Integration of congestion and awareness control in vehicular networks

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ABSTRACT

Cooperative vehicular networks require the exchange of positioning and basic status information between neighboring nodes to support vehicular applications. The exchange of information is based on the periodic transmission/reception of 1-hop broadcast messages on the so called control channel. The dynamic adaptation of the transmission parameters when broadcasting such messages will be key for the reliable and efficient operation of vehicular networks. To this aim, vehicular networks utilize congestion control protocols to control the channel load, typically through the adaptation of the transmission parameters based on certain channel load metrics. Awareness control protocols are also required to adequately support cooperative vehicular applications. These protocols typically adapt the transmission parameters of periodic broadcast messages to ensure each vehicle's capacity to detect, and possibly communicate, with the relevant vehicles and infrastructure nodes present in its local neighborhood. To date, congestion and awareness control protocols have been normally designed and evaluated separately, although both will be required for the reliable and efficient operation of vehicular networks. In this context, this paper proposes and evaluates INTERN, a new control protocol that integrates two congestion and awareness control processes. The simulation results obtained for three different scenarios demonstrate that INTERN is able to satisfy the applications' requirements of all vehicles, while effectively controlling the channel load. The results obtained highlight the challenges ahead with emerging automated vehicles.

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1. Introduction

Cooperative vehicular networks are being designed to improve traffic safety and efficiency thanks to the real time exchange of information between vehicles (V2V - Vehicle-to-Vehicle) and between vehicles and infrastructure units (V2I - Vehicle-to-Infrastructure). The exchange of information is based on the periodic transmission/reception of 1-hop broadcast packets on the so called control channel using the IEEE 802.11p radio access technology in the 5.9 GHz

frequency band [1]. These packets are formally known as WSM (WAVE Short Messages) in the US or CAM (Cooperative Awareness Messages) in Europe, and are often referred to as beacons. Each packet includes positioning and basic status information of each vehicle, which is exploited by higher layer protocols and applications. For example, applications such as intersection collision warning or lane change assistance will exploit the position and speed information of nearby vehicles to detect potential road dangers with sufficient time for the driver to react. To effectively support vehicular safety applications, each vehicle needs to continuously receive updated information from all vehicles located within certain warning distance. The requirements of safety applications can be defined in terms of warning distance [2] and packet reception frequency (inverse of packet inter-reception

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time) [3]. Different applications can have different warning distance and packet reception frequency requirements [4], which can also depend on the context of the vehicles [5].

To adequately support cooperative vehicular applications, a number of awareness control protocols have been proposed in the literature [6]. These protocols are aimed at adapting the transmission parameters of beacons to ensure each vehicle's capacity to detect, and possibly communicate, with the relevant vehicles and infrastructure nodes present in its local neighborhood. In addition, all vehicles will periodically transmit their beacons on the control channel. This can lead to possible channel congestion, in particular under high traffic densities. The critical nature of the control channel has fostered significant efforts in the research and standardization communities to design congestion control protocols that ensure the scalability and adequate operation of vehicular networks by adapting the packet transmission frequency or power [6]. In fact, the ETSI communications architecture that future connected vehicles will implement includes a key Decentralized Congestion Control (DCC) module that is currently under development [7].

To date, congestion and awareness control protocols have been normally designed and evaluated separately, although both will be required for the reliable and efficient operation of vehicular networks. For example, in a highway scenario with a traffic jam in one direction of driving and free-flow conditions in the other direction, all vehicles might suffer channel congestion and would require the use of congestion control protocols to control the channel load. However, the requirements of the applications run by the vehicles in the traffic jam are notably lower from those of the applications run by the vehicles under free-flow conditions moving in the opposite direction with higher speeds and different inter-vehicle distances. In this scenario, a congestion control protocol would require the reduction of the transmission power and packet frequency to control the channel load, while an awareness control protocol would seek to increase the transmission parameters of vehicles under free-flow conditions due to their higher applications' requirements. In this context, an independent design (and disjoint operation) of congestion and awareness control techniques could create contradictory settings or conflicts that need to be solved [6]. To this aim, this paper proposes and evaluates INTERN (INTEgRatioN of congestion and awareness control), a new control protocol that integrates congestion and awareness control processes. INTERN dynamically adapts the transmission frequency and power of beacons of each vehicle to guarantee that its application's requirements are satisfied while controlling the channel load generated.

2. State of the art

To effectively support vehicular safety applications, each vehicle needs to continuously receive updated information from its relevant neighboring vehicles. To this aim, different awareness control protocols that adapt the transmission parameters of beacons have been proposed in the literature [6]. For example, the work in [8] proposes OPRAM, an awareness control protocol that adapts each vehicle's transmission parameters to reliably and efficiently exchange a message before reaching a critical safety area such as an

intersection. The work in [9] proposes an awareness control strategy based on the random adaptation of the transmission power and a control process that adapts the packet transmission frequency. The random adaptation of the power provides different reliability levels at different distances, while mitigating correlated packet collisions by randomizing them in space. The packet transmission frequency adaptation can reuse freed channel resources by further increasing the beacon frequency. The protocol proposed in [10] dynamically selects the power and data rate required to successfully transmit a packet to a given vehicle, based on estimations of the average signal attenuation using previously received beacons. In other studies such as [11], the packet transmission frequency is adapted to bind the tracking errors of surrounding vehicles. Considering multi-hop beaconing, the work in [12] proposes a fully distributed algorithm that decides whether a vehicle has to forward a received beacon or not. Such decision is taken by the vehicle itself and its objective is to maximize the reliability of the beacon transmission. However, other studies such as [13] demonstrated that single-hop beaconing is in general more efficient than multi-hop beaconing.

The periodic transmission of beacons occupies a significant portion of the control channel, which can easily get congested. Different congestion control protocols have been proposed in the literature to control the channel load by adapting the transmission parameters of beacons. Two of the most relevant congestion protocols available in the literature are LIMERIC [14] and PULSAR [15]. Both protocols propose the adaptation of the packet transmission frequency based on the experienced channel load, and set the transmission power to a fixed value. Both protocols are able to maintain the channel load below certain target threshold independently of the vehicular traffic density. LIMERIC and PULSAR are currently being discussed at ETSI's Technical Committee on ITS to be part of the DCC set of standards [16,17]. Other congestion control approaches are also available in the literature. For example, the proposal in [18] computes the transmission power of each vehicle based on the number of detected neighboring vehicles and other metrics such as the estimated carrier sensing range. The objective of the protocol proposed in [19] is the efficient transmission of beacons as frequently as possible, while maintaining a congestion-free wireless channel. To this aim, in [19] the packet transmission frequency is adapted by taking into account the channel quality (estimated based on observed packet collisions, Signal-to-Noise ratio and number of neighboring vehicles) and the message utility. The work in [20] recently proposed the adaptation of the packet transmission frequency as a function of the channel load experienced, the target channel load and the number of neighboring vehicles. Other protocols such as the one proposed in [21] consider the adaptation of the contention window size of IEEE 802.11p. In particular, the work in [21] proposes the adaptation of the minimum contention window size based on local transmission statistics that estimate the channel load and differentiating traffic priorities. Other congestion control protocols propose sensing the wireless channel and reducing the transmission power when a channel load threshold is exceeded [22], or when the number of messages in the MAC queue is above certain maximum level [23].

Congestion and awareness control protocols have been typically designed to achieve fairness. Local fairness is achieved when neighboring nodes present similar performance/configuration. Global fairness is achieved when the minimum performance/configuration of the network is maximized [15], i.e. when the performance/configuration of the vehicle under the most adverse conditions is maximized. Congestion control protocols have been designed to provide fairness in terms of channel load and transmission parameters. However, awareness control protocols should be able to provide fairness at the application level, i.e. fairness in terms of the capacity to satisfactorily meet the applications' requirements (i.e. the applications' effectiveness).

When congestion and awareness protocols operate independently, negative interactions or conflicts can arise, which can provoke unintended and negative adaptation loops that reduce the network and system performance. Limited efforts have been conducted to jointly consider congestion and awareness control processes. In this context, this paper proposes INTERN, a protocol that integrates different congestion and awareness control techniques. In particular, INTERN integrates control mechanisms inspired by LIMERIC and PULSAR congestion control protocols with the awareness control design policy proposed in [24]. The policy proposed in [24] considers that each vehicle proactively adapts its transmission parameters to the minimum needed to satisfy its application's requirements. This paper is an extension of our previous work [25].

