On the Importance of Application Requirements in Cooperative Vehicular Communications

M. Sepulcre and J. Gozalvez

Abstract—**Cooperative vehicular systems are being developed to improve traffic safety and efficiency through the dynamic exchange of information between vehicles and between vehicles and infrastructure units. Different communication protocols and policies have been proposed in the literature with diverse objectives, normally taking into account network performance metrics only. This paper illustrates the need of taking into account cooperative vehicular application requirements in the design and operation of cooperative vehicular protocols, such as congestion control protocols. The results obtained demonstrate the impact of the application requirements on the communication settings of each vehicle, and on the overall channel load generated.**

Keywords: cooperative vehicular systems, application requirements and reliability, adaptive communication protocols

I. Introduction

Cooperative vehicular systems are expected to play a significant role in future transportation systems by enabling Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) wireless communications. Based on the real-time information exchange among vehicles, and among vehicles and infrastructure units, cooperative vehicular systems will improve traffic safety and efficiency by extending, in space and time, the drivers' awareness of the surrounding environment.

Cooperative vehicular systems will be based on the IEEE 802.11p radio access technology at the 5.9GHz band [1]. This technology has been specifically designed for the vehicular environment, and is being adapted by ETSI to the European context in the ITS-G5 standard. The operation of cooperative vehicular systems is mainly based on the exchange of two types of messages: periodic 1-hop broadcast messages (known as CAMs, Cooperative Awareness Messages) and event-driven messages (known as DENMs, Decentralized Environmental Notification Messages). On one hand, CAMs are periodically transmitted by all vehicles and infrastructure units on the so called control channel to provide and receive information about presence, movement and service announcements to/from neighbouring nodes. The information included in CAMs helps each vehicle to maintain the connectivity with its neighbouring nodes, and supports high level applications, including cooperative road safety applications. On the other hand, DENMs provide support to event-driven applications. These messages can also be transmitted on the control channel and are generated when a potential dangerous situation is detected (i.e. a car's hard braking) in order to inform surrounding vehicles about the situation type, severity and location.

Cooperative vehicular systems will enable a wide variety of new applications and services, ranging from cooperative road safety applications, to distributed traffic management services or in-vehicle Infotainment services. To achieve these objectives, several important technological challenges yet need to be overcome. In particular, the strict requirements of traffic safety applications will require timely, reliable and ubiquitous communications between the different vehicular nodes. Although numerous communication protocols with diverse objectives have been proposed in the literature for cooperative vehicular systems, to date little attention has been paid to the impact of the requirements of cooperative vehicular applications on the design and operation of communication protocols and transmission techniques. More specifically, most of the congestion control and adaptive communication protocols proposed in the literature adapt the communication settings of vehicles as a function of the experienced channel load or network connectivity, without analysing whether such communication settings are able to adequately satisfy the application requirements or not.

In this context, this paper is aimed at illustrating the importance of considering the application requirements in the design and evaluation of cooperative communication protocols and policies. Although this work focuses on 1-hop communication protocols and cooperative road safety applications, the concepts exposed and conclusions obtained could be adapted to other type of protocols and different applications. The results obtained demonstrate the impact of the application requirements on the communication settings of each vehicle, and on the overall channel load generated.

II. State of the Art

The varying environment and operating conditions under which cooperative vehicular systems operate impose the need of considering adaptive communication protocols that dynamically vary their operation. Multiple adaptive communication protocols have been proposed in the literature, based on different parameters and with different objectives. While some of them are aimed at adapting each vehicle communication settings to maintain the vehicular network connected under different and dynamic traffic conditions [2], many of them focus on the control of the channel congestion. Congestion control strategies for CAMs can be classified into three different and complementary groups [3]: transmission power control, packet transmission frequency control (control

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of the number of packets transmitted per second) and packet duration control (control of the packet length and/or coding rate). The D-FPAV (Distributed Fair Power Adjustment for Vehicular Networks) [4] protocol is one of the most referenced congestion control protocols for cooperative vehicular systems. D-FPAV controls the channel load generated by 1-hop periodic broadcast messages and fairly shares the radio channel by maximising the minimum transmission power employed in the vehicular network. It allows limiting the channel load in a distributed way, leaving enough available bandwidth for event-driven safety messages. Another interesting approach is proposed in [5], where each vehicle increases or decreases its packet transmission frequency and power based on its own speed to reduce the interference generated. This study demonstrates the potential benefits of assigning a different priority or bandwidth to vehicles with diverse road safety application requirements, although they did not consider any application requirement metric.

