Analysis of Message Generation Rules for Collective Perception in Connected and Automated Driving

Gokulnath Thandavarayan, Miguel Sepulcre, Javier Gozalvez

Abstract— **Collective Perception (CP) or cooperative sensing enables vehicles and infrastructure nodes to exchange sensor information to improve their perception of the driving environment. CP enables vehicles to detect objects (e.g. non-connected vehicles, pedestrians, obstacles, etc.) beyond their local sensing capabilities. ETSI is currently developing the European standards for collective perception or cooperative sensing. This includes defining which information should be exchanged about the detected objects, and how often it should be exchanged. To this aim, different CP generation rules for collective perception are currently under analysis, and this paper presents an in-depth analysis of their performance and efficiency. The conducted analysis highlights the existing trade-offs between performance (capacity to detect surrounding objects) and efficiency (redundant detection and transmission of the same detected objects). It also demonstrates the need to design advanced policies that dynamically control the redundancy on the wireless channel while ensuring the capacity to reliably detect the driving environment.**

Keywords— Collective perception, cooperative sensing, message generation, connected and automated vehicles, CAV, V2X, vehicular networks, C-ITS, cooperative ITS.

I. INTRODUCTION

Automated Vehicles (AVs) are equipped with multiple exteroceptive sensors (e.g. lidars, radars, sonars and cameras) to perceive their local environment. The perception capabilities of each sensor are limited to a certain detection range and a given field of view. In addition, these capabilities can be impaired due to the presence of obstacles (obstructions) in the field of view, and adverse weather conditions, among others. These limitations can significantly degrade the perception capabilities of AVs, and hence negatively influence their safety and driving efficiency.

Connected and Automated Vehicles (CAVs) can improve their perception capabilities thanks to the exchange of sensor information using wireless technologies such as IEEE 802.11p/ITS-G5 [1] or C-V2X/LTE-V [2]. This is generally referred to as collective perception or cooperative sensing. Collective perception enables CAVs to improve their perception of the surrounding environment by receiving from other vehicles information about objects that are beyond their sensing range. It can also improve CAVs' detection accuracy and increase the confidence about the detected objects. Collective perception can also help mitigate the negative impact of adverse weather conditions on the sensing capabilities as well as the initial limited CAV market penetration rate. The collective perception concept can also be extended to infrastructure nodes with ITS sensing capabilities. These nodes can transmit and receive sensor information to/from vehicles to improve their respective knowledge of the driving environment.

V2X (Vehicle-to-Everything) standards have been initially designed for vehicles to exchange basic status and positioning information through beacons (CAMs – Cooperative Awareness Messages [3] or BSM – Basic Safety Messages [4]). However, the research community [5] and standardization bodies are currently working to extend V2X communications so that vehicles and infrastructure nodes can also exchange local sensor information to improve their perception capabilities and the knowledge of the surrounding driving environment. For example, the ETSI Technical Committee on ITS is currently designing the V2X messages (known as Collective Perception Message or CPM) necessary for vehicles to exchange sensor information about the status and dynamics of detected objects. Another important aspect yet to be decided is the CPM generation rules that define when should vehicles exchange CPM messages. These generation rules will have a significant impact on the effectiveness of the collective perception service and on the wireless vehicular network. In fact, if vehicles exchange information about detected objects very frequently, they will significantly improve their perception capabilities and be able to detect their surrounding objects with higher accuracy. However, a too frequent exchange of CPM messages can also saturate the communications channel to the point that these messages cannot be transmitted, ultimately reducing the effectiveness of the collective perception service. Limited studies have been conducted to date on the impact that the CPM generation rules will have on the effectiveness of the collective perception service and the saturation of the wireless communications channel. This paper addresses this limitation and conducts an in-depth analysis of the performance and efficiency of different CPM message generation rules that are currently discussed at ETSI. These generation rules have been analyzed under different driving conditions using the networks simulator ns3. The conducted analysis provides useful information and interesting observations about the existing trade-off between perception and channel utilization.

II. RELATED WORK

Most of the existing collective perception studies have focused either on the sensor or communication technologies. For example, [6] and [7] were some of the first studies focused on analyzing different sensing and fusion techniques. In these

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Gokulnath Thandavarayan, Miguel Sepulcre and Javier Gozalvez are with Universidad Miguel Hernandez de Elche (UMH), Spain. (phone: +34-96-522-2424; fax: +34-96-665-8903; e-mail: gthandavarayan@umh.es, msepulcre@umh.es, j.gozalvez@umh.es).

two studies, the raw sensed information was directly exchanged between vehicles. Alternatively, Kim *et al*. [8] investigated the exchange of raw sensor data, processed metadata (e.g. lane information represented in the point cloud) and compressed data (e.g. images from camera sensor) for collective perception. The results show that the communication delay increases with the amount of data transmitted so unnecessary data should be avoided. To minimize the bandwidth required for collective perception and reduce the latency, [9] investigated the concept of sharing detected object data instead of raw sensor data. In this study, authors experimentally evaluate through field tests the transmission latency and range for different message sizes and rates. Günther *et al*. [10] extended the message concept proposed in [9] for collective perception with different containers in order to specify the detected object parameters, sensor configurations and the characteristics of the transmitting vehicle. This information is used by the receiving vehicle to perform the coordinate transformation and locate the detected objects. The efficiency of the proposed message is investigated with an obstacle avoidance scenario with two vehicles. The results shows that the proposed solution allows vehicles to detect earlier a possible obstruction and hence augments the reaction time to handle a potential safety risk. The collective perception message concept proposed in [10] was evaluated under different low traffic densities in [11] and high traffic densities in [12]. Both studies considered different priority queues and Decentralized Congestion Control (DCC) mechanisms [13]. These studies analyse the awareness ratio and channel load for scenarios with different CAVs market penetration rates. They conclude that collective perception or cooperative sensing increases the awareness of the driving environment but could also increase the network congestion. Suggestions were made by the authors to incorporate collective perception information in the existing CAM [3] or move collective perception messages from the control to a service channel [14]. Alternately, Gani *et al*. [5] analyze the advantages of jointly controlling the transmission rate and length of cooperative sensing messages rather than controlling them separately. The studies discussed so far focus mainly on V2V (Vehicle to Vehicle) communications. Wang *et al*. highlight in [15] the possibility to utilize V2I (Vehicle to Infrastructure) communications to support collective perception at lower CAVs penetration rates.

