obtained by interpolation. The direct comparison of the required transmission power levels derived through simulations (Fig. 4) and field tests (Fig. 18) shows similar trends and a reasonable match.

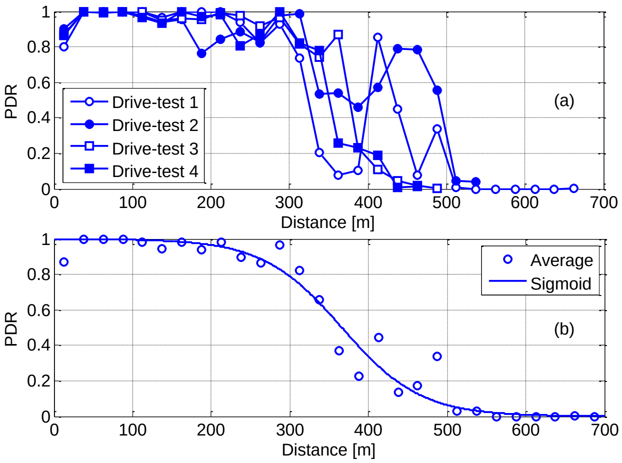


Fig. 15. PDR curves (a) obtained in 4 drive-tests and (b) obtained by averaging all drive-tests and adjusting a sigmoid function. Parameters: P_t=15dBm, data rate = 6Mbps, urban environment.

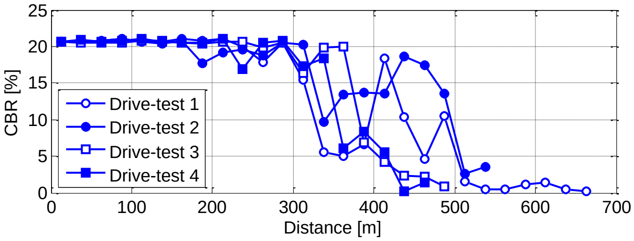


Fig. 16. CBR curves obtained in 4 drive-tests. Parameters: Pt=15dBm, data rate=6Mbps, urban environment.

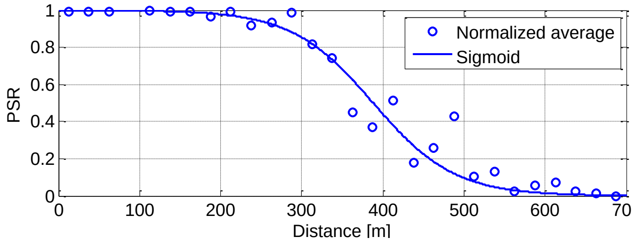
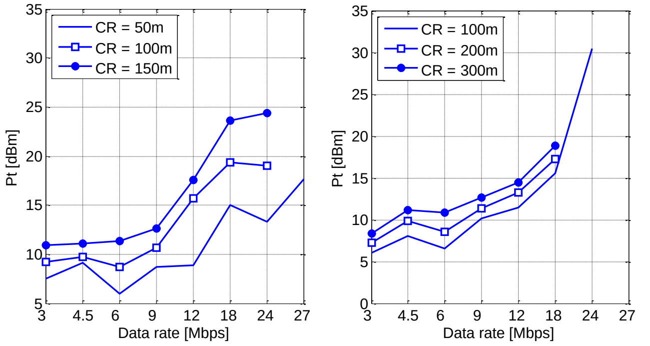


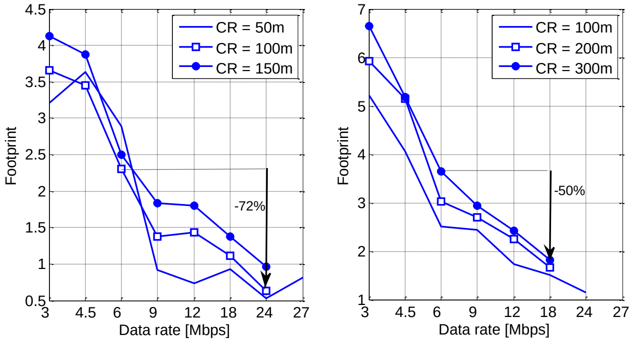
Fig. 17. PSR model obtained by averaging and normalizing all drive-tests of Fig. 14 and adjusting a sigmoid function. Parameters: P_t=15dBm, data rate=6Mbps, urban environment.



(a) Urban (b) Highway

Fig. 18. Transmission power needed to obtain a PDR equal to 0.95 at different communication range for all data rates. The power levels are obtained from field tests in urban and highway-like environments.