With the aim of reducing the channel load by adapting the packet transmission frequency of each vehicle, the work in [6] proposed that 1-hop broadcast packet transmissions are only triggered when the positioning tracking error of neighbouring vehicles exceeds certain threshold. As a result, the number of transmitted broadcast packets is minimised (it is mentioned in the paper that it can be as low as 2 packets/s), position tracking errors are bounded, and the channel load is reduced. With this approach, packets are only transmitted when the vehicle varies its speed or direction, i.e. when tracking errors are produced. As a result, it is especially designed for tracking neighbouring vehicles, but it is not clear whether it could support other road safety applications or not, such as applications aimed at detecting new neighbouring vehicles with sufficient time for the driver to react and avoid potential dangerous situations. Other packet transmission frequency control approaches are based on prioritization and re-scheduling techniques, such as the work in [7], which proposes the use of an application-specific utility function to share the broadcast medium by adjusting packet scheduling based on applications' priorities. With their approach, the amount of information sent is controlled while maximising the utility of the information transmitted through the wireless channel. Similarly, to prevent network overloads and efficiently exploit the available network resources, a dynamic message scheduling mechanism was proposed in [8] based on the application's priority, the vehicle speed and the message utility. Although being interesting approaches, they do not consider the specific transmission range requirements of cooperative applications, which plays a significant role in cooperative systems, as it will be shown in this paper.

Despite the fact that most of the road safety applications currently identified by standardization bodies (see section IV) require one hop communications, only few studies such as [9] analyse the reliability of 1-hop cooperative vehicular communication systems at the application level. In particular, the work in [9] demonstrates the suitability of these systems to improve traffic safety based on real-world experimental data in highways. The work analyses the performance of different applications based on basic performance metrics, and highlights the need of differentiating between communication and application's reliability. Similarly, the work in [10] evaluates the safety performance of 1-hop broadcast transmissions by means of extensive simulations with different combinations of transmission parameters. In particular, the authors propose and evaluate the traffic safety effective range as the distance within which 1-hop broadcast packets are received with a probability higher than 90%.

Limited work has been carried out regarding the detailed performance metric definition of traffic safety applications. The work in [11] shows an example of detailed definition of safety performance metrics for rear-end, lane change, and roadway departure crashes for different ITS (Intelligent Transportation Systems) technologies, based on uniform kinematics equations. This work was part of the US IVBSS (Integrated Vehicle-Based Safety Systems) initiative to integrate multiple crash warning systems on vehicles. The authors evaluate the safety benefits by estimating the number of crashes that could be avoided, and the total harm that might be reduced with the full deployment of integrated systems. Some studies propose to extend these performance metrics to cooperative vehicular systems. For example, the work published in [12] derives analytical bounds for the maximum acceptable message delivery latency and minimum required retransmission frequency to satisfy the traffic safety requirements of rear-end collision avoidance applications. The author demonstrates the strong impact of the traffic and operating conditions (speed, state of the road surface, radio channel variability conditions, etc.) on these two metrics.

III. IEEE 802.11P

The demanding requirements of cooperative vehicular applications cannot be met by communication systems initially designed for other purposes, which motivated the development of the IEEE 802.11p radio access technology [1]. This technology is being considered in the different vehicular communications architectures and protocol stacks (ISO, ETSI and IEEE). The IEEE 802.11p is an amendment of the popular IEEE 802.11 standard to enable its operation in the vehicular environment, and is being especially designed for V2V and V2I ad-hoc 1-hop and multihop communications.

The IEEE 802.11p standardization process originates from the allocation of the Dedicated Short Range Communications (DSRC) spectrum band in the US in 1999. In particular, a 75MHz bandwidth at the 5.9GHz frequency band was allocated to be used exclusively for V2V and V2I communications to mainly enable cooperative road safety and traffic efficiency applications. In Europe, only 30MHz have currently been allocated for traffic safety cooperative communications.

At the MAC (Medium Access Control) level, the IEEE 802.11p standard reduces the initial connection setup overhead required in traditional IEEE 802.11 networks, for the fast exchange of messages in vehicular environments. The basic access method of IEEE 802.11p is the DCF (Distributed Coordination Function) of IEEE 802.11, which is a CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) MAC protocol. Moreover, the MAC layer of IEEE 802.11p is improved with EDCA (Enhanced Distributed Channel Access) from IEEE 802.11e to support service priority differentiation.

At the PHY level, the IEEE 802.11p is based on the IEEE 802.11a radio, which also operates at the 5GHz band, to minimise the necessary changes to the IEEE 802.11 PHY. While MAC level amendments are fundamentally software updates that are relatively easy to build, PHY level amendments should be limited to avoid designing an entirely new wireless access technology. IEEE 802.11p re-uses the IEEE 802.11a OFDM (Orthogonal Frequency Division Multiplexing) modulation and coding schemes. In particular, IEEE 802.11p considers 52 subcarriers that are modulated using BPSK (binary phase shift keying), QPSK (quadrature phase shift keying), 16-QAM (16-quadrature amplitude modulation) or 64-QAM. Forward error correction coding (convolutional coding) is used with a coding rate of 1/2, 2/3, or 3/4. As opposed to the 20MHz IEEE 802.11a channel bandwidth, in vehicular environments the channel bandwidth is reduced to 10MHz to better combat the multipath delay spread and Doppler effects, caused by high mobility and roadway environments.

