Adaptive Beaconing for Congestion and Awareness Control in Vehicular Networks

Miguel Sepulcre[1], Javier Gozalvez[2], Onur Altintas[1] and Haris Kremo[1]
[1]TOYOTA InfoTechnology Center, Tokyo, Japan
[2]UWICORE, Ubiquitous Wireless Communications Research Laboratory, Miguel Hernandez University of Elche
Elche (Alicante), Spain
msepulcre@jp.toyota-itc.com, j.gozalvez@umh.es, onur@jp.toyota-itc.com and hkremo@jp.toyota-itc.com

***Abstract*—Cooperative vehicular networks require the exchange of positioning and basic status information between neighboring nodes to support higher layer protocols and applications, including active safety applications. The information exchange 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 of such messages will be key for the reliable and efficient operation of the system. On one hand, congestion control protocols need to be applied to control the channel load, typically through the adaptation of the transmission parameters based on certain channel load metrics. On the other hand, awareness control protocols are also required to adequately support cooperative vehicular applications. Such 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 the system. To this aim, this paper proposes and evaluates INTERN, a new control protocol that integrates two congestion and awareness control processes. The simulation results obtained demonstrate that INTERN is able to satisfy the application's requirements of all vehicles, while effectively controlling the channel load.**

Keywords*— Vehicular networks, congestion control, awareness control

I. 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 information exchange 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 5.9GHz frequency band [1]. Such 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 such applications, each vehicle needs to continuously receive updated information from all vehicles located within certain warning distance. The requirements of this type of applications can be defined in terms of warning distance [2] and packet reception frequency (inverse of packet inter-reception time) [3]. Different applications can have different warning distance and packet reception frequency requirements [4] and they can also depend on the context conditions of the vehicle [5].

To adequately support cooperative vehicular applications, a number of awareness control protocols have been proposed in the literature [6]. Such 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. For example, the work in [7] 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 protocol proposed in [8] 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 [9], the packet transmission frequency is adapted to bound the tracking errors of surrounding vehicles.

Given that beacons are periodically transmitted by all vehicles, a significant portion of the control channel is likely to be occupied by them, and the control channel can easily get congested. To ensure its efficient operation, congestion control protocols that dynamically adapt the transmission parameters of beacons have also been proposed. Two of the most relevant congestion protocols available in the literature are LIMERIC [10] and PULSAR [11]. They propose the adaptation of the packet transmission frequency based on the channel load experienced, and set the transmission power to the maximum level allowed. Both protocols are able to maintain the channel load below certain target threshold, irrespective of the vehicular traffic density, and are being discussed at ETSI TC ITS, given their potential to be part of the DCC (Decentralized Congestion Control) set of standards. Other congestion control approaches are also available in the literature. For example, in [12] the transmission power of each vehicle is calculated based on the number of neighboring vehicles detected and other metrics such as the estimated carrier sensing range. Other studies propose sensing the wireless channel and reducing the transmission power when a channel load threshold is exceeded [13], or when the number of messages in the MAC queue is above certain maximum level [14].

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 [11], i.e. when the performance/configuration of the vehicle under the most adverse conditions is maximized. Congestion control protocols have been therefore 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 application's effectiveness.

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 the system. 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 distances between vehicles. 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 communication parameters of vehicles under free-flow conditions due to their higher application's requirements. As a result, the separated design 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 two 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. To this aim, INTERN integrates the awareness control design policy proposed in [15], where each vehicle proactively adapts its transmission parameters to the minimum needed to satisfy its application's requirements, with some mechanisms proposed in LIMERIC and PULSAR congestion control protocols.

II. BENCHMARK CONGESTION AND AWARENESS CONTROL PROTOCOLS

A. Congestion control

LIMERIC [10] 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, $r(t\text{-}1)$ represents the measured overall packet frequency by the vehicle in the previous time window, and α=0.1 and β=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. As a result, r_g and $r(t\text{-}1)$ can be substituted by CBR_{max} and $CBR(t\text{-}1)$, respectively, being CBR_{max} the target channel busy ratio and $CBR(t\text{-}1)$ the channel busy ratio measured by vehicle j. As noted in [10], α and β have a high influence on the system stability, i.e. the capability to reach a stable solution in which the transmission parameters of the vehicles are stable if the conditions remain constant; 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) is reached. With an additional mechanism that establishes a maximum gain in equation (1), LIMERIC has been demonstrated to provide high accuracy and stability in scenarios where all the nodes measure the same channel load. One of the latest evolutions of LIMERIC incorporates a mechanism to bound the tracking error of surrounding vehicles [16]. This mechanism triggers the transmission of additional packets when the estimation of such error is higher than a given threshold.