The footprint produced by a vehicle is estimated using the PSR models[4]. These models were experimentally derived for a limited set of transmission power levels. The PSR curves for the transmission power levels needed to achieve a PDR equal to 0.95 were hence derived by interpolation. These PSR curves are then used to compute the footprint following eq. (4). Fig. 19 shows the footprint that would be generated by a vehicle that configures its transmission power to obtain a PDR equal to 0.95 at different communication ranges when using each IEEE 802.11p data rate. The experimental results depicted in Fig. 19 clearly confirm that high data rates can notably reduce the footprint and channel load compared to the default 6Mbps data rate. In particular, the footprint generated by a vehicle can be reduced by more than 50% in both urban and highway-like environments. It is important to remember that the reduction in channel load is achieved without decreasing the applications' effectiveness since vehicles are configured for each data rate with the transmission power necessary to guarantee the same PDR at exactly the same communication range.



(a) Urban (b) Highway

Fig. 19. Experimentally derived footprint when the transmission power is configured to obtain a PDR equal to 0.95 at different communication ranges.

7 DISCUSSION

The results obtained show that the 18Mbps data rate provides the best performance (in terms of PDR and channel load) under the evaluated conditions. It is important to note that these conditions are representative of urban and highway scenarios. In fact, the conclusions achieved with simulations and field tests in real conditions coincide. However, many factors could affect the propagation conditions, and hence it could be audacious to claim that 18 Mbps is always the optimal data rate. To illustrate this, let's consider a generic two-slope pathloss model [21] with a breakpoint at distance d_c and a reference distance d_0:

$$PL(d)=\begin{cases} PL_0+10\cdot n_1\cdot Log_{10}\left(d/d_0\right) & if \quad d<d_c \\ PL_0+PL_c+10\cdot n_2\cdot Log_{10}\left(d/d_c\right) & if \quad d\geq d_c \end{cases} \tag{6}$$

where

$$PL_0=20\cdot Log_{10}\left(\frac{4\pi\cdot d_0\cdot f}{c}\right) \tag{7}$$

and

$$PL_c=10\cdot n_1\cdot Log_{10}\left(d_c/d_0\right) \tag{8}$$

In these equations, d represents the distance between transmitter and receiver, f is the carrier frequency, c represents the speed of light, and n_1 and n_2 are the pathloss exponents corresponding to the two slopes. We have calculated for different combinations of pathloss exponents (n_1 and n_2), the transmission power needed for each data rate to reach the target CR, and then their footprint. Fig. 20 shows for each combination of n_1 and n_2 the data rate that minimizes the footprint. The figure shows that different optimum data rates could be possible for different propagation conditions[5], and it is hence audacious to claim that the 18 Mbps data rate is the optimal one. The authors would like to highlight that Fig. 20 is for illustration only, and hence all possible combinations of n_1 and n_2

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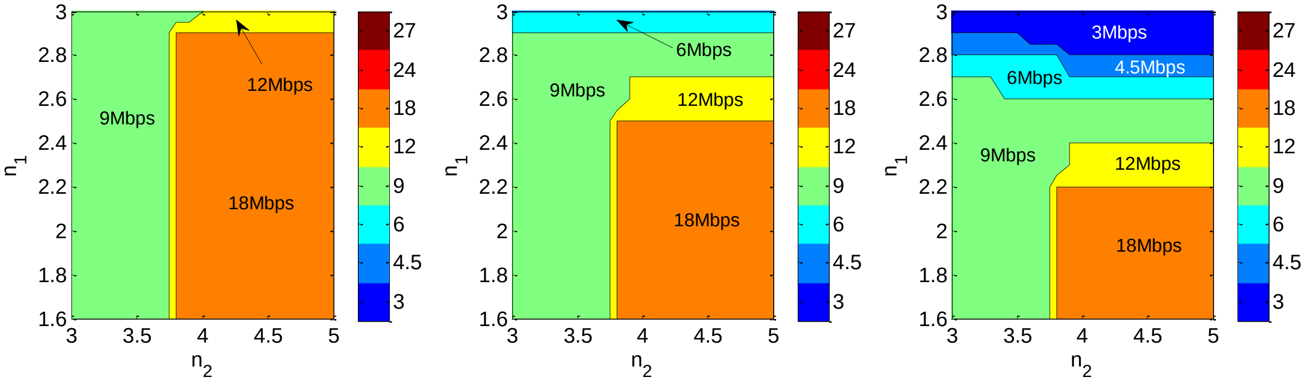
[4] In the field experiments, only the footprint (i.e. the channel load generated by one vehicle) is used to analyze the impact of the 802.11p data rates on the channel load. This is the case because due to hardware limitations, the authors only had one vehicle transmitting in the channel. In this case, it was not possible to recreate a scenario where multiple vehicles transmit beacons simultaneously over the same channel, and analyze the resulting CBR.

