Optimizing Adaptive Transmission Policies for Wireless Vehicular Communications

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Abstract—**The adoption of wireless vehicular communication technologies would strongly depend on the technologies transmission reliability, required by QoS demanding traffic safety applications, and the system's scalability as the technology is gradually introduced. To this aim, this work proposes the use of opportunistic transmission policies that dynamically adapt the transmission parameters based on the operating conditions and potential traffic safety risks. The work analyses different configuration proposals with the aim to meeting the strong traffic safety QoS requirements, while maximizing the technology's robustness and minimising channel congestion, which in turn is crucial to guarantee the future system's scalability.**

Keywords; wireless vehicular communication systems, radio resource management, opportunistic and adaptive transmission

I. Introduction

Important worldwide research efforts are currently in place to develop wireless vehicular communications technologies allowing vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications to improve traffic safety and efficiency and provide Infotainment services while traveling. The development and future deployment of such technologies requires solving an important number of social and technological challenges including the development of a robust and efficient wireless communications system. In particular, it is important that future wireless vehicular communication systems are able to guarantee the ubiquitous robust transmission reliability required by traffic safety applications while ensuring the system's scalability and correct operation as the technology is gradually adopted. In fact, the potential benefits from wireless vehicular technologies will strongly depend on its market introduction, but in traffic dense scenarios, a wide adoption of the technology could result in high channel congestion and system's instability. To avoid such problems, it is necessary to develop and implement efficient vehicular communication protocols achieving the application QoS (Quality of Service) requirements while efficiently using the wireless channel, which in turn reduces congestion and favours the system's scalability.

Adaptive transmission policies based on the specific operating conditions have been shown to improve the system performance and scalability in traditional mobile and wireless systems and vehicular scenarios. For example, it has been proposed to adapt the transmission power level to mitigate interferences [1] or maintain the network connected [2]. Other works, such as [3], present interesting approaches to reorganize the information to be transmitted based on its relevance and the vehicle's situation to improve the system performance and scalability. While providing valuable insights, most of the studies on this topic focus on the system level operation without adequately considering the instantaneous specific QoS requirements for traffic applications. Such requirements can be especially challenging for traffic safety applications that rely on maximum transmission reliability. In this context, the authors proposed in [4] an OPportunistic-driven adaptive RAdio resource Management (OPRAM) mechanism aimed at guaranteeing the strict traffic safety QoS requirements while efficiently using the available channel resources. While [4] focused on demonstrating OPRAM's traffic safety QoS performance benefits considering a basic initial solution, this work is aimed at analyzing different OPRAM configurations from the point of view of traffic safety performance, efficiency and robustness, both at the system and instantaneous levels.

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II. Wireless Access in Vehicular Environments

To overcome the vehicular limitations of current wireless communication systems, the IEEE is developing a set of standards to improve and adapt the IEEE 802.11 operation to the vehicular environment: the IEEE 802.11p or WAVE standard (Wireless Access in Vehicular Environments) [5] and the IEEE 1609 series of standards [6]. In the US, WAVE is based on seven ten-megahertz channels consisting of one control channel and six service channels in the 5.9GHz band. The service channels are used for public safety and private services, while the control channel is used as the reference channel to initially detect surrounding vehicles and establish all communication links. As a consequence, the traditional IEEE 802.11 channel scanning process is disabled and the control channel is used to periodically broadcast announcements of available application services, warning messages and safety status messages.

WAVE adapts the IEEE 802.11a standard to the vehicular environment and thereby employs its DCF (Distributed Coordination Function) functionality. As a result, WAVE makes use of the CSMA/CA medium access mechanism to grant the vehicles access to the channel. The ad hoc mode is the only operational mode allowed in the WAVE control channel, which requires distributed channel management

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policies. It is important to note that the control channel's reference status to initiate any V2V and V2I communications or to detect the presence of a nearby vehicle could result in a high channel load in scenarios with a large number of nearby vehicles and broadcasted services. Such potential channel congestion, together with the strict traffic safety needs, requires the definition of advanced radio resource and channel management policies that efficiently uses the WAVE control channel while guaranteeing the applications QoS. It is interesting to note that ensuring such efficient use will improve the system's scalability as V2V and V2I communication technologies gradually penetrate the market.