PULSAR [11] is a congestion control protocol that adapts the packet transmission frequency of each vehicle using an Additive Increase Multiplicative Decrease (AIMD) technique. Given that each vehicle transmissions can influence the load up to approximately two hops distance, each vehicle piggybacks its locally experienced *CBR* and the maximum *CBR* experienced by its neighbors. The *CBR* used by a given vehicle for the adaptation is the maximum 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 based on the information it receives from neighboring vehicles (the packet transmission frequency of each vehicle is also piggybacked in its beacons). The combination of this mechanism with the AIMD process ensures that the convergence packet transmission frequency of vehicles within two hops distance is nearly the same.

A congestion control protocol that combines LIMERIC and PULSAR is being discussed within the ETSI standardization process. The combined scheme uses LIMERIC's linear control process and PULSAR's *CBR* information exchange and has been used as a reference for comparison in this paper. It will be referred to as LIMERIC+PULSAR.

B. Awareness control

The awareness control protocol considered in this paper is MINT (minimum packet transmission frequency) and follows the design policy proposed in [15]. 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 packet reception frequency. As a result, MINT sets the packet transmission frequency equal to the application's packet reception frequency plus a fixed margin ΔT_f=1Hz. 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.

III. INTEGRATING CONGESTION AND AWARENESS CONTROL

The overall objective of INTERN is that each vehicle configures its transmission parameters taking into account its application's requirements, while maintaining the channel load below the target *CBR*. As a result, under high traffic density conditions, all vehicles will use the minimum transmission parameters that satisfy their individual application's requirements. However, under lower traffic densities, vehicles will be able to increase their transmission parameters so that the target *CBR* is achieved and the channel is fully utilized. To this aim, INTERN integrates MINT with the linear control process proposed in LIMERIC. Additionally, to achieve global fairness, INTERN exploits the benefits of the 2-hops piggybacking proposed in PULSAR. Finally, INTERN calculates the transmission power following MINT, i.e. once the transmission frequency has been configured, the transmission power is set to the 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 plus certain margin ΔT_f. Then, the ΔT_f parameter is dynamically calculated by each vehicle using a linear control process. Please note that LIMERIC proposes the adaptation of T_f to provide similar packet transmission frequency values to nearby vehicles (i.e. similar bandwidth allocated), but INTERN adapts ΔT_f to ensure that the individual application's requirements are satisfied. The control process is designed so that the channel load is maintained below the target *CBR* level, i.e. CBR_{max}, considering the following linear control equation:

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

This equation is similar to the one proposed in LIMERIC, but with a dynamic value for the β parameter:

$$\beta = \frac{\Delta T_f^T}{CBR_{2hops}} \quad (3)$$

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.

To achieve the goal of fairness at the application level, all vehicles should have a similar value for ΔT_f, i.e. similar increments of the packet transmission frequency used with respect to the minimum they need. To ensure that the ΔT_f parameter of vehicles within two hops distance is nearly the same, INTERN incorporates the PULSAR piggybacking approach for the ΔT_f parameter. In particular, each vehicle also attaches to its beacons its current ΔT_f and the minimum ΔT_f received from its neighboring vehicles. ΔT_f^T in equation (2) is then calculated by each vehicle as the minimum ΔT_f reported by its neighbors. Thanks to this mechanism, vehicles will also rapidly adapt to variable traffic density conditions. For example, when a vehicle that is using a high ΔT_f in an empty road enters a congested road, it will detect and rapidly adapt to the ΔT_f values received from its new neighboring vehicles.

To ensure that the application's requirements are satisfied and avoid operating with packet transmission frequencies much higher than the ones required by the application, the ΔT_f parameter has a minimum and a maximum value of 1Hz and 3Hz, respectively (different values would be possible). The minimum packet transmission frequency configured by a vehicle will be therefore at least 1Hz above the minimum required by its application.

IV. PERFORMANCE EVALUATION

The performance of INTERN has been evaluated 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 previously described (LIMERIC+PULSAR).