IV. COOPERATIVE VEHICULAR APPLICATIONS

A. *Classification*

Important efforts are being done towards the identification, definition and characterization of applications and use cases for cooperative vehicular systems. Applications play a fundamental role in the development of cooperative vehicular systems, and require a detailed definition and understanding. In this context, the ETSI TC on ITS has identified a set of applications and use cases to be considered as a reference for the deployment and standardization of cooperative vehicular systems [13]. These applications and use cases have been selected considering the strategic, economical, performance, legal and organizational requirements and needs from users and stakeholders. They are classified in four application classes: active road safety, cooperative traffic efficiency, co-operative local services, and global Internet services. Active road safety applications can be in turn classified in two groups: cooperative awareness applications, which base their operation in the exchange of periodic messages, and road hazard warning applications, which are event-driven applications triggered in certain events. Table I presents the list of the main road safety applications identified by ETSI [13].

B. *Basic requirements*

Each identified application or use case can present different operating and driving conditions, and therefore their requirements in terms of communications setting and performance vary. The ETSI TC on ITS also defined in [13] a set of basic communication requirements for each identified use case. Vehicles should be capable of transmitting and receiving messages satisfying specific communications requirements defined in terms of:

- Minimum packet transmission frequency [Hz]. It represents the minimum packet transmission frequency at which the vehicles should transmit their position, speed, acceleration, and basic status data. Values between 1Hz (e.g. traffic condition warning) and 10Hz (e.g. intersection collision warning) are required.
- Maximum latency time [ms]. It denotes the maximum latency allowed between the packet generation at the higher layers and the actual packet transmission through the wireless channel. Values between 50ms and 500ms are required.
- Minimum duration of the total exchange [s]. It depends on the use case and vehicles speeds and transmission ranges. No specific values are provided in [13].
- Absolute / relative positioning accuracy [m]. It is especially required when the lane differentiation is needed. Values between 1m and 20m are specified.
- Authentication/security requirements. It is particularly required for emergency vehicles and commercial operations.
- Availability of digital map information. Some applications require the knowledge of the specific road environment to adequately operate.

Apart from the ETSI work on the identification of cooperative vehicular applications and use cases, the USDOT VSC (Vehicle Safety Communications) project developed a comprehensive list of communications-based vehicle safety and non-safety application scenarios [14]. More than 75 application scenarios were identified and analyzed resulting in 34 safety and 11 non-safety application scenario descriptions. Each safety application scenario was further defined to include an initial estimate of potential safety benefits, and eight high potential benefit safety application scenarios were selected for further study: traffic signal violation warning, curve speed warning, emergency electronic brake lights, pre-crash warning, cooperative forward collision warning, left turn assistant, lane change warning and stop sign movement assistance [14]. Currently, the IntelliDrive program is leading the activities on cooperative vehicular systems in the US [15].

C. *Detailed requirements*

ETSI and VSC definitions propose fixed communication requirements for each specific application or use case.

TABLE I
Active road safety applications identified by ETSI [13]

Application	Use case
Driving assistance - Co-operative awareness	Emergency vehicle warning
	Slow vehicle indication
	Intersection collision warning
	Motorcycle approaching indication
Driving assistance - Road Hazard Warning	Emergency electronic brake lights
	Wrong way driving warning
	Stationary vehicle - accident
	Stationary vehicle - vehicle problem
	Traffic condition warning
	Signal violation warning
	Roadwork warning
	Collision risk warning
	DFCD - Hazardous location, Precipitations, etc.

Although these values could be used in the initial communications protocol design and testing, the critical nature of cooperative vehicular applications requires a more detailed definition of the operation and specific requirements of each application and use case. For example, the distance at which vehicles should be able to communicate with each other should be defined; this distance could depend on the operating and driving conditions, such as the vehicle's speed or the state of the road surface, and therefore could represent a dynamic communication requirement.

To illustrate the need of detailed performance metrics for cooperative vehicular applications, and highlight the fact that different applications can present considerably different requirements, this section develops the detailed requirements of an overtaking assistance and a lane change assistance application, illustrated in Fig. 1. Both applications are based on the periodic exchange of CAMs to collect information about surrounding vehicles, and inform the driver about the suitability of an overtaking or a lane change manoeuvre, respectively. To reliably support these applications, the potentially colliding vehicles (vehicles A and B in Fig. 1) need to communicate at a distance higher than a certain warning distance (D_w) that depends on the driving and operating conditions. D_w represents the application requirement, and is equivalent to the minimum distance at which the vehicles need to exchange at least one message to alert of each other's presence before considering the possibility to start an overtaking or a lane change manoeuvre.