3. Considered congestion and awareness control protocols

3.1. Congestion control

LIMERIC [14] adapts the packet transmission frequency of each vehicle based on a target channel load level and the channel load it locally measures every time window. The packet transmission frequency of vehicle j at time instant t is calculated with the following equation:

$$r_j(t) = (1 - \alpha)r_j(t - 1) + \beta(r_g - r(t - 1)) \tag{1}$$

where r_g is the overall target packet frequency, $r(t - 1)$ represents the measured overall packet frequency by the vehicle in the previous time window, and $\alpha = 0.1$ and $\beta = 1/150$ are system constants. In practical implementations, vehicles can measure the load in terms of Channel Busy Ratio (*CBR*), i.e. the fraction of time that the channel is sensed as busy. r_g and $r(t - 1)$ can then be replaced by CBR_{max} and $CBR(t - 1)$, respectively, with CBR_{max} representing the target channel busy ratio and $CBR(t - 1)$ the channel busy ratio measured by vehicle j. As noted in [14], α and β have a high influence on the system's stability that is represented by the capacity to reach a solution in which the transmission parameters of vehicles are stable if the conditions remain constant (e.g. traffic density conditions). A stable system operation ensures that the convergence point, i.e. the channel busy ratio at which the system converge in a stable situation and the convergence speed, i.e. the velocity with which the final solution (channel busy ratio and transmission parameters of each vehicle) have been reached. LIMERIC has been shown to provide high accuracy and stability in scenarios where all the nodes measure

the same channel load when utilizing an additional mechanism that establishes a maximum gain in Eq. (1) [14].

PULSAR [15] is a congestion control protocol that adapts the packet transmission frequency of each vehicle using an Additive Increase Multiplicative Decrease (AIMD) technique. PULSAR proposes that each vehicle piggybacks its locally experienced *CBR* and the maximum *CBR* experienced by its neighbors since the transmissions from each vehicle can influence the load up to a distance of approximately two hops. Each vehicle adapts its packet transmission frequency based on the maximum *CBR* among its experienced *CBR* and the *CBR* levels reported by its neighbors (i.e. the maximum *CBR* within two hops). If the resulting *CBR* is above CBR_{max}, the packet transmission frequency is decreased by a multiplicative factor; otherwise the packet transmission frequency is increased by an additive factor. Additionally, the multiplicative and additive factors are modified depending on whether the current packet transmission frequency of the vehicle is above or below the packet transmission frequency of neighboring vehicles. To this aim, each vehicle periodically calculates the average packet transmission frequency of the neighboring vehicles; each vehicle also piggybacks in its beacons its packet transmission frequency. This mechanism and the AIMD process ensure that vehicles within two hops distance converge to the same packet transmission frequency.

A congestion control protocol that combines LIMERIC and PULSAR is being discussed within the ETSI standardization process [16,17]. The combined scheme uses LIMERIC's linear control process and PULSAR's *CBR* information exchange. The combined protocol (referred to as LIMERIC+PULSAR) is used as benchmark in this study.

3.2. Awareness control

This study implements the MINT (minimum packet transmission frequency) awareness control protocol that follows the design policy proposed in [24]. Following this policy, each vehicle proactively adapts its transmission parameters to the minimum needed to satisfy its individual application's requirements. An application is satisfactorily supported if the number of beacons correctly received per second at the established warning distance is higher than the application's requirement in terms of packet reception frequency. MINT sets the packet transmission frequency equal to the application's packet reception frequency plus a fixed margin $\Delta T_f = 1$ Hz. The transmission power is then set to the level needed to ensure that the demanded packet reception frequency is guaranteed at the application's warning distance. To this aim, MINT identifies the transmission power needed utilizing the analytical model that relates the Packet Delivery Ratio (PDR) with the transmission power and the distance between transmitter and receiver proposed in [26].

4. INTERN - Integration of Congestion and Awareness Control

INTERN aims to configure the transmission parameters of each vehicle so that its applications' requirements can be satisfied and the channel load can be maintained below the target *CBR*. In this context, all vehicles implementing INTERN will tend to use the minimum transmission settings that satisfy their individual application's requirements under high

traffic density conditions. On the other hand, INTERN will enable vehicles to increase their transmission settings under low traffic densities so that the target *CBR* is reached and the channel is fully utilized. To achieve its objectives, INTERN integrates MINT with a control process inspired by LIMERIC and PULSAR. INTERN exploits the benefits of the 2-hops piggybacking proposed in PULSAR in order to achieve global fairness. Once INTERN configures the transmission frequency, it calculates the transmission power following the MINT protocol: the transmission power is set to the minimum power level needed to ensure that the demanded packet reception frequency is guaranteed at the application's warning distance.

INTERN configures the packet transmission frequency of each vehicle, T_f, as the minimum required by its application, R, plus certain margin ΔT_f.

$$T_f = R + \Delta T_f \tag{2}$$

The ΔT_f parameter is dynamically calculated by each vehicle using a control process. LIMERIC proposes to adapt T_f so that nearby vehicles are assigned similar packet transmission frequency values (and hence are allocated similar bandwidth). Instead, INTERN adapts ΔT_f to ensure that the individual application's requirements of each vehicle are satisfied. The control process is designed so that the channel load is maintained below the target *CBR* level CBR_{max}. ΔT_f is then adapted as a follows:

$$\Delta T_f = \Delta T_f^T + \frac{\Delta T_f^T}{CBR_{2hops}}(CBR_{max} - CBR_{2hops}) = \Delta T_f^T \frac{CBR_{max}}{CBR_{2hops}} \tag{3}$$

CBR_{2hops} is the maximum *CBR* experienced within two hops and is obtained following the PULSAR approach. To this aim, INTERN requires that each vehicle attaches to each beacon its locally experienced *CBR* and the maximum *CBR* experienced by its neighboring vehicles. Vehicles implementing INTERN increase ΔT_f (following Eq. (3)) when $CBR_{max} > CBR_{2hops}$. Similarly, vehicles decrease ΔT_f when $CBR_{max} < CBR_{2hops}$.

To achieve fairness at the application level, all vehicles should have a similar ΔT_f, i.e. they should apply similar increments of the packet transmission frequency with respect to the minimum they need. To ensure this is actually the case

for vehicles within two hops distance, INTERN applies the PULSAR piggybacking scheme to the ΔT_f parameter. As a result, each vehicle attaches to its beacons its current ΔT_f and the minimum ΔT_f received from its neighboring vehicles. ΔT_f^T in Eq. (3) is then calculated by each vehicle as the minimum ΔT_f reported by its neighbors. Thanks to this mechanism, vehicles will rapidly adapt to variable traffic density conditions.

We consider minimum and maximum values of 1 and 3 Hz (different minimum and maximum values could be considered) for the ΔT_f parameter so that the application's requirements can be satisfied but we avoid operating with packet transmission frequencies much higher than the ones required by the applications. The minimum packet transmission frequency of a vehicle will be therefore at least 1 Hz above the minimum required by its application.

5. Performance evaluation

The performance of INTERN has been evaluated using Matlab in different scenarios and considering different traffic densities. The results obtained have been compared to the ones obtained with MINT and the congestion control protocol that combines LIMERIC and PULSAR (LIMERIC+PULSAR).

5.1. Evaluation scenarios

Three evaluation scenarios have been selected to demonstrate the benefits of INTERN:

- Scenario 1 – intersection with LOS (Fig. 1a). In this scenario, vehicles are uniformly distributed on the roads shown in Fig. 1a. The scenario is characterized by the traffic density in vehicles/km/lane, and the length of each one of the four roads (3.5 km). This scenario does not consider buildings at intersection corners, and therefore all vehicles have LOS (Line-of-Sight) propagation conditions.
- Scenario 2 – intersection with NLOS (Fig. 1b). This scenario is similar to scenario 1, but considers the presence of buildings blocking the radio signal at intersection corners. The obstructing buildings have an important effect on the experienced propagation losses and the quality of vehicular communications [27]. In this scenario, vehicles that are close to the intersection can detect and receive messages from vehicles in all four intersecting streets. The obstruction caused by buildings results in that the rest of
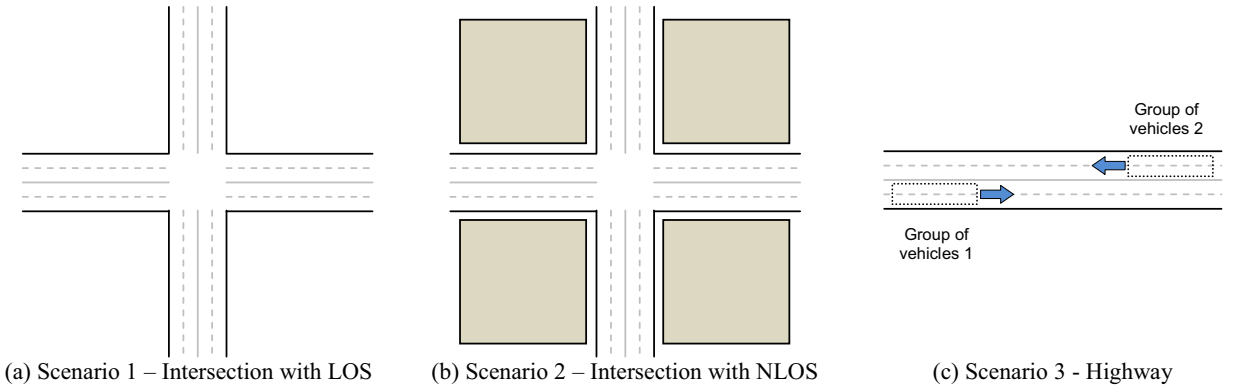

(a) Scenario 1 – Intersection with LOS   (b) Scenario 2 – Intersection with NLOS   (c) Scenario 3 - Highway

Fig. 1. Evaluation scenarios.

vehicles can only detect vehicles on the same street, and therefore experience a significantly lower channel load.