III. OPPORTUNISTIC-DRIVEN TRANSMISSION TECHNIQUES

To define a wireless vehicular communications policy capable to achieve the strict traffic safety QoS requirements while efficiently using the communications channel, the authors proposed OPRAM [4]. OPRAM is an opportunistic communications policy that adapts the vehicles transmission parameters based on its position and proximity to an area where a potential collision could occur. This adaptation is decentralised and can be based on the information provided by digital maps, surrounding vehicles or any other source. For traffic safety applications, the OPRAM proposal adapts the transmission power and packet rate only in a small region, named AR (Algorithm Region), before the critical distance (*CD*). This critical distance is the minimum distance to a potential collision area at which a warning message needs to be received in order to provide the driver with sufficient time to react, stop and avoid the accident; it has been calculated considering a uniform deceleration model. A target scenario for OPRAM's application is intersections (see Fig. 1) where over 25% of road accidents occur in the US. By modifying the communications parameters in AR, OPRAM aims to guarantee the successful reception from a potentially colliding vehicle of at least one broadcast safety message before reaching *CD*. As illustrated in Fig. 1, OPRAM transmits N_T broadcast safety packets in AR at a transmission power equal to that needed to ensure that each of the N_T messages is correctly received with probability $p_e(i)$, with i=1,2,…N_T. As further explained in [4], $p_e(i)$ is selected to ensure that at least one of the N_T transmitted messages in AR is successfully received by the vehicle approaching the intersection and that represents a potential collision risk in 99% of the cases; this is equivalent to define a probability of not receiving a warning alert before *CD* equal to p_n=0.01. Outside AR, OPRAM maintains a constant 0.25W transmission power level and a constant packet transmission rate of 10 packets/s. These communication conditions are sufficient to guarantee a vehicle's connectivity with the vehicles located along the same street in a 150m range under Line of Sight (LOS) propagation conditions, as established by the WAVE guidelines for cooperative collision warning applications [7].

In order to demonstrate the feasibility and potential benefits derived from the use of adaptive opportunistic transmission policies, a constant probability value $p_e(i)=p_e$ was proposed in [4] for all N_T packets transmitted in AR. This initial configuration efficiently satisfies the traffic safety QoS requirements, but it is not the only possible solution to guarantee such QoS requirements. In a more general framework, the probability of not receiving a packet before *CD*, p_n, can be calculated using a Bernoulli process with the following equation:

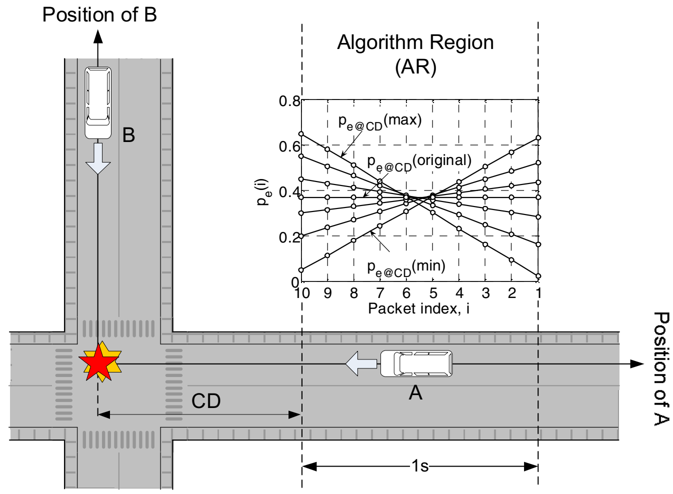

Figure 1. OPRAM configuration for traffic safety.