In the scenario depicted in Fig. 1a, the overtaking assistance application should warn vehicle A about the presence of vehicle B to avoid any dangerous situation. To this aim, vehicles A and B should communicate with each other at a distance higher than the distance needed by vehicle A to overtake vehicle C and avoid the collision with vehicle B. This distance required by the application could be estimated as follows. Assume that, at $t=0$, vehicle A is moving at v_A *m/s* and starts accelerating with a_A m/s^2 to change the lane and overtake vehicle C. The distance travelled by vehicle A from $t=0$ can be then represented by the following equation:

$$d_A(t) = \frac{1}{2} a_A t^2 + v_A t \quad (1)$$

Similar equations can be derived for vehicles B and C, taking into account their respective speeds and accelerations. To obtain the distance at which vehicles A and B need to communicate to avoid dangerous overtaking situations in Fig. 1a, the time needed by vehicle A to overtake vehicle C needs first to be obtained. It can be derived from the following equation:

$$d_A(t) > d_C(t) + D_0 + L_A + L_C + D_s \quad (2)$$

where D_0 is the distance between vehicles A and C at $t=0$, L_A and L_C are the length of vehicles A and C, respectively, and D_s the safety distance that could depend on the vehicle's speed. The time needed by vehicle A to overtake vehicle C (t_{AC}) can be approximated by the time at which the two terms of equation (2) are equal, plus the time needed by vehicle A to change lane. Assuming that vehicles A and C are moving at the same speed before the overtaking manoeuvre starts, t_{AC} can be approximated with the following equation:

$$t_{AC} = t_{ov} + 2T_{ch} = \sqrt{\frac{2(D_0 + L_A + L_C + D_s)}{a_A - a_C}} + 2T_{ch} \quad (3)$$

where $2T_{ch}$ is the time needed to change the lane (from right to left and vice versa). Please note that, for simplification, this calculation assumes that the speed of vehicle A is constant during the lane changing process, and more detailed approaches are certainly possible.

Once t_{AC} has been obtained, the distance travelled by vehicles A and B during the overtaking manoeuvre can be calculated. Since vehicles A and B are moving in opposite directions (see Fig. 1a), the distance at which they need to communicate can be estimated as the sum of the distance travelled by each of them during the overtaking manoeuvre of vehicle A:

$$D_w = d_A(t_{ov}) + (2v_A + t_{ov}a_A)T_{ch} + v_B t_{AC} \quad (4)$$

The value of the warning distance D_w in equation (4) represents the application requirement of the overtaking assistance application previously described. It clearly depends on the vehicles driving conditions, highlighting the dynamic nature of the metric.

A similar analysis can be done to obtain the distance at which vehicles A and B need to communicate to avoid a dangerous lane change manoeuvre in the scenario illustrated in Fig. 1b. In this case, vehicles A and B are moving in the same direction, and the distance between them can be approximated by the following equation:

$$d_{AB}(t) = d_A(t) + D_o - d_B(t) \quad (5)$$

where D_o is the distance between the vehicles A and B when the lane change manoeuvre starts (i.e. at $t=0$). To avoid a dangerous situation, the distance between the two vehicles during the lane change manoeuvre needs to be higher than the length of vehicle A plus a certain safety distance that could depend on their speed:

$$d_{AB}(t) > L_A + D_s \quad (6)$$

Equation (6) can be used to calculate the minimum initial distance, D_o, so that a dangerous situation is avoided. This minimum initial distance is equivalent to the minimum distance at which the two vehicles need to communicate for a safe lane change manoeuvre, and results in:

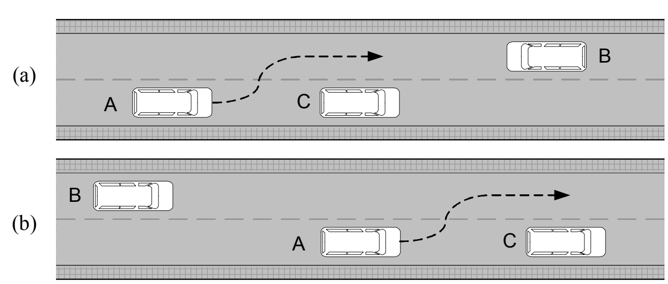

Fig. 1. Scenarios for (a) overtaking assistance application and (b) lane change assistance application.

$$D_w = -\frac{1}{2}\frac{(v_A - v_B)^2}{a_B - a_A} + L_A + D_s \quad (7)$$

Based on these basic definitions, the D_w distances for the two applications and scenarios analysed are shown in Fig. 2. The results shown in this figure demonstrate that the communications distance requirements can be very different for different applications, and can present a notable (inverse) dependence on the speed of the vehicles.