- Scenario 3 - highway (Fig. 1c). This scenario is aimed at evaluating the impact of the movement and speed of vehicles. In particular, this third scenario is used to evaluate the convergence and stability properties of the protocols when two groups of vehicles approach each other as illustrated in Fig. 1c. Each group of vehicles is 2 km long, occupies 2 lanes and is characterized by a uniform traffic density. All vehicles move at a constant speed of 120 km/h. The length of the road is 7 km, and the two groups of vehicles get perfectly aligned next to each other after $t = 75$ s.

All vehicles in the three scenarios periodically broadcast beacons and dynamically adapt their transmission parameters following the operation of the protocol under evaluation. All vehicles start using the same transmission power (by default $P_t = 33$ dBm) and a random packet transmission frequency (T_f) between 1 Hz and 10 Hz. Following the indications provided in [26], the Nakagami-m propagation model has been employed with $m = 3$.

Each vehicle in all three scenarios runs a vehicular application that requires that at least R beacons are correctly received per second by all vehicles within a given warning distance, W_d. To avoid limiting this study to a particular application, different combinations of application warning distance and required packet reception frequency have been considered. A first analysis has been performed considering that each vehicle sets its initial application requirements randomly, with the warning distance varying between 50 and 200 m and the packet reception frequency varying between 1 and 10 Hz. From these initial settings, the application requirements linearly vary during the simulation. A second analysis has been conducted considering constant and equal application requirements for all vehicles.

The capacity of each protocol to satisfy the application requirements is evaluated using the D_p metric. This metric represents the difference between the packet reception frequency demanded by the application and the number of packets that are actually received per second at the applications' warning distance. The requirements of an application are therefore satisfied if $D_p > 0$. The D_p values reported in this paper have been calculated taking into account packet losses due to propagation conditions.

CBR_{max} has been set to 0.6 following [14] that indicates that this is the CBR value that maximizes the throughput or number of successful messages exchanged per second. The CBR values computed in this study have been obtained from the aggregation of all packets sensed by each vehicle's radio interface, i.e. with a received signal higher than –90 dBm. Table 1 summarizes some of the most relevant communications and simulation parameters.

5.2. Scenario 1 – intersection with LOS

Scenario 1 has been mainly utilized to evaluate the spatial distribution of the channel load and the application's effectiveness (D_p). Figs. 2 and 3 plot the average spatial distribution of the CBR and D_p, respectively, as a function of the distance of the vehicles to the intersection; the results

Table 1
Communications and simulation parameters.

| Parameter	Value
Packet size [Bytes]	250
Min. and Max. transmission power [dBm]	−10 and 33
Min. and Max. packet transmission frequency [Hz]	1 and 20
Min. and Max. ΔT_f [Hz]	1 and 3
Data rate [Mbps]	6
Carrier sense threshold [dBm]	−90
Reception threshold [dBm]	−82
Target channel busy ratio (CBR_{max})	0.6
CBR measurement period [ms]	250
Warning distance required (W_d) [m]	50–200
Packet reception frequency required (R) [Hz]	1–10
Traffic density [vehicles/km/lane]	50, 75, 100
Simulation time [s] and simulation runs	150 and 10

are reported for different traffic densities. The vertical lines in Figs. 2 and 3 represent the 5th and 95th percentiles.

The MINT results in Fig. 2 show that high CBR levels are obtained at short distances to the intersection since the number of neighboring vehicles increases as a vehicle approaches the intersection. Additionally, the CBR experienced with MINT increases with the traffic density. This is the case because MINT configures each vehicle with the minimum transmission power and frequency required to satisfy its application requirements, and the protocol does not control the channel load. This results in that the application requirements are satisfied with a constant D_p metric independently of the traffic density (see Fig. 3). Under low and medium traffic densities, the use of the minimum required transmission settings also results in that the channel is not utilized to its full capacity since the maximum experienced CBR is below CBR_{max}. The experienced CBR with MINT only surpasses CBR_{max} under the highest simulated traffic density and for vehicles close to the intersection. This result demonstrates that in this situation it is not possible to satisfy the application requirements of all vehicles without exceeding CBR_{max}.

Fig. 2 shows that LIMERIC+PULSAR is able to strictly maintain the CBR experienced below CBR_{max} irrespective of the traffic density and the transmission power; Fig. 2 shows the results achieved with 3 fixed transmission power levels. Vehicles use a constant transmission power but dynamically adapt their packet transmission frequency to the channel load. When vehicles utilize the maximum transmission power ($P_t = 33$ dBm in this study), they are able to detect other vehicles at large distances, and therefore the number of detected vehicles increases. In this context, LIMERIC+PULSAR results in a packet transmission frequency of around 2 Hz when P_t is equal to 33 dBm. This results in negative D_p values for nearly all vehicles when utilizing a transmission power of 33 dBm (see Fig. 3). Reducing the transmission power decreases the vehicles' transmission range and enables the use of higher packet transmission frequencies with LIMERIC+PULSAR. This results in that LIMERIC+PULSAR experiences higher D_p values as the transmission power is reduced (Fig. 3). For $P_t = 23$ dBm, vehicles located at longer distances to the intersection can achieve positive D_p values since they are able to use higher packet transmission frequencies compared to vehicles close to the intersection. For $P_t = 13$ dBm, Fig. 3 shows that a high percentage of vehicles experience positive D_p values,
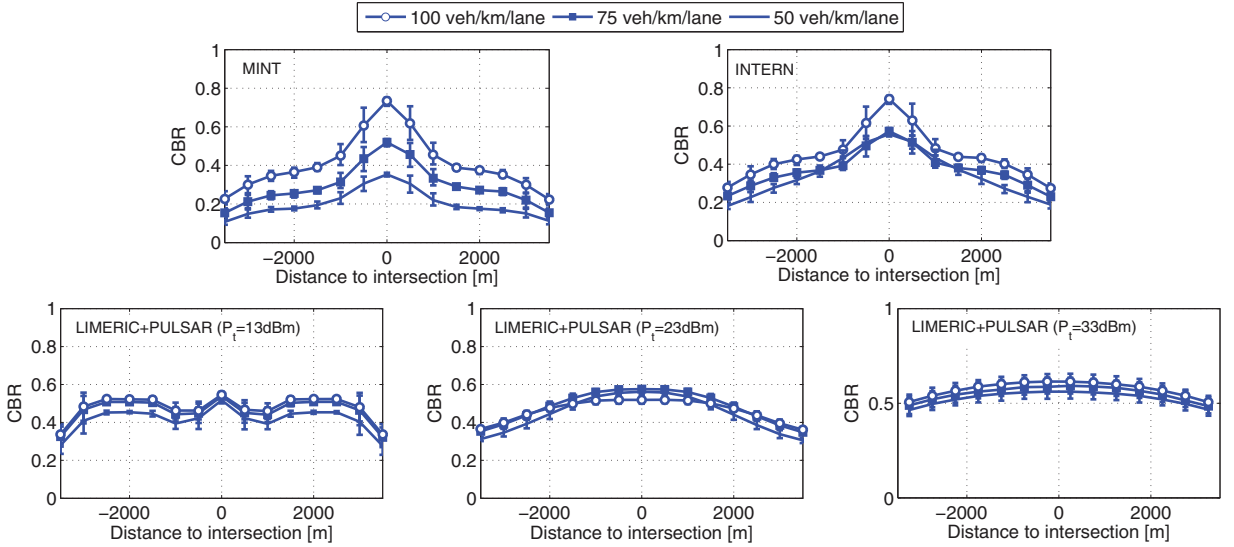
Fig. 2. Average spatial distribution of the *CBR* (Channel Busy Ratio) under different traffic densities in scenario 1 (intersection with LOS). The vertical lines represent the 5th and 95th percentiles.
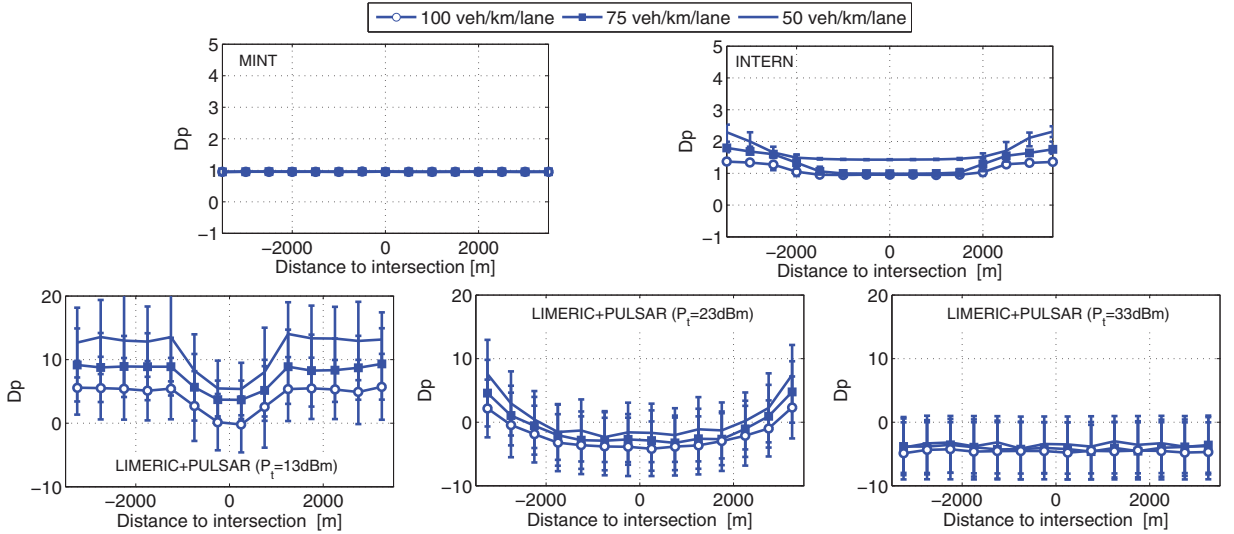
Fig. 3. Average spatial distribution of the D_p metric under different traffic densities in scenario 1 (intersection with LOS). The application requirements are satisfied if $D_p > 0$. The vertical lines represent the 5th and 95th percentiles.