[5] Similar trends are obtained when modifying the shadowing standard deviation or the breakpoint distance.



(a) CR=100m (b) CR=200m (c) CR=300m

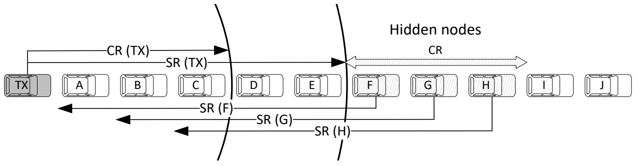
Fig. 20. Optimum data rates for different combinations of pathloss exponents (n_1 and n_2) considering a generic two-slope pathloss equation. Parameters: d_0=1m, d_c=220m (highway environment), f=5.9GHz, c=3·10^8m/s and a log-normal shadowing standard deviation of σ=3dB.

have been analyzed. Determining which of these combinations represent real propagation environments (and their most relevant characteristics) is out of the scope of this study.

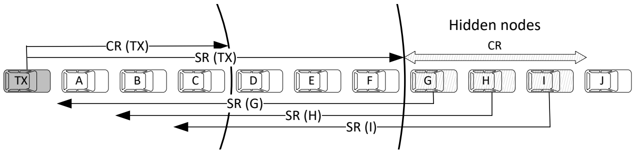
The results presented in this paper demonstrate that the use of data rates higher than 6Mbps can reduce the channel load generated while maintaining (or even improving) the PDR at the target communication range. However, high data rates require the use of high transmission power levels, and it is hence necessary to take into account possible transmission power limitations present in the standards or in the specifications of commercial hardware. The standard currently limits the maximum transmission power level to 33dBm [3]. Fig. 4a shows that under certain conditions (urban environment and CR=150m) the transmission power level needed by the 24 Mbps and 27 Mbps data rates would not be allowed by the standard. Further limitations can be introduced by commercial hardware. In fact, several commercial IEEE 802.11p-based devices limit the maximum output power to 25dBm [18]-[20]. This limitation could again prevent the use of certain high data rates under specific conditions.

The transmission power also has an effect on the well-known hidden terminal problem. However, for a given CR of a transmitting vehicle the number of vehicles that contribute to the hidden-terminal problem is maintained irrespective of the data rate considered. This is the case because such number is proportional to the target CR and the traffic density. This effect is illustrated in Fig. 21 for a scenario where all vehicles have the same CR, although it could be extended for scenarios with vehicles with different CR. Fig. 21a shows the case when a vehicle transmits with a low data rate and configures the transmission power to reach the target CR. In this case, vehicles A, B and C will be able to correctly receive the beacons from the transmitting vehicle. Vehicles D and E (i.e. vehicles between CR and SR - Sensing Range) will not correctly receive these beacons, but will be able to detect them. Vehicles F to H will not detect the channel as busy when the TX vehicle transmits, and could therefore simultaneously transmit and create a packet collision to vehicles A, B and C. For a traffic density of β veh/km, the number of hidden nodes would approximately be CR·β for the situation in Fig. 21a. In Fig. 21b, the transmitting vehicle augments the data rate, and therefore increases the transmission power to reach the target CR (the same CR than in Fig. 21a) with the same quality of service (i.e. PDR) as when using a lower data rate and transmission power. The higher transmission power augments the SR. However, the number of hidden nodes that could create a packet collision to vehicles A, B and C is the same as in Fig. 21a. It is also important to note that if the number of hidden nodes is maintained for all data rates, the probability of packet collision as a result of the hidden terminal problem is smaller with higher data rates. Higher data rates reduce the beacons' transmission time. In this case, the probability that two vehicles that do not sense each other transmit at the same time (and hence collide) is smaller with high data rates than with low ones.

This study has shown that the use of high data rates can reduce the channel load and hence contribute towards controlling the channel congestion. This is also the objective of congestion control protocols. Congestion control protocols in vehicular networks are typically designed to adapt the beacon transmission frequency and maintain the channel load close to certain target level [12]. This paper has demonstrated that the use of high data rates can reduce the channel load. Therefore, if the beacon



(a) Low data rate and low transmission power



(b) High data rate and high transmission power

Fig. 21. Illustration of the hidden-terminal problem when the transmission power is configured to reach certan communication range (CR) with two different data rates.

frequency is adapted to operate close to the target load, higher beacon transmission frequencies would be possible when using high data rates. This could have a positive effect on road safety since information about neighboring vehicles will be received more frequently. In any case, from a general congestion control perspective, this paper demonstrates that the data rate is an important factor that should be considered in the design of congestion control mechanisms.