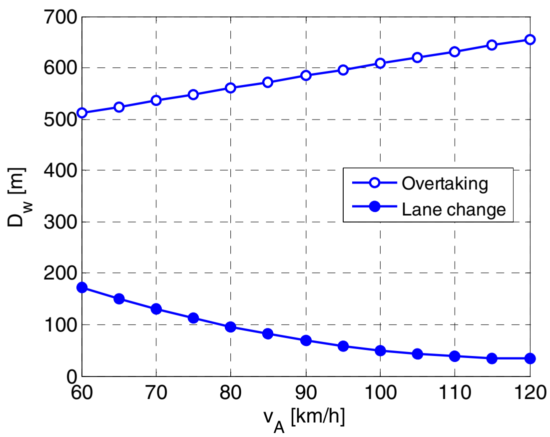

Fig. 2. Distance at which vehicles A and B need to communicate to avoid a dangerous situation in the scenarios and applications illustrated in Fig. 1. Configuration: v_B=120km/h, T_{ch}=2s, L_A=L_B=L_C=4m, D_s=30m, a_A=4m/s^2 (overtaking), a_A=1m/s^2 (lane change), a_B=0, a_C=0.

D. *Application's reliability*

Given the probabilistic nature of the radio environment, an application's reliability metric needs to be defined to quantify the probability of successfully communicating the two vehicles before the target distance D_w. In this case, the application's reliability (p_{app}) is defined as the probability of receiving at least one packet before D_w in a given time window *TWindow*. This metric extends and contextualizes the application's reliability concept defined in [9] to the specific requirements of cooperative applications. In [9], the *TWindow* concept is proposed to evaluate the application's reliability. However, it is applied to static distances that do not depend on the driving parameters, such as the speed of the vehicles. The *TWindow* parameter can be seen as an application-related parameter, that could depend on the vehicle's speed or the driver's reaction time; as it will be shown in next sections, application designers and communications engineers should take into account its high impact on the communications settings and channel load.

Considering that N_T packets can be independently received by the other vehicle during *TWindow*, and that each packet is successfully received with probability p_i, $1 \le i \le N_T$, the application's reliability can be calculated as:

$$p_{app} = 1 - \prod_{i=1}^{N_T} (1 - p_i) \quad (8)$$

V. Applications-based Communications

Following the analysis and results shown in previous section, different vehicles and different applications can present different requirements. To individually satisfy such requirements while minimising the channel load generated, the work in [16] proposed a proactive congestion control policy for cooperative vehicular systems, with which each vehicle proactively selects the minimum communications parameters needed to satisfy its application requirements. In particular, with the communications policy proposed in [16], each vehicle dynamically calculates its application requirements, and adapts its communications parameters so that such requirements are satisfied with certain reliability imposed by the application. Following the application examples previously detailed, each vehicle could dynamically calculate its D_w based on information locally available, and accordingly adapt its communication parameters (e.g. transmission power and packet transmission frequency) so that at least one message is exchanged at D_w with the target reliability.

To dynamically calculate the transmission power level required by each vehicle to achieve their individual application's reliability, this work considers the open-loop approach of [16] based on propagation models. In particular, the transmission power needed is extracted from a power-range map that takes into account the propagation effects, the D_w distance, the number of packets generated per second, and the *TWindow* parameter. The methodology to obtain the power-range map is based on the work published in [17], adapted to the scenario and propagation conditions considered in this work. In particular, the power-range map constructed is based on the computation of the probability of packet reception (p_i) as a function of the distance between transmitter and receiver, taking into account the propagation model considered. Fig. 3 shows this probability for two different transmission powers and packet transmission frequencies (T_f), and considering the Nakagami-m propagation model with m=3, typically considered for highway scenarios [18]. The next step to build the power-range map is the computation of the D_w for different vehicular speeds. For each speed, the *TWindow* parameter is mapped into a different *DWindow* (see Fig. 3 for an example of D_w and *DWindow*). Then, for each D_w and *DWindow*, N_T=T_f·*TWindow* values of the probability of packet reception are used to compute the corresponding application's reliability p_{app} using equation (8). These N_T values are uniformly distributed over *DWindow*, as highlighted in Fig. 3 with white circles for T_f=2Hz and T_f=10Hz. All computed values are used to build the power-range map, and such power-range map to dynamically determine the transmission power needed by each vehicle.