in particular under low traffic densities. LIMERIC+PULSAR provides similar packet transmission frequencies to nearby vehicles irrespective of their application requirements. These results emphasize the need for the integration of congestion and awareness control protocols so that the requirements of the maximum possible number of vehicles are satisfied while efficiently utilizing the channel capacity.

Fig. 2 also illustrates the average spatial distribution of the *CBR* experienced when implementing the new proposal INTERN. Rather than configuring vehicles with the minimum transmission settings required, INTERN increases them until the CBR_{max} level is reached at the center of the intersection. Fig. 2 shows that INTERN can maintain the *CBR* below CBR_{max} in the scenarios with low and medium traffic densities. INTERN does not increase the transmission set-

tings of vehicles experiencing low *CBR* values so that vehicles close to the intersection do not experience a *CBR* level above CBR_{max}. This is possible thanks to the piggybacking process incorporated into INTERN. When the traffic density increases to 100 veh/km/lane, the vehicles close to the intersection use the minimum transmission power and packet frequency required to satisfy their application requirements. This results in that these vehicles experience with INTERN the same *CBR* (Fig. 2) and D_p values (Fig. 3) they would experience with MINT. This feature demonstrates the capacity of INTERN to adapt its operation to the traffic density conditions and experienced load levels. The results in Fig. 3 also show that when the traffic density decreases, vehicles can increase their packet transmission frequency to fully utilize the channel; this results in higher D_p levels. Higher D_p levels reduce
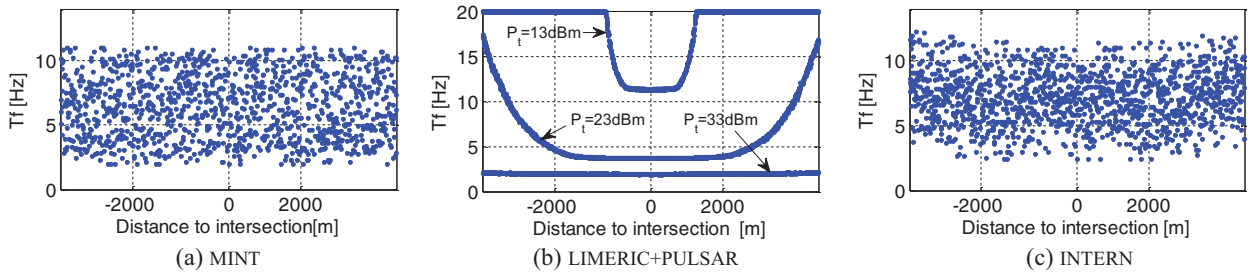
Fig. 4. Snapshot of the packet transmission frequency used by each vehicle after 50 s of simulation time. Scenario 1 and a traffic density of 50 veh/km/lane.
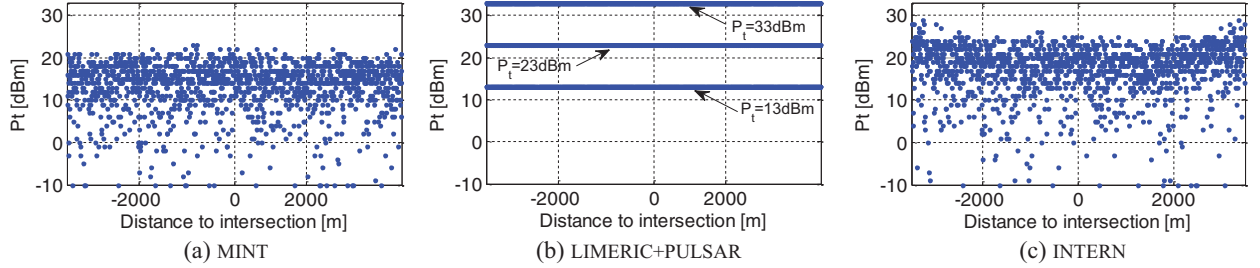

Fig. 5. Snapshot of the transmission power used by each vehicle after 50 s of simulation time. Scenario 1 and a traffic density of 50 veh/km/lane.

the risks provoked by sudden or unexpected channel variations that could result in that the transmission settings are not capable of guaranteeing the application requirements.

Figs. 4 and 5 represent a snapshot of the packet transmission frequency and power used by each vehicle after 50 s of simulation time. INTERN and MINT adapt the vehicles' packet transmission frequency based on their individual application requirements. This results in that vehicles implementing INTERN and MINT utilize very different packet transmission frequency and power (Fig. 4 and Fig. 5). On the other hand, the use of LIMERIC+PULSAR results in that all vehicles always use the same power, but their packet transmission frequency is adapted so that similar values are utilized by neighboring vehicles. Fig. 4b shows how reducing the transmission power with LIMERIC+PULSAR allows increasing the packet transmission frequency. For $P_t = 13$ dBm, most of the vehicles are configured with the maximum packet transmission frequency considered in this study ($T_f = 20$ Hz).

The variability shown in Figs. 4 and 5 for the packet transmission frequency and power utilized when implementing INTERN is due to the fact that the application requirements for each vehicle have been randomly selected so that the study is not restricted to a particular application. Another way of observing the performance of the proposal is to look into the stability of the D_p metric for two selected vehicles. This is shown in Fig. 6. The oscillations of the D_p metric are due to INTERN's control process and are in the same order or lower than e.g. the variations in packet transmission frequency reported in the literature [14].

5.3. Scenario 2 – intersection with NLOS

The second scenario is characterized by the presence of buildings at the intersection corners. These buildings block radio propagation and can severely impact the communications between vehicles approaching the intersec-
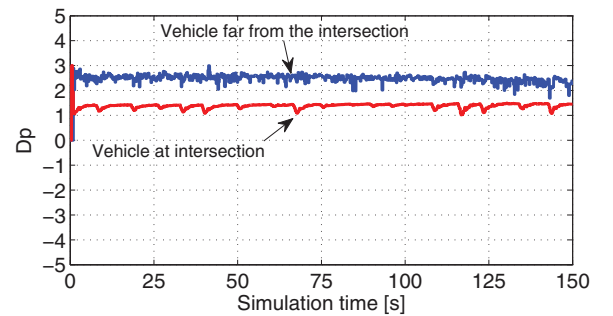

Fig. 6. Stability of the D_p metric with INTERN for two selected vehicles. Scenario 1 and a traffic density of 50 veh/km/lane.

tion from different directions. This has been shown, for example, to have an important negative effect for applications such as intersection collision warning [8]. However, the signal attenuation produced by buildings also reduces the channel load levels experienced by the majority of vehicles in the scenario. This is the case because vehicles can only detect packets transmitted by other vehicles under NLOS conditions if they are at short distances. In scenario 2, vehicles located at the intersection have LOS conditions with all vehicles in the scenario, and therefore are not affected by the attenuation produced buildings.