A. Evaluation scenarios

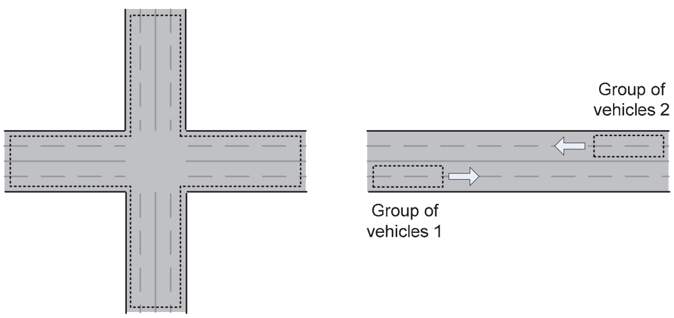
Two evaluation scenarios have been selected to demonstrate the benefits of INTERN under different challenging conditions. Similar scenarios and simulation conditions were considered e.g. in [11].

Scenario 1 – highway crossing (Fig. 1a). This scenario is especially aimed at evaluating the spatial distribution of the channel load and the application's effectiveness experienced by each vehicle. In this scenario the vehicles are uniformly distributed in the area highlighted in Fig. 1a. This scenario can be characterized by the traffic density in vehicles/km/lane, and the length of each of the four roads (3.5 km).

Scenario 2 - highway (Fig. 1b). This scenario is aimed at evaluating the influence of the movement of vehicles on the operation of the protocols. In particular, it will be used to evaluate the convergence and stability properties of the selected protocols when two groups of vehicles approach each other, as illustrated in Fig. 1b. Each group of vehicles is 2km long, occupies 2 lanes and has a uniform traffic density. All vehicles move at a constant speed of 120km/h. The length of the road is 7km, so that the two vehicle groups are perfectly aligned, one next to each other, after t=75 seconds.

All vehicles in the scenario periodically transmit beacons and dynamically adapt their transmission parameters based on one of the protocols selected. By default, all vehicles start using the maximum transmission power (P_t=33dBm) and a random packet transmission frequency, T_f, between 1Hz and 10Hz. Based on [17], the Nakagami-m propagation model has been employed with m=3.

To be able to evaluate if the application's requirements of each vehicle are satisfied or not, each vehicle in the scenario runs a cooperative awareness 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, each vehicle sets its initial application's requirements randomly, with the warning distance varying between 50 and 200m and the packet reception frequency between 1Hz and 10Hz. The application's requirements of each vehicle are dynamic, and from the initial settings they linearly vary during the simulation.



(a) Scenario 1 (b) Scenario 2

Fig. 1. Evaluation scenarios.

TABLE I. 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

To evaluate each protocols' capacity to satisfy the applications' requirements, we have defined 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.

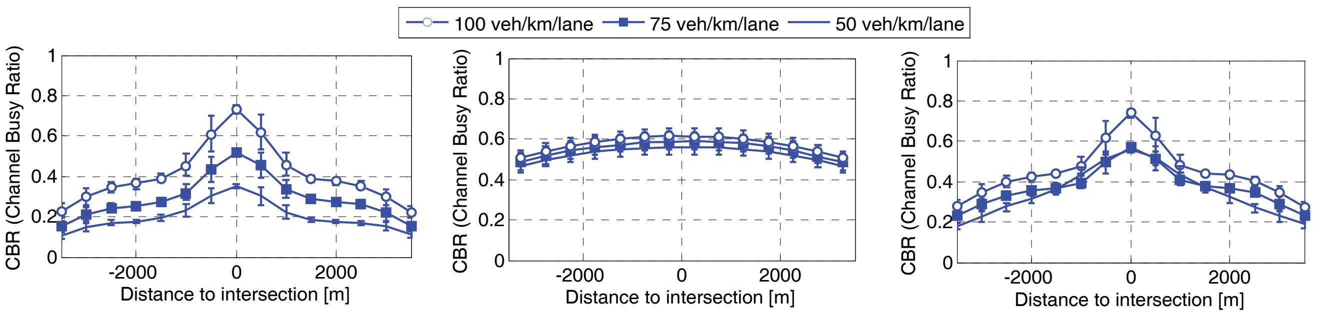
CBR_{max} has been set to 0.6 following [10], since it is the CBR value that maximizes the throughput or number of successful messages exchanged per second. Table I summarizes some of the most significant communication and simulation parameters considered in this paper.