Additionally, a packet collision compensation technique based on the work in [19] has been applied, to combat the negative effect of packet collisions on the packet reception probability p_i and, consequently, on the application's reliability. The work in [19] proposed two different packet collisions compensation techniques. These techniques are based on the evaluation of the experienced channel load, and the consequent adaptation of each vehicle's transmission power or packet transmission frequency to combat the negative effect of packet collisions on the application performance.

Fig. 4 shows the inverse of the lane change assistance application's reliability (i.e. the probability that a vehicle does not receive a message before D_w and during *TWindow*) as a function of the transmission power, and considering different packet transmission frequencies. This figure has been obtained considering a highway scenario with 6 lanes simulated with ns-2 [20], in which all vehicles periodically transmit broadcast messages at the same packet transmission frequency and power. These results clearly show the need of using high transmission power levels to achieve high application's reliability levels, especially when considering low packet transmission frequencies. These results also demonstrate that the variation of the transmission power or packet transmission frequency without taking into account the application requirements can notably impact the reliability obtained.

VI. Performance and Efficiency Analysis

For the highway scenario previously described, Fig. 5 shows the transmission power configuration that satisfies the application requirements with p_{app}=0.99 reliability. As it can be observed, different packet transmission frequencies and *TWindow* parameters result in different transmission power levels to satisfy the same application's reliability. This figure represents the existing trade-off between transmission power, packet transmission frequency and *TWindow* for a given application's reliability. In particular, Fig. 5 shows that the increase of the packet transmission frequency and the *TWindow* parameter results in a reduction of the transmission power needed to maintain the application's reliability. In fact, the increase of the *TWindow* parameter or the packet transmission frequency increases the number of messages that could be received to satisfy the target application's reliability; as a consequence, each of these messages can be transmitted with a lower transmission power to maintain the same application's reliability level, since only one of these messages is required to avoid the dangerous situation.

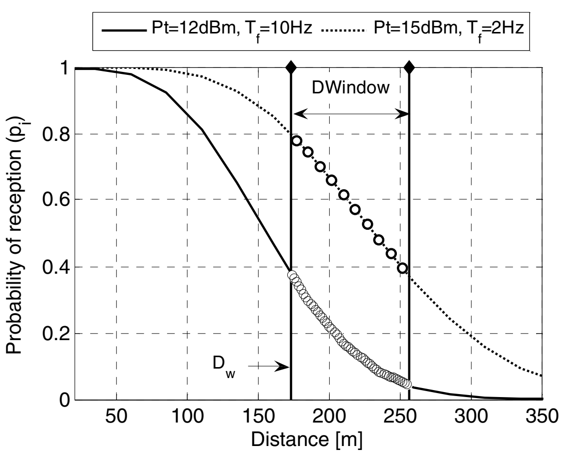

Fig. 3. Probability of packet reception as a function of the distance between vehicles A and B. Configuration: lane change application, v_A=60km/h, v_B=120km/h, traffic density = 15veh/km/lane, payload = 250B, *TWindow*=5s.

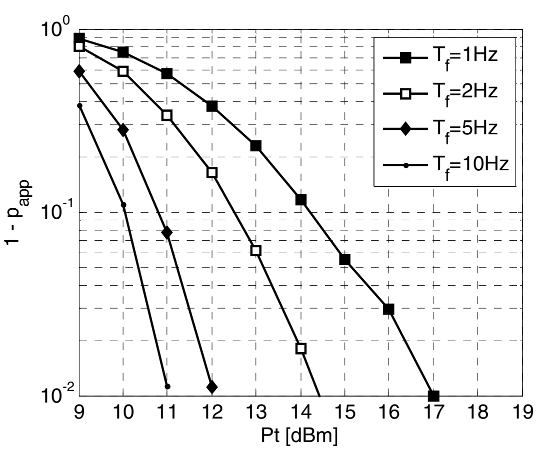

Fig. 4. Inverse of the application's reliability as a function of the transmission power, and considering different packet transmission frequencies. Configuration: lane change application, v_A=60km/h, v_B=120km/h, traffic density = 15veh/km/lane, payload = 250B.

Given that the same the application's reliability can be obtained with the different combinations of transmission power, packet transmission frequency and *TWindow* parameter, the final communications configuration presents two degrees of freedom. This results in that additional performance metrics need to be taken into account to select the optimum combination of transmission power, packet transmission frequency and *TWindow*. As initially shown in [16], network-based configuration policies would select the communications configuration that generates a higher system throughput, or higher number of messages correctly received. As shown in Fig. 6, to maximize the number of packets correctly received per second, the highest packet transmission frequency and the lowest *TWindow* value would be selected. However, it is important to note that the increase of the number of packets correctly received per second does not produce any application's reliability improvement, since all configurations shown in the figure obtain the same p_{app}=0.99. A more convenient approach for cooperative vehicular systems would be the selection of the communications configuration that generates the minimum channel load, in order to minimise the interference generated and increase the system scalability. Fig. 7 shows the Channel Busy Time (CBT), i.e. the average fraction of time that the channel is sensed as busy, for the configurations (transmission power, packet transmission frequency and *TWindow*) shown in Fig. 5. According to the results shown in Fig. 7, this approach would