Figs. 7 and 8 plot the average spatial distribution of the *CBR* and D_p as a function of the distance of the vehicles to the intersection. The results are plotted for different traffic densities in scenario 2, and the vertical lines represent the 5th and 95th percentiles. The comparison of Figs. 2 and 7 shows that MINT produces similar channel load levels for vehicles located at medium and high distances to the intersection in scenarios 1 and 2. This is the case because MINT adapts the transmission parameters of each vehicle to the minimum needed to satisfy its requirements. As a result,
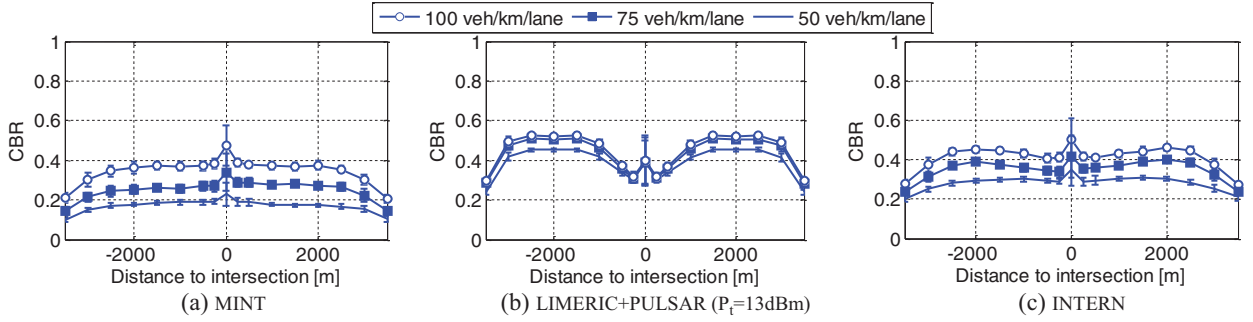
Fig. 7. Average spatial distribution of the *CBR* (Channel Busy Ratio) under different traffic densities in scenario 2 (intersection with NLOS). The vertical lines represent the 5th and 95th percentiles.
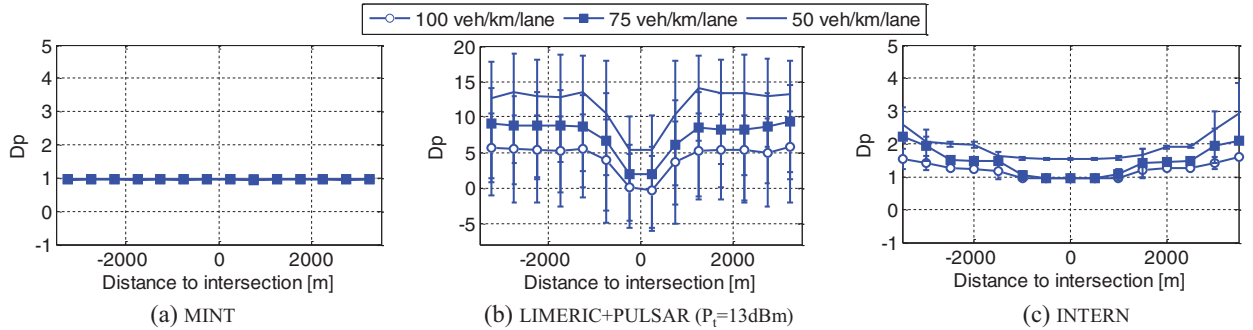
Fig. 8. Average spatial distribution of the D_p metric under different traffic densities in scenario 2 (intersection with NLOS). The application requirements are satisfied if $D_p > 0$. The vertical lines represent the 5th and 95th percentiles.

vehicles at medium and high distances to the intersection do not detect vehicles at perpendicular streets independent of whether there are buildings at the intersection corners or not. However, the channel load experienced by vehicles close to the intersection is significantly different for scenarios 1 and 2. Fig. 7a shows that only vehicles located at the intersection experience high *CBR* levels when implementing MINT in scenario 2. The results in Fig. 8a show that the same conclusions can be reached in scenario 1 and 2 with regards to the impact of MINT on the D_p metric: the application requirements are satisfied with a constant D_p metric independent of the traffic density.

LIMERIC+PULSAR uses a fixed transmission power and adapts the packet transmission frequency of each vehicle to maintain the *CBR* below CBR_{max}. In scenario 1, the best results for LIMERIC+PULSAR in terms of application' effectiveness were obtained with the lowest considered transmission power. The results obtained by LIMERIC+PULSAR in scenario 2 are then only shown for $P_t = 13$ dBm. The packet transmission frequency obtained with LIMERIC+PULSAR in scenario 2 is similar to the one obtained in scenario 1. This is due to the fact that vehicles adapt their packet transmission frequency based on the highest *CBR* experienced at 2 hops. This *CBR* corresponds to the one experienced at the intersection, and that is less affected by the presence of the obstructing buildings. As a consequence, the presence of buildings in scenario 2 results in a reduction of the channel load levels obtained with LIMERIC+PULSAR (Fig. 7b) compared to scenario 1 except for vehicles located at the intersection. Since vehicles use similar packet transmission frequency values in scenarios 1 and

2, no significant differences are observed with regards to the experienced D_p levels between both scenarios.

Compared to MINT, INTERN increases the transmission parameters until the CBR_{max} level is reached at the center of the intersection. The results in Fig. 7c show that INTERN is capable to maintain the *CBR* below CBR_{max} in scenario 2. Fig. 7c also shows that vehicles experiencing low *CBR* values do not increase their transmission parameters to avoid augmenting the *CBR* experienced by vehicles close to the intersection. The presence of buildings in scenario 2 results in that INTERN can increase the vehicles' transmission parameters compared to scenario 1. This explains why higher D_p levels are obtained in scenario 2 (Fig. 8c) compared to scenario 1 (Fig. 3).
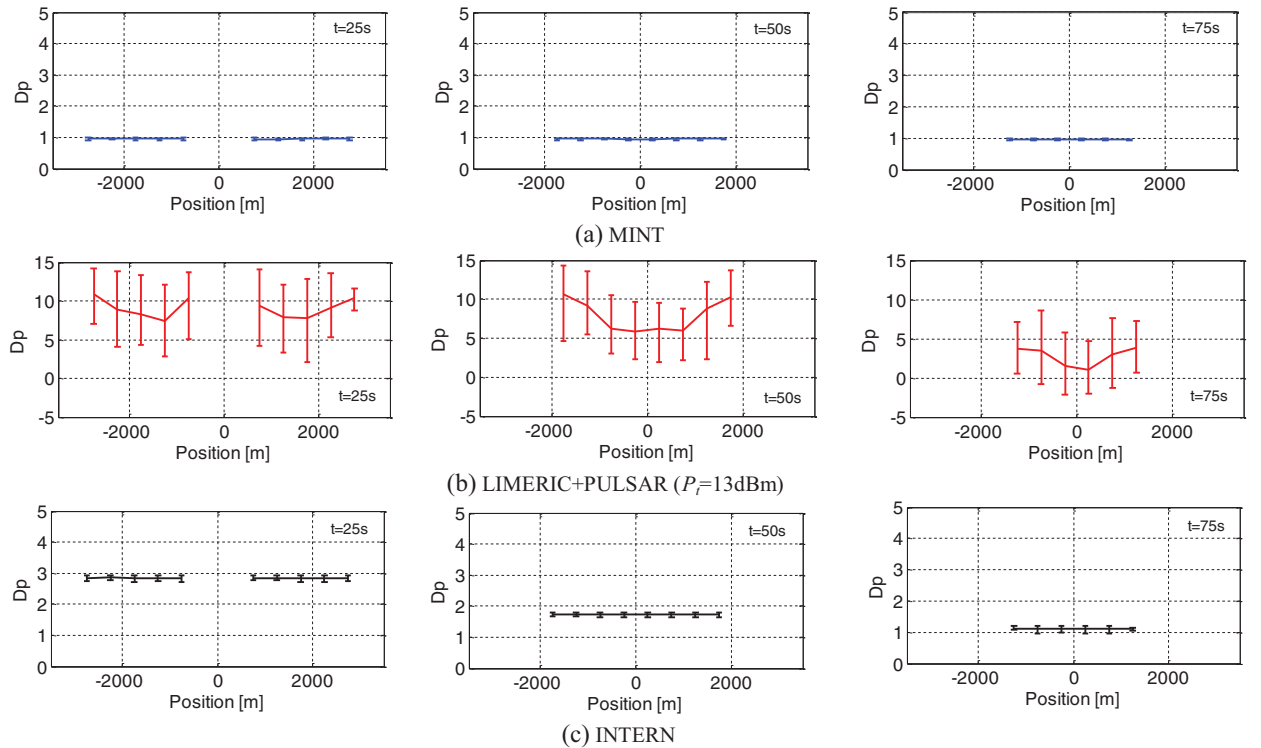
5.4. Scenario 3 - highway

Scenario 3 was selected to analyze the stability and convergence of the protocols. Figs. 9 and 10 plot the *CBR* and D_p metrics experienced in scenario 3 as a function of the position of the vehicles in the highway (Position = 0 represents the center of the scenario). The metrics are depicted for a traffic density of 75 veh/km/lane and time instants $t = 25$ s, $t = 50$ s (when approximately the two groups of vehicles reach the center of the scenario) and $t = 75$ s (when the two groups of vehicles are aligned one next to each other).