B. *Congestion and awareness control in scenario 1 – highway crossing*

This scenario has been mainly used to evaluate the spatial distribution of the channel load and the application's effectiveness experienced when using the 3 protocols under study. In particular, Figures 2 and 3 plot the average spatial distribution of the *CBR* and D_p, respectively, as a function of the distance to the intersection under different traffic densities; the vertical lines represent the 5th and 95th percentiles.

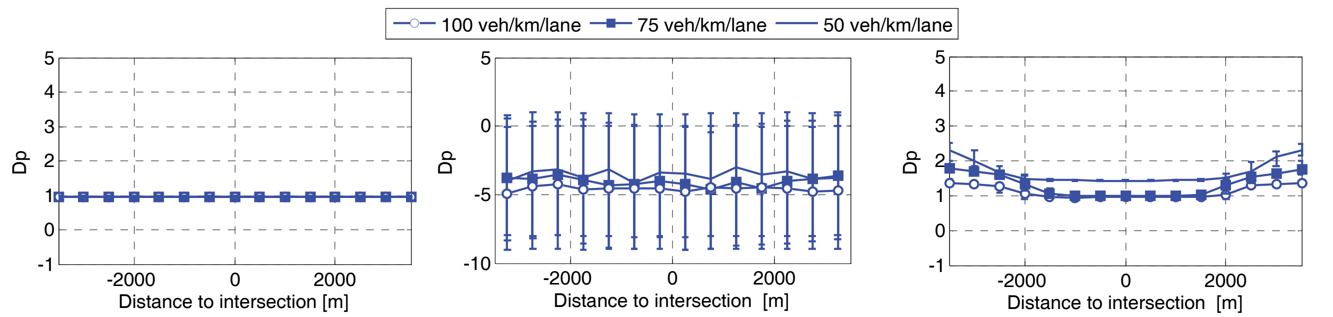
The results depicted in Fig. 2a show that higher *CBR* levels are obtained at short distances to the intersection due to the higher number of neighboring vehicles in that area. Additionally, the *CBR* experienced with MINT increases as the traffic density increases. This is the case because with MINT each vehicle is configured with the minimum transmission power and frequency required to satisfy its application's requirements, without any specific control of the channel load. As a consequence, the application requirements are satisfied with a constant D_p metric, independently of the traffic density (see Fig. 3a). Under low and medium traffic densities, the use of the minimum transmission parameters required also results in that the maximum *CBR* level experienced is lower than CBR_{max} and therefore vehicles do not exploit the full channel capacity. With very high traffic densities, i.e. 100veh/km/lane, even the use of the minimum transmission parameters required results in *CBR* levels above the target CBR_{max}=0.6 for vehicles close to the intersection. This result demonstrates that in this situation the application's requirements of all vehicles cannot be satisfied simultaneously without exceeding the target *CBR*.

Fig. 2b shows that LIMERIC+PULSAR is able to strictly maintain the *CBR* experienced below CBR_{max} irrespective of the traffic density. Vehicles dynamically adapt their packet transmission frequency to the channel load, while using the maximum power. The constant use of the maximum power by all vehicles results in that vehicles are able to detect each other at large distances. As a consequence, similar *CBR* levels can be obtained by vehicles located at larger distances than with e.g. MINT. Moreover, LIMERIC+PULSAR does not take into account that vehicles may have varying application's requirements, and accordingly set their packet transmission frequency to similar values. Since the packet reception frequency required by each vehicle was set between 1Hz and 10Hz in this work, this results in that the application's



(a) MINT (b) LIMERIC+PULSAR (c) INTERN

Fig. 2. Average spatial distribution of the *CBR* (Channel Busy Ratio) experienced to evaluate the channel load for different traffic densities in scenario 1. The vertical lines represent the 5th and 95th percentiles.