$$p_n = \prod_{i=1}^{N_T} \left(1 - p_e(i)\right) \tag{1}$$

While [4] evaluated a first OPRAM implementation where $p_e(i)$ was constant and established based on the target probability p_n and the Bernoulli process expressed in equation (1), in this work a linear configuration for the $p_e(i)$ values is analysed following equation (2):

$$p_e(i) = p_{e@CD} + \Delta p_e \cdot (N_T - i) \tag{2}$$

Considering packet index $i=1$ for the first packet transmitted in AR (i.e. the one transmitted at a larger distance to the intersection) and $i=N_T$ for the packet transmitted closest to *CD*, $p_{e@CD}$ represents the probability of reception of the last packet transmitted in AR, $p_{e@CD}=p_e(N_T)$. The Δp_e parameter corresponds to the linear variation of the $p_e(i)$ function between two consecutive packets. The system of equations has been solved by assigning values to $p_{e@CD}$ and then numerically calculating Δp_e. Fig. 1 illustrates some of the solutions obtained for $p_e(i)$ as defined in equation (2). The curves shown in Fig. 1 have been created for $p_{e@CD}$ values ranging from 0.05 to 0.65 for N_T=10 (for N_T=20 and N_T=30, the $p_{e@CD}$ values range from 0.025 to 0.375 and from 0.02 to 0.26, respectively). In Fig. 1, the curves corresponding to the minimum and maximum $p_{e@CD}$ values are highlighted ($p_{e@CD}(min)$ and $p_{e@CD}(max)$). The curve named as $p_{e@CD}(original)$ corresponds to the OPRAM version in [4] where $p_e(i)$ is constant across the AR.

IV. PERFORMANCE, EFFICIENCY AND ROBUSTNESS ANALYSIS

A. Evaluation scenario

To conduct this investigation, a wireless vehicular simulator developed in The Network Simulator ns2 has been implemented. It considers the critical intersection scenario illustrated in Fig. 1 where vehicles periodically broadcast safety messages on the WAVE control channel at 6Mbps, corresponding to the WAVE ½ QPSK transmission mode. The vehicular speed has been set to *v*=70km/h and the driver's reaction time to *RT*=1.5s. In terms of traffic density, two scenarios have been simulated. In the first one, only the two vehicles approaching the intersection are emulated. In this case, transmission errors result solely from propagation effects. In the second scenario, other nearby vehicles also transmitting broadcast safety alerts are emulated, resulting in transmission errors that can now be due to the propagation effects and channel congestion.

In order to ensure accurate and valid results and conclusions, realistic evaluation scenarios are needed. For that reason, a detailed urban micro-cell propagation model developed in the WINNER project [8] that considers pathloss, shadowing and multipath fading has been implemented. Despite not being developed for V2V communications, the operating conditions of the WINNER urban micro-cell model are to the authors' knowledge those that currently best fit the system level V2V communications scenario[1]. Moreover, despite considerable progress in V2V channel modeling, to the authors' knowledge there is currently no complete system level V2V channel model that considers all radio propagation effects. In addition to propagation loses, this work models the probabilistic nature resulting from radio transmission effects through the inclusion of the PER (Packet Error Rate) performance for the WAVE control channel transmission mode [9].

B. Traffic safety performance

The main objective of the OPRAM transmission technique in the proposed traffic safety scenario is to guarantee the correct exchange of at least one broadcast safety message with enough time for the driver to stop and avoid the accident at the intersection, i.e. through the reception of at least one broadcast safety message before *CD*. The results shown in Fig. 2 demonstrate that all the different OPRAM configurations are able to guarantee that in 99% of the cases approaching vehicles receive at least one broadcast safety alert from the potentially colliding vehicle before *CD* (p_n=0.01); such performance is illustrated in Fig. 2 by the fact that only 1% of vehicles for all OPRAM configurations receive zero broadcast alerts before *CD*. Fig. 2 plots the results for three values of the $p_{e@CD}$ parameter (minimum, original and maximum values) and two values of N_T, under the scenario where only the two vehicles with a risk of collision at the intersection are emulated. Fig. 2 shows that all OPRAM configurations achieve the required QoS level without any substantial difference. However, in addition to the required QoS levels, there are other important factors that could influence the decision on the optimal OPRAM configuration. Such factors, which will be analysed in the following sections, include the resource's efficiency, capacity to overcome and reduce channel congestion, and the impact of channel correlation on the performance and operation of OPRAM.