Fig. 9a shows that the *CBR* increases as the two groups of vehicles approach the center of the scenario when utilizing MINT. This is due to the fact that vehicles implementing MINT do not adapt their parameters as a function of the experienced channel load. As a result, when the two groups are far
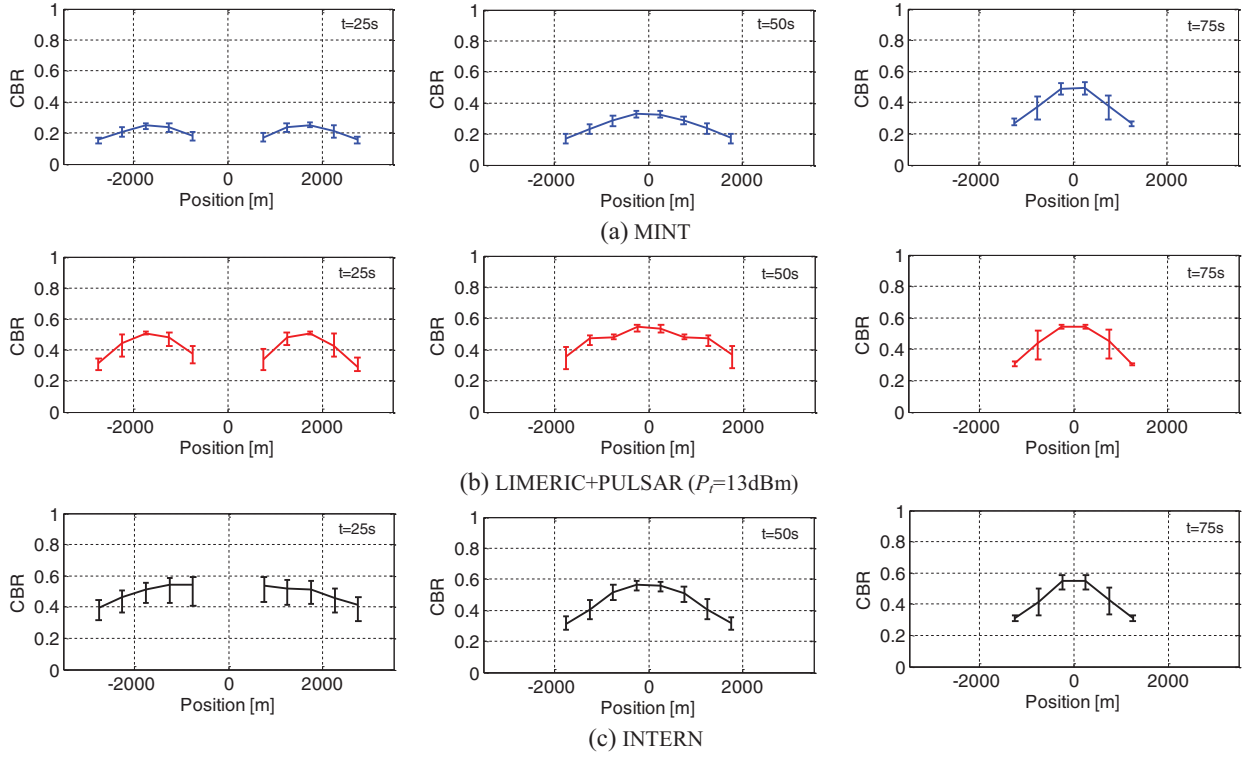
Fig. 9. CBR (Channel Busy Ratio) at $t = 25$ s, $t = 50$ s and $t = 75$ s. Scenario 3 (highway) and a traffic density of 75 veh/km/lane. The vertical lines represent the 5th and 95th percentiles.

Fig. 10. D_p metric at $t = 25$ s, $t = 50$ s and $t = 75$ s. Scenario 3 (highway) and a traffic density of 75 veh/km/lane. The vertical lines represent the 5th and 95th percentiles. The application requirements are satisfied if $D_p > 0$.
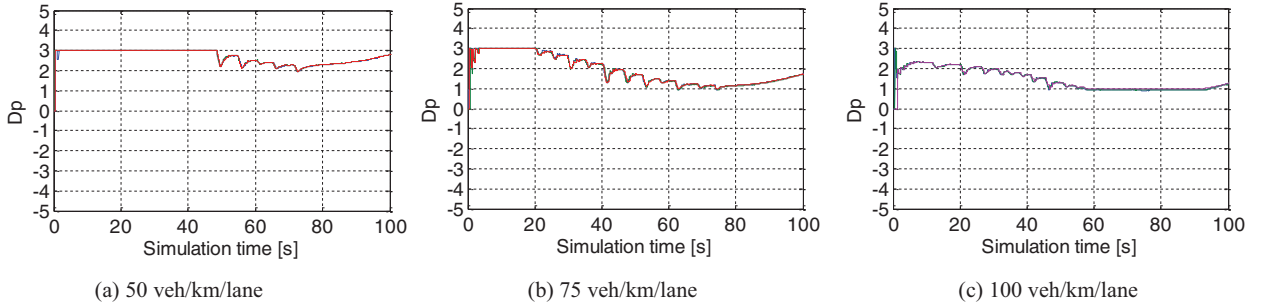
Fig. 11. Stability of the D_p metric when implementing INTERN. Scenario 3 (highway) and different traffic densities.

from each other ($t = 25$ s), the CBR is much lower than when the two groups of vehicles are aligned ($t = 75$ s). Since vehicles always use the minimum required transmission settings, the D_p metric is constant during the simulation (Fig. 10a). Similar trends have been obtained for 50 veh/km/lane despite the different experienced channel load levels. When the traffic density increases to 100 veh/km/lane, the target CBR_{max} level is exceeded at the center of the scenario when the two groups of vehicles align at $t = 75$ s. This result demonstrates that it is not possible either to satisfy the application requirements of all vehicles in scenario 3 without exceeding CBR_{max}.

Vehicles implementing LIMERIC+PULSAR transmit at a constant transmission power level and adapt the packet transmission frequency based on the experienced channel load. Fig. 9b shows that LIMERIC+PULSAR maintain the maximum CBR level below CBR_{max} as the two groups of vehicles approach each other. With LIMERIC+PULSAR, neighboring vehicles tend to use similar packet transmission frequencies. Since they can have different application requirements, they can experience different D_p levels (Fig. 10b) and negative values can be observed at $t = 75$ s (i.e. when the two groups of vehicles are aligned).

With INTERN, vehicles adapt their transmission parameters based on their individual application requirements and the channel load experienced. At $t = 25$ s, the two groups of vehicles are far from each other and the experienced channel load is low (Fig. 9c). In this case, vehicles operate at the maximum ΔT_f and constant D_p values are obtained (Fig. 10c). As the two groups of vehicles approach each other, the channel load increases and the ΔT_f parameter decreases, which results in lower but still positive D_p metric. Using the information exchange process that is integrated into INTERN, nearby vehicles exhibit very similar D_p values, thereby satisfying the objective of fairness at the application level. Similar trends have been obtained for 50 veh/km/lane: the CBR level was also maintained below CBR_{max} and the D_p metric was positive (higher D_p levels were observed due to the lower traffic density). When traffic density increases to 100 veh/km/lane, all vehicles are configured to use the minimum transmission settings they need to satisfy their requirements at $t = 75$ s. Despite this configuration, the target CBR_{max} level is again exceeded when the two groups of vehicles are aligned.

After $t = 75$ s, the two groups of vehicles start moving away from each other. At $t = 100$ s, the measured channel load and application's effectiveness are similar than the ones experienced at $t = 50$ s for all three protocols under evaluation. At $t = 125$ s, the values obtained are similar to the ones experienced at $t = 25$ s. These results show that the 3 protocols are able to recover from the maximum load experienced at $t = 75$ s, and return to the initial values as the two groups of vehicles separate from each other.

Fig. 11 illustrates the evolution of the D_p metric with the simulation when vehicles implement the INTERN proposal. The evolution is represented for three selected vehicles in scenario 3 and with different traffic densities. The vehicles were selected at the head, middle and tail of group 1 in scenario 3 (Fig. 1c). After a short initial transition period, INTERN reaches a stable condition, and provides similar and constant D_p values to all vehicles. After $t = 50$ s, the experienced channel load increases and the D_p metric decreases with smooth and similar variations for the three vehicles. The minimum D_p values are experienced around $t = 75$ s as the two groups of vehicles align; the alignment produces the highest traffic density level in the simulation. After $t = 75$ s, the traffic density decreases and INTERN is able to recover to the initial D_p metrics.