(a) MINT (b) LIMERIC+PULSAR (c) INTERN

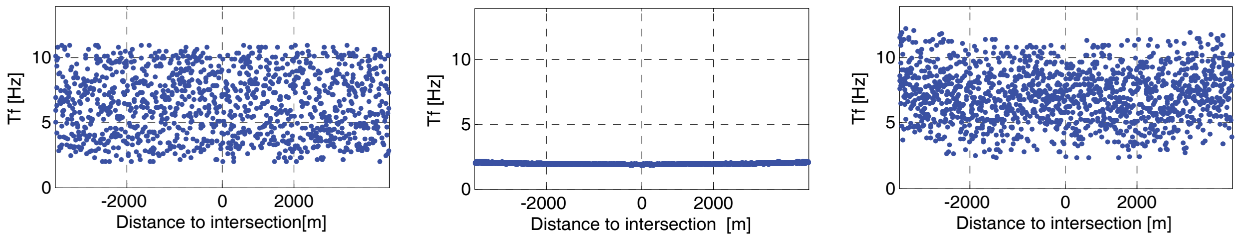
Fig. 3. Average spatial distribution of the D_p metric (difference between the number of packets per second demanded by the application and the number of packets that are received per second at the warning distance) to evaluate the application's effectiveness for different traffic densities in scenario 1. The vertical lines represent the 5th and 95th percentiles. The application's requirements are satisfied if D_p>0.

requirements are not satisfied: negative D_p values are obtained for nearly all vehicles in the scenario as shown in Fig. 3b.

It is interesting to remark that in the scenarios with traffic densities of 50 and 75 vehicles/km/lane, there was sufficient channel capacity to satisfy the requirements of all vehicles, as demonstrated with MINT. However, the configuration of each vehicle's transmission parameters focusing only on the channel load experienced with LIMERIC+PULSAR results in that only the application's requirements of some of them could be satisfied. These results demonstrate the need of a proper integration of congestion and awareness control protocols to more efficiently distribute the radio resources so that the requirements of all vehicles are satisfied, which is the objective of INTERN.

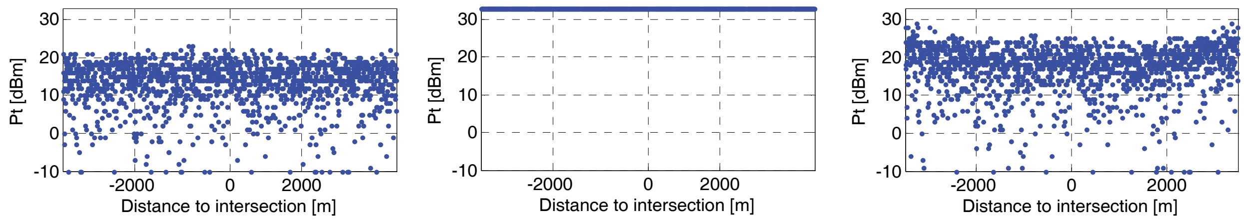
The average spatial distribution of the *CBR* experienced with INTERN is shown in Fig. 2c. Instead of using the minimum parameters required, they are increased until the CBR_{max} level is reached at the center of the intersection, following the control process proposed. As it can be observed, INTERN successfully maintains the *CBR* strictly below CBR_{max} in the low and medium traffic density scenarios. In fact, vehicles experiencing low *CBR* values do not increase their transmission parameters to avoid increasing the *CBR* levels of the vehicles that are close to the intersection, thanks to the information piggybacking process considered. In the scenario with 100veh/km/lane, vehicles that are close to the intersection use the minimum transmission power and packet frequency required to satisfy their application's requirements. As a consequence, the *CBR* experienced with INTERN for these vehicles is equivalent to the one experienced with MINT, demonstrating the adaptability of INTERN to the traffic density conditions. Finally, the results plotted in Fig. 3c show the D_p metric obtained with INTERN. As previously mentioned, with 100veh/km/lane, INTERN detects that vehicles close to the intersection need to operate using the minimum transmission parameters and therefore their D_p levels are equivalent to the ones obtained with MINT. As long as the traffic density is decreased, vehicles are able to increase their packet transmission frequency to fully utilize the channel and therefore they experience higher D_p levels, as shown in Fig. 3c. Higher D_p levels reduce the risks of unexpected channel variations that provoke that transmission settings are not capable of guaranteeing the applications requirements at the receiving vehicles. In any case, the D_p metric obtained is always positive, demonstrating the capability of INTERN to satisfy the application's requirements, i.e. the number of received packets per second at the applications' warning distance is higher than the required one.