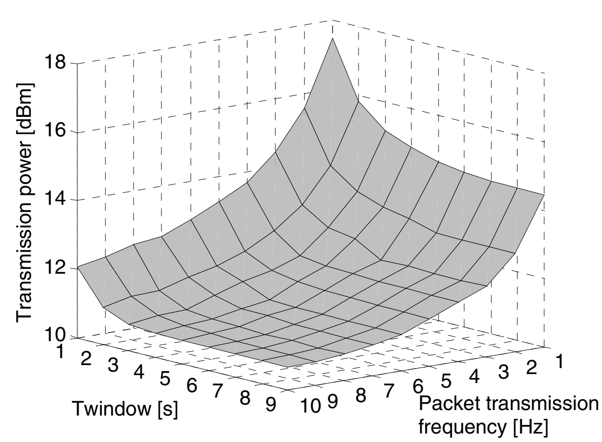

Fig. 5. Transmission power configuration that satisfies the application requirements with the target reliability (D_w and p_{app}=0.99). Configuration: lane change application, v_A=60km/h, v_B=120km/h, traffic density = 15veh/km/lane, payload = 250B.

select the minimum packet transmission frequency and highest *TWindow* to reduce the channel load in the considered scenario and application. Please note that a different application could present different requirements, for example in terms of information updates or freshness, which could result in a different optimum combination of transmission power, packet transmission frequency and *TWindow*.

The results previously shown have considered a fixed application's reliability, p_{app}=0.99. As illustrated in Fig. 8, the increase of the target application's reliability requires the increment of the transmission power level, and results in an increase of the channel load. A limiting factor for the increase of the transmission power to maximize the application's reliability could be the maximum power allowed by the standards (33dBm in Europe and 44.8dBm en the US). Moreover, in traffic congested scenarios, the use of high transmission power levels could provoke channel congestion situations and potential system instabilities due to excessive packet collisions and interferences. Advanced communication protocols, communication configuration policies and optimized application designs will be needed to improve the reliability of cooperative applications without exceeding the power limits and avoiding channel congestion situations. For example, the *TWindow* parameter previously analysed has demonstrated a non negligible effect on the transmission power needed (see Fig. 5), and therefore on the application's reliability. The increment of the *TWindow* parameter could be used to combat the increment of transmission power required when targeting higher application's reliability levels. The increment of the *TWindow* parameter also results in a reduction of the channel load generated, as it can be observed in Fig. 9. For a given channel load level, a higher application's reliability can be obtained if the *TWindow* parameter is increased, which represents an example of application design optimization for an improved system scalability.

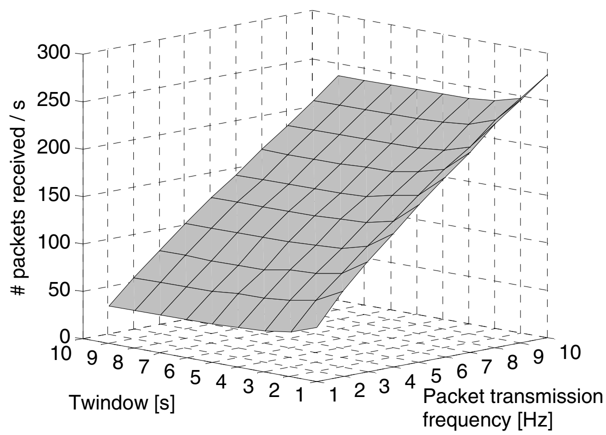

Fig. 6. Average number of packets correctly received per second and per vehicle for the transmission power configuration that satisfies the application requirements with the target reliability (D_w and p_{app}=0.99). Configuration: lane change application, v_A=60km/h, v_B=120km/h, traffic density = 15veh/km/lane, payload = 250B.

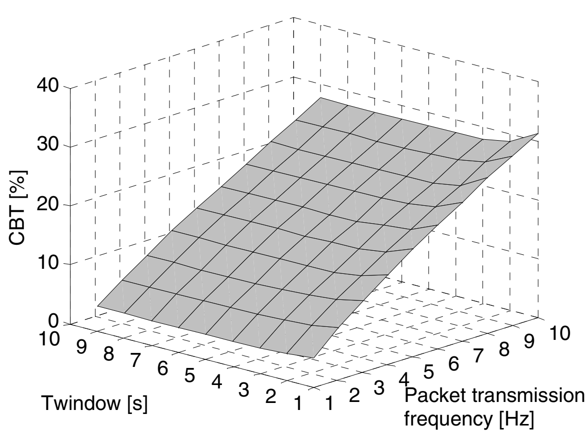

Fig. 7. Average Channel Busy Time for the transmission power configuration that satisfies the application requirements with the target reliability (D_w and p_{app}=0.99). Configuration: lane change application, v_A=60km/h, v_B=120km/h, traffic density = 15veh/km/lane, payload = 250B.