5.5. Constant and equal application requirements

Previous sections considered that each vehicle selected randomly its application requirements so that the study was not limited to a particular application. The vehicles selected randomly a warning distance (W_d) between 50 and 200 m, and a packet reception frequency (R) between 1 and 10 Hz. In this section, we evaluate the performance of the three protocols considering constant and equal application requirements for all vehicles during each simulation run. Different simulation runs have been executed with the warning distance selected within the range of 50–150 m, and the packet reception frequency within the range of 1–10 Hz. The objective behind this analysis is to study the influence of the application requirements on the channel load and the applications' effectiveness.

With MINT, each vehicle sets its transmission power and packet transmission frequency to the minimum level needed to satisfy its application requirements. As a result, the experienced channel load is directly influenced by the application requirements, and the application requirements are satisfied with a constant D_p metric. Fig. 12 illustrates the average CBR experienced with MINT for varying application requirements and different traffic densities in scenario 1 (intersection with LOS). Fig. 12 shows that augmenting the application

(a) 50 veh/km/lane

(b) 75 veh/km/lane

(c) 100 veh/km/lane
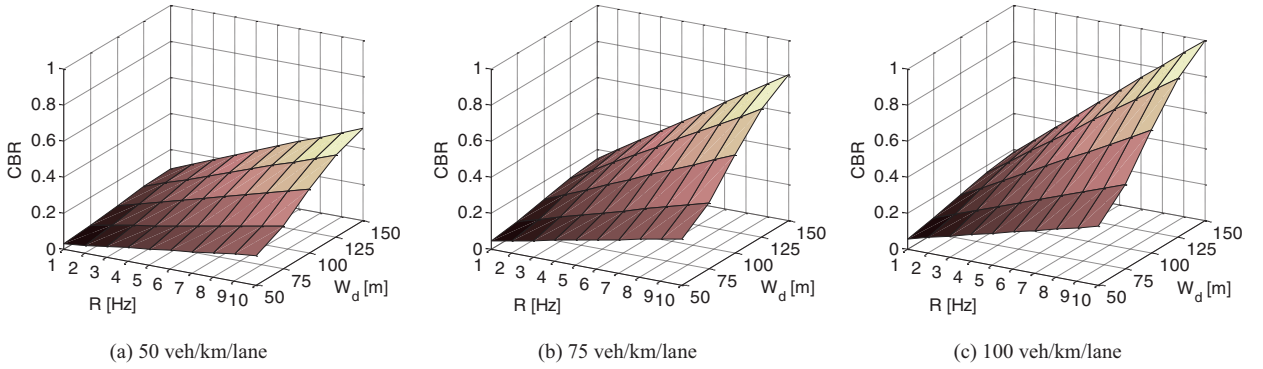
Fig. 12. Average CBR (Channel Busy Ratio) experienced with MINT for different application requirements in scenario 1 (intersection with LOS).

(a) 50 veh/km/lane

(b) 75 veh/km/lane

(c) 100 veh/km/lane
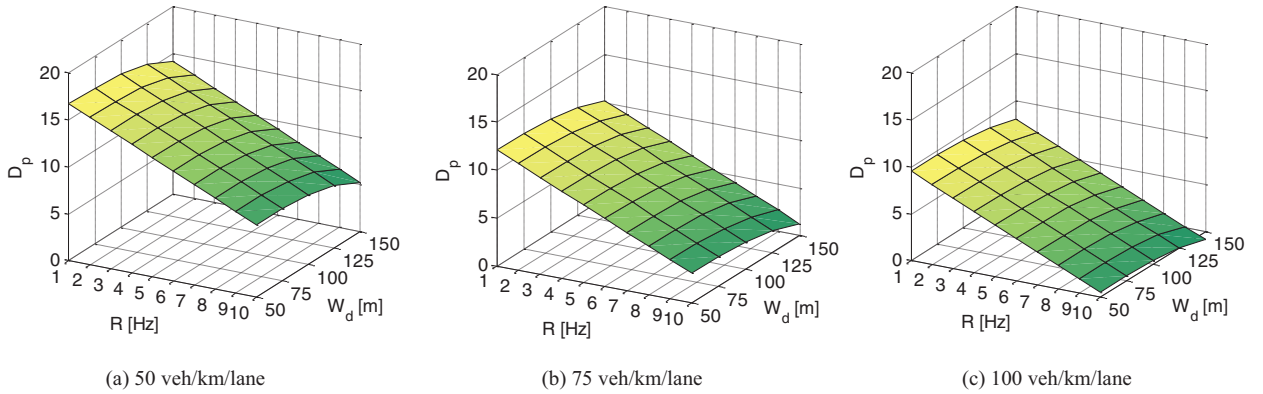
Fig. 13. Average D_p metric experienced with LIMERIC+PULSAR (P_t = 13 dBm) for different application requirements in scenario 1 (intersection with LOS).

requirements (W_d and R) increases the experienced *CBR* level with MINT since each vehicle adapts its transmission parameters according to its application requirements. The experienced *CBR* level also increases with the traffic density. Fig. 12 also shows that the impact of the application requirements on the *CBR* can be important, and high channel load levels can be experienced even at medium traffic densities when applications have high requirements.

LIMERIC+PULSAR adapts the packet transmission frequency of each vehicle to strictly maintain the *CBR* below CBR_{max} irrespective of the traffic density or the application requirements. Fig. 13 depicts the average D_p metric obtained with LIMERIC+PULSAR for different application requirements and traffic densities in scenario 1 with P_t = 13 dBm. Fig. 13 shows that an increment of the required packet reception frequency decreases the average D_p. This is due to the fact that the D_p metric represents the difference between the packet reception frequency required by the application and the number of packets that are actually received per second at the applications' warning distance. With LIMERIC+PULSAR, the number of packets correctly received per second at the warning distance does not change with R. As a result, if R is increased, the average D_p metric decreases.

Figs. 14 and 15 represent the average *CBR* and D_p obtained with INTERN. When the requirements and the traffic density are low, INTERN increases the transmission settings to all vehicles, which improves their D_p metric accordingly. Fig. 15

shows that the maximum D_p value (D_p = 3 in this study) is obtained with the lowest application requirements. On the other hand, INTERN sets each vehicle's parameters to the minimum needed to satisfy their requirements and minimize the channel load when the traffic density and application requirements increase to their maximum simulated values. The experienced *CBR* can surpass CBR_{max} when the requirements are high, although in that case the vehicles are configured with the minimum parameters needed to satisfy their application's requirements. This result demonstrates that in this situation it is not possible to satisfy the application requirements of all vehicles without exceeding the target CBR_{max} value.

6. Discussion

The results reported in this paper have shown the relevant influence of the transmission parameters on the channel load generated and the applications' effectiveness. Congestion control protocols that solely adapt the transmission parameters to control the channel load can hence have an important influence on the applications' effectiveness. Similarly, awareness control protocols that adapt the transmission parameters to control the capacity of each vehicle to communicate with nearby vehicles can also influence the experienced channel load. This study therefore suggests that congestion and awareness control protocols can be considered together. Existing protocols such as LIMERIC are being
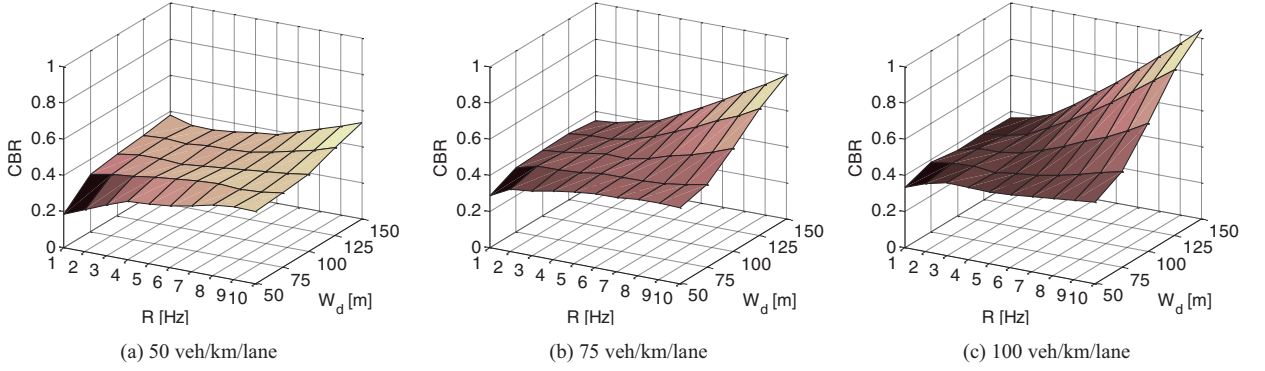
(a) 50 veh/km/lane　　　　　　　　(b) 75 veh/km/lane　　　　　　　　(c) 100 veh/km/lane

Fig. 14. Average CBR (Channel Busy Ratio) experienced with INTERN for different application requirements in scenario 1 (intersection with LOS).

(a) 50 veh/km/lane　　　　　　　　(b) 75 veh/km/lane　　　　　　　　(c) 100 veh/km/lane

Fig. 15. Average D_p metric experienced with INTERN for different application requirements in scenario 1 (intersection with LOS).