To provide more details about the spatial distribution of the configuration parameters used by each vehicle, Fig. 4 and 5 present a snapshot of the packet transmission frequency and power used by each vehicle after 50 seconds of simulation time. As it can be observed, with INTERN and MINT vehicles adapt their packet transmission frequency to their individual application's requirements and therefore very different values can be used. However, with LIMERIC+PULSAR the packet transmission frequency and power used by all vehicles is very



(a) MINT (b) LIMERIC+PULSAR (c) INTERN

Fig. 4. Snapshot of the packet transmission frequency used by each vehicle in scenario 1 for 50 veh/km/lane after 50s of simulation time.



(a) MINT (b) LIMERIC+PULSAR (c) INTERN

Fig. 5. Snapshot of the transmission power used by each vehicle in scenario 1 for 50 veh/km/lane after 50s of simulation time.

similar. While all vehicles always use the maximum power, their packet transmission frequency is adapted so that similar values are obtained for neighboring vehicles, irrespective of their application's requirements.

The randomness shown in Fig. 4 and 5 for the packet transmission frequency and power for INTERN is due to the randomly selected applications requirements for each vehicle to avoid limiting this study to a particular application and considering that they can be context dependent [5]. To demonstrate the stability obtained with INTERN, Fig. 6 shows the time evolution of the D_p metric for two selected vehicles. The requirements of their applications are satisfied, since D_p is higher than 0. The oscillations of the D_p metric resulting from the control process are maintained under control and are in the same order or even lower than e.g. the packet transmission frequency variations obtained in [10].

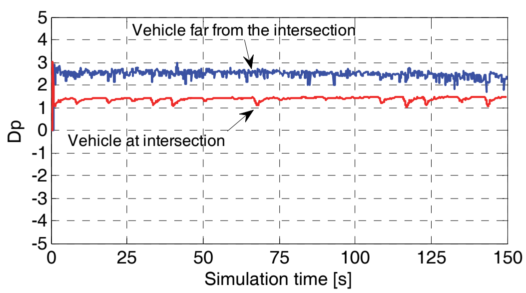


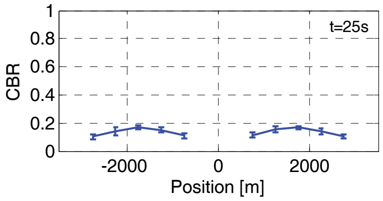
Fig. 6. Stability of the D_p metric with INTERN for two selected vehicles in scenario 1 for 50 veh/km/lane.

C. Congestion and awareness control in scenario 2 - highway

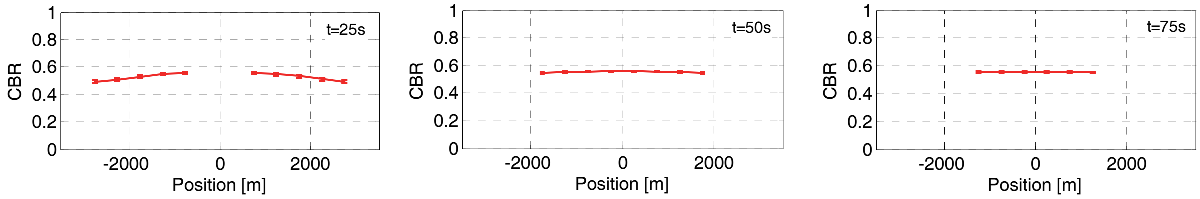
Scenario 2 has been designed to analyze the stability and convergence of the evaluated protocols. Fig. 7 and 8 plot the *CBR* and D_p metrics experienced in scenario 2 with respect to the position in the highway (Position=0 represents the center of the scenario) for three representative time instants: *t*=25s, *t*=50s (when approximately the two groups of vehicles reach the center of the scenario) and *t*=75s (when the two groups of vehicles are aligned one next to each other) and considering 50veh/km/lane. These three representative time instants have been selected to show the evolution of the channel load and application's effectiveness obtained.

With MINT, the *CBR* increases as the two groups of vehicles approach the center of the scenario (Fig. 7a), given that vehicles do not adapt their parameters based on the channel load experienced. As a consequence, when the two groups are far from each other (*t*=25s), the CBR experienced is much lower than the one experienced when the two groups of vehicles are aligned (*t*=75s). Since vehicles always use the minimum transmission parameters needed, the D_p metric is constant during the simulation (see Fig. 8a). Similar trends have been obtained for 75veh/km/lane, but with higher channel load levels. For 100veh/km/lane the target CBR_{max} level is exceeded at the center of the scenario when the two groups are aligned one next to each other at *t*=75s. This result demonstrate again that in this scenario the application's requirements of all vehicles cannot be satisfied without exceeding the target channel load level.