[1] The model was developed for the 5GHz band and allowed for a base station height as low as 5m.

C. Channel and resources utilization

Given that all OPRAM configurations exhibit identical traffic safety QoS levels, a potential differentiating factor is the channel and resources utilization. As previously mentioned, the scalability and future wide adoption of wireless vehicular technologies requires the design and implementation of transmission policies capable to reach the required QoS levels while efficiently using the communications channel. Fig. 3 shows that the N_T and $p_{e@CD}$ parameters considerably vary the transmission power level during AR. In fact, Fig. 3 shows that the $p_{e@CD}(max)$ OPRAM configuration results in the lower average transmission power, with 19% reduction compared to the OPRAM original proposal for N_T=10 while achieving the same QoS levels. OPRAM configured with lower $p_{e@CD}$ values require the higher transmission power given that higher $p_e(i)$ values are needed at the farthest distances to the intersection and the potentially colliding vehicle, thereby experiencing the higher propagation loses.

As a consequence of the varying transmission powers, each OPRAM configuration results in a different channel utilization or load. Considering a traffic density of 100 vehicles/km, Fig. 4 plots the average number of vehicles that detect each transmitted packet from the AR region for all emulated OPRAM configurations while employing OPRAM. As shown in Fig. 4, each OPRAM configuration results in a different number of vehicles detecting each transmitted packet during OPRAM's application and therefore in a different channel

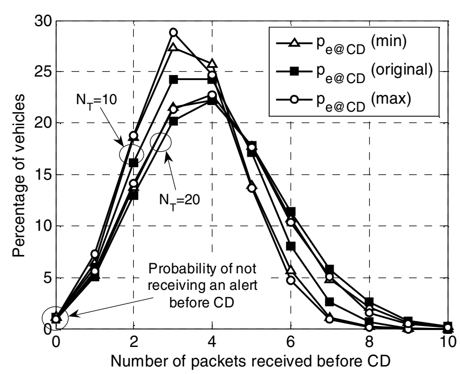

Figure 2. Percentage of vehicles that receive a given number of broadcast safety alerts before *CD*.

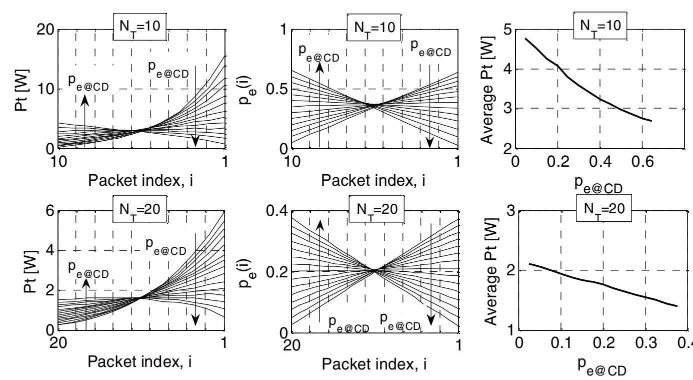

Figure 3. Transmission power levels and packet reception probabilities for different OPRAM configurations.

load. Given that all configurations exhibit the same traffic safety performance, the detection of the transmitted packets by vehicles that do not represent a danger for the transmitting vehicles might not be necessary and could result in an unnecessary channel load that could increase channel congestion and interference and compromise the system's capacity and scalability. Fig. 4 shows that the higher $p_{e@CD}$ values result again in a lower channel load, with $p_{e@CD}(max)$ reducing the channel load by over 5.5% compared to the original OPRAM configuration. Similar trends are observed among varying OPRAM configurations as N_T increases, although with higher channel loads; although increasing N_T reduces the transmission power of each packet (Fig. 3), it also increases the number of packets transmitted during AR.