8 CONCLUSIONS

This study has demonstrated that the use of high data rates for beaconing in vehicular networks has the potential to reduce the channel load compared to the default 6Mbps data rate without reducing the vehicular awareness and link quality. High data rates make use of less robust modulation and coding rates, and therefore require higher transmission power levels to satisfy the application requirements (e.g. a given PDR level at a given communication range). However, high data rates reduce the channel load and interference as they decrease the transmission time of beacons. A reduction of the channel load in turn decreases the number of packet collisions and improves the communication performance. The same trends have been observed in urban and highway environments and through simulations and field experiments. The conclusions reached in this study open the door for the use of other data rates than the default 6 Mbps one, and for the introduction of a dynamic adaptation of the data rate in congestion and awareness control protocols for vehicular networks. These protocols have mainly focused to date on the dynamic adaptation of the beacon transmission frequency and in some cases of the transmission power as well.

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Miguel Sepulcre (msepulcre@umh.es) received a Telecommunications Engineering degree in 2004 and a Ph.D. in Communications Technologies in 2010, both from the University Miguel Hernández of Elche (UMH), Spain. He was awarded by the COIT (Spanish official association of Telecommunication Engineers) with the ONO prize to the best Ph.D. thesis. He has been visiting researcher at ESA in Noordwijk (The Netherlands) in 2004, at Karlsruhe Institute of Technology (Germany) in 2009, and at Toyota InfoTechnology Center in Tokyo (Japan) in 2014. He serves as Associate Editor for IEEE Vehicular Technology Magazine. He is now Assistant Professor at the Communications Engineering Department of UMH, and member of UWICORE research laboratory working in wireless vehicular networks.

Javier Gozalvez (j.gozalvez@umh.es) received an electronics engineering degree from the Engineering School ENSEIRB (Bordeaux, France), and a PhD in mobile communications from the University of Strathclyde, Glasgow, U.K. Since October 2002, he is with the Universidad Miguel Hernández de Elche (UMH), Spain, where he is currently an Associate Professor and Director of the UWICORE laboratory. At UWICORE, he leads research activities in the areas of vehicular networks, multi-hop cellular networks and D2D communications, and wireless industrial networks. He has published over 125 papers in international conferences and journals. He was an elected member to the Board of Governors (2011-2016) and currently serves as President of the IEEE Vehicular Technology Society (IEEE VTS). He was an IEEE Distinguished Lecturer for the IEEE VTS, and currently serves as Distinguished Speaker. He serves as Mobile Radio Senior Editor of the IEEE Vehicular Technology Magazine, and on the Editorial Board of the Computer Networks journal. He was the General Co-Chair for the IEEE VTC-Spring 2015 conference in Glasgow (UK), ACM VANET 2013, ACM VANET 2012 and 3rd ISWCS 2006. He also was TPC Co-Chair for 2011 IEEE VTC-Fall and 2009 IEEE VTC-Spring. He was the founder and General Co-Chair of the IEEE International Symposium on Wireless Vehicular communications (WiVeC) in its 2007, 2008, and 2010 editions.

B. Coll-Perales (bcoll@umh.es) received a Telecommunications Engineering degree in 2008 and a Ph.D. in Industrial and Telecommunications Technologies in 2015, both from the Miguel Hernandez University (UMH) of Elche, Spain. He received Best Student awards in Telecommunications Engineering both by UMH and the professional organization of Telecommunications Engineers and the Outstanding Ph.D. Thesis Award by UMH. In April 2010, he obtained a Ph.D. fellowship from the Valencia regional government and joined the UWICORE research laboratory to work on the development of networking and communication protocols for multi-hop cellular systems using mobile relays under the Opportunities, m-HOP and ICARUS projects. As part of his thesis, in 2012 he spent three months at the Institute of Telecommunications of King’s College London (UK) working on the design of efficient opportunistic multi-hop cellular networks. In September 2016, he obtained a postdoctoral fellowship from the Valencia regional government. He is currently a research fellow at UWICORE and postdoctoral associate at WINLAB (Rutgers, The State University of New Jersey) working on the design of device-centric technologies for future wireless 5G network and connected vehicles under the 5GEAR project.