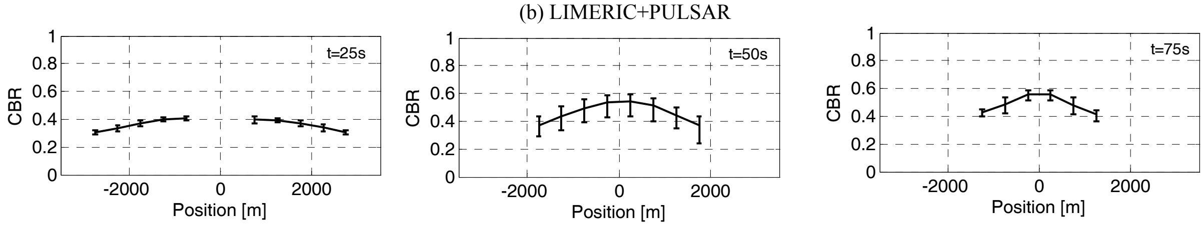
When using LIMERIC+PULSAR, vehicles transmit using the maximum power and adapt the packet transmission frequency based on the channel load. As shown in Fig. 7b, the maximum *CBR* level experienced in the scenario is maintained below CBR_{max} as the two groups of vehicles approach each other. With LIMERIC+PULSAR, neighboring vehicles tend to use similar packet transmission frequencies. Since they can have different application's requirements, the D_p levels they experience are different (see Fig. 8b) and negative values can be obtained. Under higher traffic densities, the packet transmission frequency is decreased to maintain the *CBR* below CBR_{max}, and therefore lower D_p values are obtained. These results demonstrate again that the application's requirements are not necessarily satisfied with LIMERIC+PULSAR, although there is sufficient channel capacity.



(a) MINT

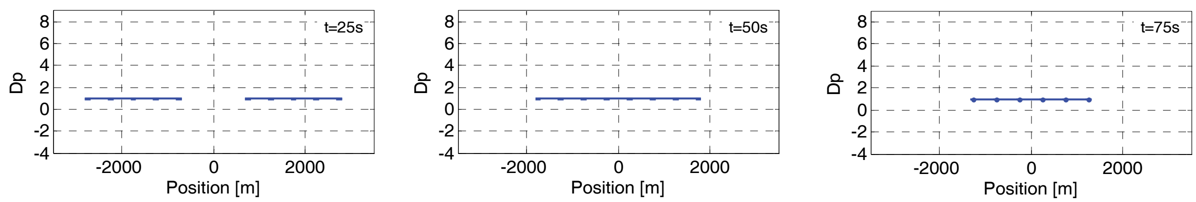


(b) LIMERIC+PULSAR

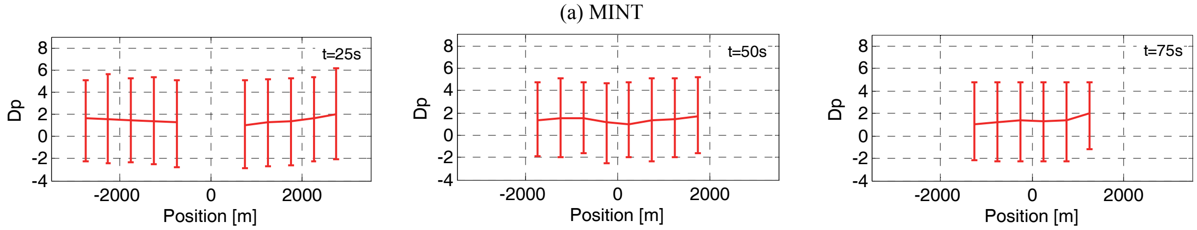


(c) INTERN

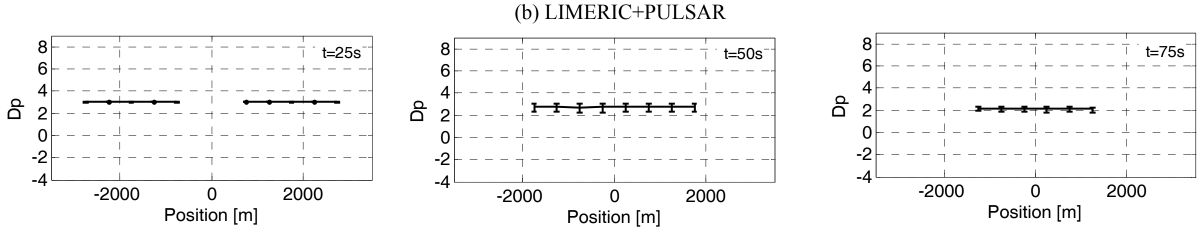
Fig. 7. CBR (Channel Busy Ratio) metric to evaluate the channel load for 3 representative time instants and 50veh/km/lane in scenario 2. The vertical lines represent the 5th and 95th percentiles.