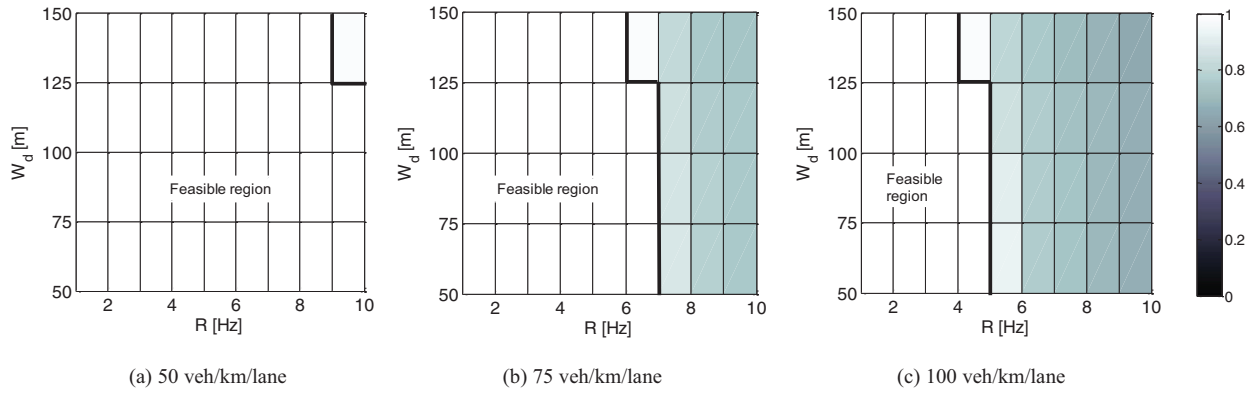(a) 50 veh/km/lane　　　　　　　　(b) 75 veh/km/lane　　　　　　　　(c) 100 veh/km/lane
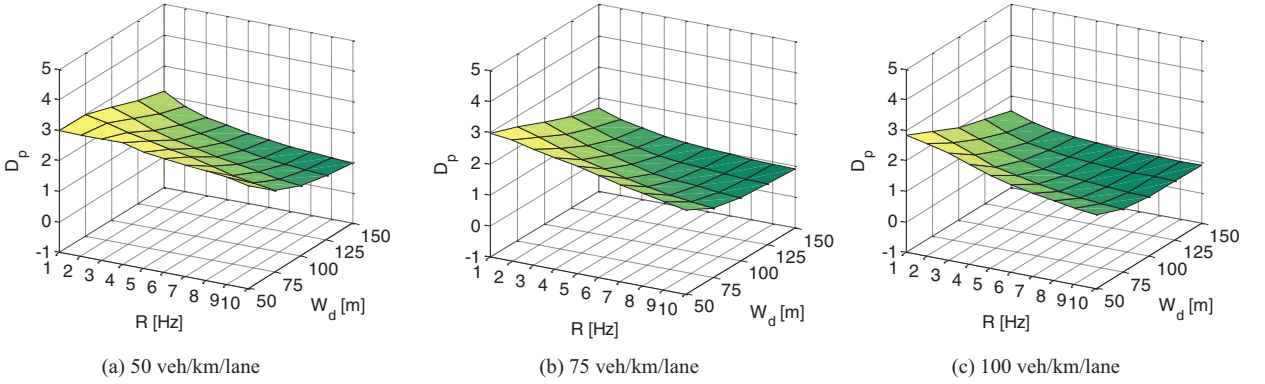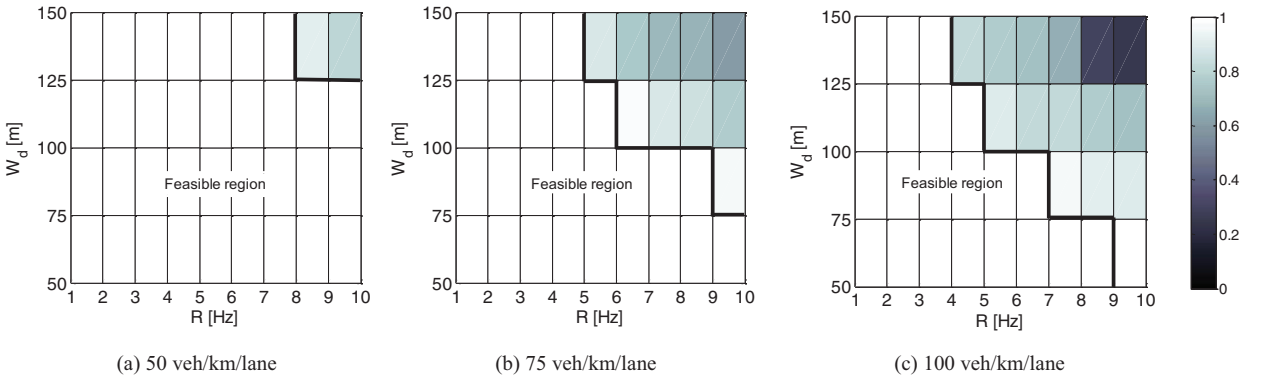
Fig. 16. Feasible regions for different combinations of application requirements considering INTERN. The results are shown for different traffic densities under scenario 1 (intersection with LOS). Each region is colored based on the proportion of vehicles experiencing a channel load below $CBR_{max} = 0.6$ and an application's effectiveness $D_p > 0$.

evolved in this direction to differentiate the requirements from different vehicles. For example, EMBARC [28] adapts each vehicle's packet transmission frequency using LIMERIC, but allows specific vehicles (e.g. highly dynamic vehicles) to transmit additional packets to reduce the tracking error of surrounding vehicles. With EMBARC, the target channel load can be maintained by reducing the packet transmission frequency to vehicles that do not have stringent needs. Specific vehicles can then be prioritized. LIMERIC was also extended in [29] to converge to weighted fair packet transmission fre-

quencies. With this extension, two (or more) vehicles could converge to a desired ratio of packet transmission frequencies, if such ratio is known. This approach enables differentiating vehicles with different needs while controlling the channel load. For example, emergency vehicles could be provided with double packet transmission frequency than the rest of vehicles.

Another way of looking into the protocol performance is presented in Figs. 16 and 17. These figures identify the feasible regions for scenario 1 (intersection with LOS)

Fig. 17. Feasible regions for different combinations of application requirements considering LIMERIC+PULSAR. The results are shown for different traffic densities under scenario 1 (intersection with LOS). Each region is colored based on the proportion of vehicles experiencing a channel load below $CBR_{max} = 0.6$ and an application's effectiveness $D_p > 0$.

considering INTERN (the same feasible regions are obtained with MINT) and LIMERIC+PULSAR, respectively. The figures consider that all vehicles have equal and constant application requirements. The figures depict a score (between 0 and 1) for each combination of warning distance and packet reception frequency required by the application. This score is equal to the proportion of vehicles experiencing a channel load below $CBR_{max} = 0.6$ and an application's effectiveness $D_p > 0$. As a result, a score equal to 1 is obtained when the requirements of all vehicles could be satisfied without overloading the channel (i.e. without exceeding CBR_{max}). Feasible regions are hence defined as the regions (i.e. the combinations of W_d and R) with a score equal to 1. Figs. 16 and 17 show the feasible regions that can be obtained with IN-TERN and LIMERIC+PULSAR for various traffic densities. Despite the significant improvements provided by both protocols, Figs. 16 and 17 also show the difficulties to ubiquitously satisfy the application requirements when operating under medium and high traffic densities. A higher number of lanes or packet payload could in fact further increase the limitations observed in Figs. 16 and 17.

An additional communications challenge will also emerge with the introduction of future automated and connected vehicles. First, the relation between relative speed and intervehicle distance will notably change when vehicles are automatically driven, so higher traffic densities at higher speeds might be possible. Automated vehicles could also require the exchange of richer information between vehicles, for example, sensors (including video) information. Cooperative perception technology is currently being investigated to increase situational awareness for cooperative automated driving. Recent studies suggest that cooperative perception could require the transmission of processed images and laser scans 20 times per second [30], which would notably increase the channel load and the communication requirements of future automated and connected vehicles.

7. Conclusions

This paper has proposed and evaluated INTERN, an integrated congestion and awareness control protocol that dy-namically adapts the transmission parameters taking into account the vehicle's application requirements and the experienced channel load. The obtained results demonstrate that INTERN is able to maintain the channel load under control while ensuring that the application requirements of each vehicle are satisfied. The conducted investigation has also shown that INTERN can maintain stable levels of the channel load and the applications' effectiveness. Moreover, INTERN is able to dynamically adapt its operation to variations in traffic density and in terms of application requirements. The study has also highlighted the challenges ahead with emerging automated vehicles. Further investigations are hence needed to efficiently and reliably support the communication requirements of future vehicular applications, which could be especially demanding with the introduction of automated connected vehicles.

Acknowledgment

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