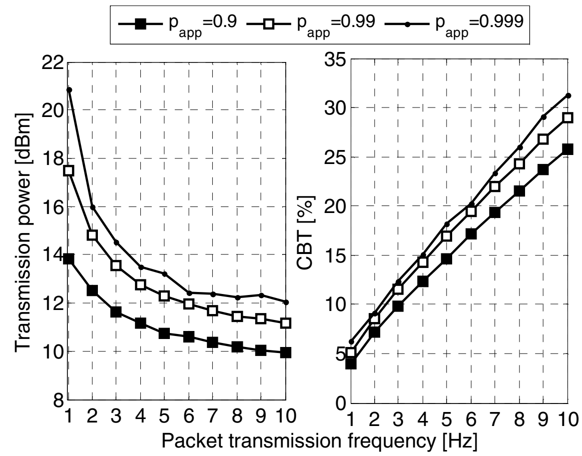

Fig. 8. Transmission power configuration that satisfies the application requirements with different target reliability levels, and resulting Channel Busy Time. Configuration: lane change application, v_A=60km/h, v_B=120km/h, traffic density = 15veh/km/lane, payload = 250B, *TWindow*=2s.

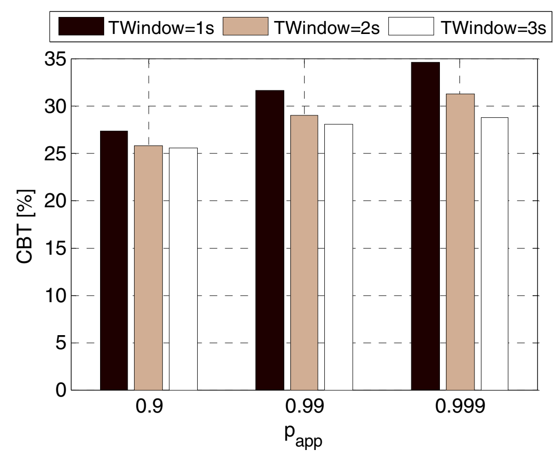

Fig. 9. Channel Busy Time for the communications configurations that satisfy the application requirements with different target reliability levels, and *TWindow* parameter. Configuration: lane change application, v_A=60km/h, v_B=120km/h, traffic density = 15veh/km/lane, payload = 250B, packet transmission frequency = 10Hz.

VII. CONCLUSIONS

This paper has illustrated the importance of taking into account the application requirements in the design and operation of cooperative vehicular protocols and communication policies. In particular, this paper has shown the different requirements imposed by different cooperative vehicular applications. The obtained results have shown the importance of considering individual and dynamic application requirements, given their dependence on parameters such as the vehicle's speed. Considering the lane change assistance application, the paper has also demonstrated the important trade-off between parameters such as the transmission power and packet transmission frequency, which can considerably impact the application's reliability and channel load. Finally, the obtained results have shown the close relationship between the channel load generated and the application's reliability.

To date, most of the congestion control protocols proposed in the literature dynamically adapt each vehicle communication parameters to maintain the overall channel load generated below a certain limit. To reliably support cooperative applications while efficiently sharing the radio channel, congestion control protocols should take into account also the requirements imposed by cooperative applications. In this context, the concepts described in this paper enable the design of advanced congestion control policies such as the one proposed in [21]. The work in [21] proposes a contextual cooperative congestion control policy that exploits the traffic context information of each vehicle to reduce the channel load without sacrificing the traffic application's reliability. With the policy proposed in [21], vehicles cooperate to reduce unnecessary interferences and decrease the channel load, while satisfying the application's requirements.

Given the different objectives and operation of network-based and application-based communication techniques previously highlighted, new definitions are clearly needed. To establish the difference between both approaches, the work in [22] defines *awareness* control protocols as those techniques aimed at ensuring each vehicle's capacity to detect, and possibly communicate with the relevant vehicles and infrastructure nodes present in their local neighborhood, through the dynamic adaptation of their transmission parameters. In contrast to congestion control protocols, awareness control protocols are then used to reliably and efficiently support higher-layer protocols and applications. The work in [22] surveys various key congestion and awareness control approaches, discusses in detail three techniques based on transmit power control, and exposes the main open research challenges.

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