(a) MINT



(b) LIMERIC+PULSAR



(c) INTERN

Fig. 8. D_p metric (difference between the number of packets per second demanded by the application and the number of packets that are received per second at the warning distance) to evaluate the application's effectiveness for 3 representative time instants and 50veh/km/lane in scenario 2. The vertical lines represent the 5th and 95th percentiles. The application's requirements are satisfied if $D_p>0$.

With INTERN, vehicles adapt their transmission parameters based on their individual application's requirements and the channel load experienced. At *t*=25s, the two groups of vehicles are far from each other and the channel load experienced is low (Fig. 7c). As a result, vehicles operate at the maximum ΔT_f and therefore constant D_p values are obtained (Fig. 8c). As the two groups of vehicles approach each other, the channel load increases and the ΔT_f parameter decreases, resulting in smooth variations of the D_p metric. Thanks to the information exchange of INTERN, nearby vehicles present very similar D_p values, thereby satisfying the objective of fairness at the application level. Similar trends have been obtained for 75 veh/km/lane: the *CBR* level was also maintained below CBR_{max} and the D_p metric measured was positive, although with lower D_p levels due to the higher traffic density. For the scenario with 100veh/km/lane, all vehicles are configured to use the minimum transmission parameters they need to satisfy their requirements at *t*=75s, and the target CBR_{max} level is again exceeded when the two groups of vehicles are aligned.

It is interesting to note that after *t*=75s the two groups of vehicles start moving away from each other. At *t*=100s, the channel load and application's effectiveness measured are similar than the ones experienced at *t*=50s. At *t*=125s, the values obtained are similar than the ones experienced at *t*=25s. Therefore, the 3 protocols are able to recover from the maximum load experienced at *t*=75s and return to the initial values as the two groups of vehicles separate from each other.

To further demonstrate the stability of INTERN, Fig. 9 analyzes the D_p metric experienced by three selected vehicles in scenario 2 for 50veh/km/lane. After a short initial transition period, INTERN provides similar and constant D_p values to all vehicles. After *t*=50s, the channel load experienced increases and the D_p metric decreases with smooth and similar variations for different vehicles thanks to the two hops piggybacking. The minimum D_p values are experienced around *t*=75s, due to the alignment of the two groups of vehicles one next to the other, which produces the highest traffic density level in the simulation. After *t*=75s, the traffic density decreases and INTERN is able to recover to the initial D_p metrics.

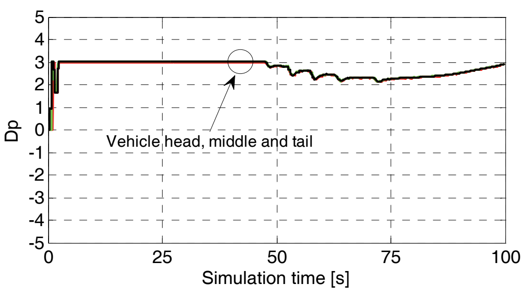


Fig. 9. Stability of the D_p metric with INTERN for three selected vehicles in scenario 2 for 50 veh/km/lane.

V. Conclusions

This paper has proposed and evaluated INTERN, an integrated congestion and awareness control protocol that dynamically adapts the transmission parameters of beacons taking into account each vehicle's application's requirements and the channel load. The results obtained demonstrate that INTERN is able to maintain the channel load under control while ensuring that the application's requirements of each vehicle are satisfied. The channel load and application's effectiveness experienced with INTERN are shown to be stable. Moreover, INTERN is able to dynamically adapt to traffic density changes and variations of the application's requirements. Further investigations will be needed to solve scenarios in which the maximum channel load level allowed is exceeded even when all vehicles are configured to use the minimum transmission parameters required.

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