D. *Vehicle-to-vehicle interference*

Section *IV.B* demonstrated that all the different OPRAM configurations proposed are able to guarantee the traffic safety QoS requirements, with a varying impact on the channel and resources utilization. The performance analysis was conducted considering the scenario where only the two vehicles with a risk of collision were periodically transmitting broadcast safety messages on the WAVE control channel. However, in realistic scenarios other nearby vehicles will be also transmitting broadcast safety alerts on this channel. These transmissions will increase channel congestion and result in packet data losses due to packet collisions that can significantly degrade the traffic safety performance, as shown in [10] for the original OPRAM configuration. It is then necessary to evaluate the robustness to the channel congestion of the different OPRAM configurations. Fig. 5 shows the OPRAM performance degradation for N_T=10 packets and all different OPRAM configurations when surrounding vehicles periodically broadcast safety messages on the control channel with 100 vehicles/km average traffic density. As it can be observed in Fig. 6, nearby vehicles increase packet collisions and reduce the packet reception probability, which results in that only in 95% of OPRAM applications the two potentially colliding vehicles receive the broadcast safety alert with sufficient time for the driver to react and avoid the collision (the original OPRAM target was 99%).

To overcome the channel congestion negative impact on the OPRAM performance, [10] proposed a compensation mechanism based on increasing the transmission power of the N_T packets transmitted during AR to compensate for the $p_e(i)$ reduction as channel congestion increases; i.e. if for example in the original OPRAM proposal the probability to correctly receive a packet was established to $p_e(i)=p_e$=0.37 for guaranteeing the target probability p_n=0.01 following the Bernoulli process defined in equation (1), and such probability was decreased the 25% due to channel congestion, OPRAM was redesigned and the N_T transmission power levels recalculated considering that the probability to correctly receive a packet is now equal to $p_e(i)=p_e$=0.493. Fig. 5 shows that the proposed congestion policy is capable to meet the OPRAM traffic safety QoS target by increasing the transmission power during AR (Fig. 7). However, Fig. 7 shows that the increase in the transmission power to compensate channel congestion varies based on the considered OPRAM configuration. The results depicted in Fig. 7 highlight that the $p_{e@CD}(max)$ OPRAM configuration is the one with the lowest average transmission power after applying the channel congestion compensation policy. In terms of channel utilization, the $p_{e@CD}(max)$ OPRAM configuration also results in that a lower number of vehicles detect the N_T transmitted packets during AR (Fig. 8). It is important to note that such reduction is achieved without compromising the traffic safety QoS target, confirming the channel efficiency conclusions reached in section *IV.C*.

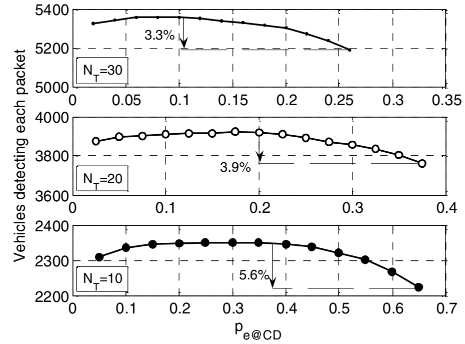

Figure 4. Average number of times that the N_T packets transmitted by a vehicle from AR are detected by surrounding vehicles.

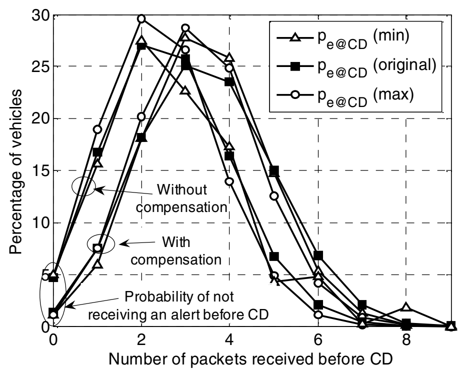

Figure 5. Percentage of vehicles that receive a given number of broadcast safety alerts before CD for N_T=10.

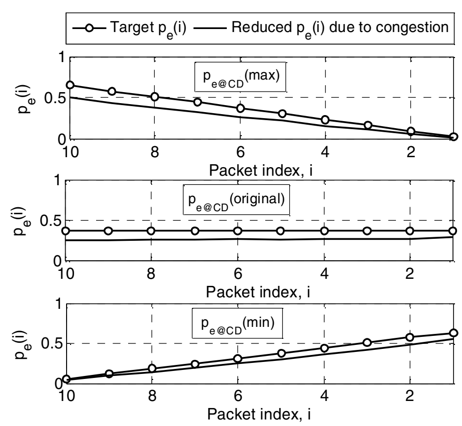

Figure 6. Packet reception probabilities with and without channel congestion for N_T=10.

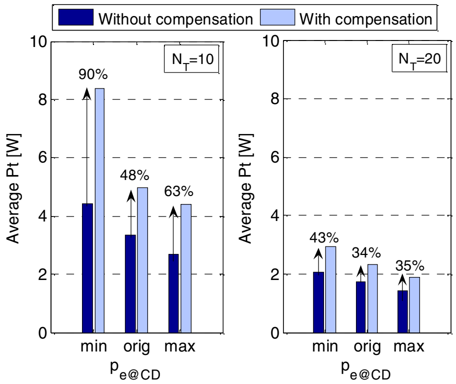

Figure 7. Average transmission power level of the N_T packets.

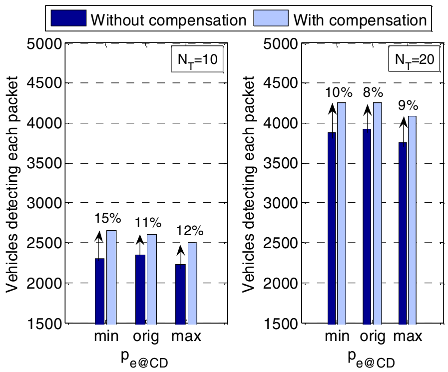

Figure 8. Average number of times that the N_T packets transmitted by a vehicle from AR are detected by surrounding vehicles, with and without the developed channel compensation policy.

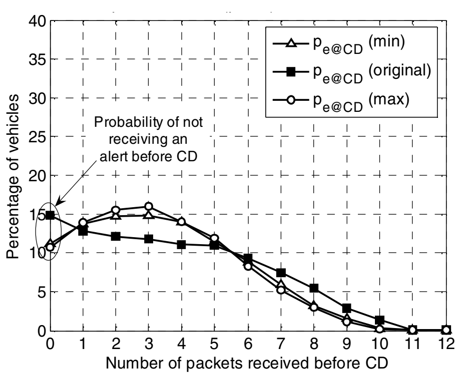

Figure 9. Percentage of vehicles that receive a given number of messages before *CD* taking into account channel correlation.

E. Robustness to radio channel correlation

Radio communications are generally characterised by important channel correlation levels, for example those identified for the shadowing [11]. Given that the OPRAM transmission mechanism considers the probability of reception of the N_T packets transmitted in AR to be independent of each other in order to estimate the required transmission power levels, it is important to evaluate its performance when such correlation is experienced. Consequently, the shadowing correlation has been introduced in the WINNER shadowing modeling following the Gudmundson proposal [11]. Fig. 9 shows that channel correlation can significantly degrade OPRAM's traffic safety performance. However, what is important to note is that the $p_{e@CD}(max)$ OPRAM configuration not only results in the lower transmission power and channel utilization, but also in the lower traffic safety performance degradation due to channel correlation. This is due to the fact that the $p_{e@CD}(max)$ and $p_{e@CD}(min)$ configurations rely on high $p_e(i)$ and transmission power values at the end or beginning of AR, which are capable to better combat channel correlation than relying on constant $p_e(i)$ values across AR. In any case, the authors are working on a novel policy to compensate channel correlation effects, and guarantee OPRAM's traffic safety performance even under correlated channels.

V. Conclusions

This paper has investigated the performance and capacity of adaptive wireless vehicular communication policies to efficiently use the channel and power resources, while robustly overcoming the negative channel interference and correlation effects. The conducted investigation has shown that all the transmission policies proposed are capable to guarantee the established traffic safety performance, but some exhibit better properties to efficiently use the communication resources and overcome undesired channel effects.

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