This study extends existing CP literature by providing an in-depth analysis of the performance and efficiency of different CPM generation rules under different traffic densities. The objective is to investigate the effectiveness of the CPM generation rules (i.e. the capacity of vehicles to accurately be aware of their surrounding driving environment), and also the communications overhead and CP-related redundancy that they generate. This analysis provides important information to further optimize the CPM generation rules so that the CP effectiveness can be maintained while reducing the communications overhead to avoid saturating the communications channel.

III. CPM Standardization

ETSI TC ITS WG1 is currently working on the standardization of the Collective Perception Service (CPS) through the work items DTS/ITS-00167 and DTR/ITS-00183. The current developments are described in the Technical Report in [16] that will serve as a baseline for the specification of CPS in ETSI TS 103 324. The document reports the CPM format and its Data Elements, and the current CPM generation rules. In addition, the document discusses on the use of message fragmentation and segmentation for large CPM messages, and the need to utilize multiple channels to avoid saturating the control channel.

The current structure of the CPM includes an ITS PDU header and 4 types of containers: one Management Container, one Station Data Container, one or more Sensor Information Containers, and one or more Perceived Object Containers (POCs) [16]. The ITS PDU header was specified in [17] and includes Data Elements such as protocol version, the message ID and the Station ID. The Management Container is mandatory and provides basic information about the transmitting vehicle, including its type and position. The position is used to reference the detected objects. The Station Data Container is optional and includes additional information about the transmitting vehicle, such as its speed, heading, or acceleration. Part of this information is also included in the CAM transmitted by the same vehicle, but it is also needed in the CPM. If this information was not included in the CPM, the transmitting vehicle dynamics would need to be estimated by the receiving vehicle from the last received CAM. This estimation could reduce the accuracy of the positioning and speed estimation of the transmitting vehicle and its perceived objects.

The Sensor Information Containers describe the sensing capabilities of the transmitting vehicle. The Sensor Information Containers are used by receiving vehicles to derive the areas that are currently sensed by nearby vehicles. A Sensor Information Container includes the ID of a sensor, its type (e.g. radar, lidar or a sensor fusion system) and its detection area, among other Data Elements. Up to ten Sensor Information Containers can be included in a CPM.

The POCs describe the dynamic state and properties of the detected objects. Each POC includes information about a detected object, including its object ID, the ID of the sensor that detected it, the time of measurement, the distance between the detected object and the transmitting vehicle in the XY-plane, and the speed and dimensions of the object, among others. A single CPM can include up to 255 POCs. Multiple POCs could report information about the same detected object but obtained with different sensors. Alternatively, the sensed information could also be fused and reported in a single POC. The first approach reduces the computational needs and processing delays at the transmitting vehicle but may increase the channel load and processing needs at the receiver.

IV. CPM Generation Rules

The CPM generation rules should define how often a CPM is generated by the transmitting vehicle and which information (detected objects and sensors information) is included in the CPM. Periodic and dynamic policies are being investigated and discussed as part of the ETSI standardization process.

The periodic policy generates CPMs periodically every *T_GenCpm*. In every CPM, the transmitting vehicle includes the information about all the objects it has detected. The CPM should be transmitted even if no objects are detected. The periodic policy is being used as a baseline in the standardization process to compare its performance and efficiency with more advanced policies such as the dynamic one. With the dynamic policy, the transmitting vehicle checks every *T_GenCpm* if the environment has changed and it is necessary to generate and transmit a new CPM. If it is, the vehicle also decides the objects that should be included in the CPM. A vehicle generates a new CPM if it has detected a new object, or any of the following conditions are satisfied for any of the previously detected objects:

1. Its absolute position has changed by more than 4m since the last time it was included in a CPM.
2. Its absolute speed has changed by more than 0.5m/s since the last time it was included in a CPM.
3. The last time the object was included in a CPM was 1 second ago.
4. It is classified as Vulnerable Road User (VRU) or an animal.

All new detected objects and those that satisfy at least one of the previous conditions are included in the CPM. In all the generated CPMs, the Management Container, the Station Data Container are included, but the Sensor Information Containers are added only once per second. If no object satisfies the previous conditions, a CPM is still generated every second, but only including the Management Container, the Station Data Container and the Sensor Information Containers. It should be noted that these CPM generation rules are an adaptation of the CAM generation rules [3] for detected objects. In addition, these generation rules are preliminary and only a first proposal (hence subject to possible changes in the final specifications) that must be now carefully analyzed to understand its road traffic and communication implications.

V. SCENARIO

This study evaluates the impact of the CPM generation rules through simulations using ns3 and SUMO. We have extended ns3 with a CPS component and different onboard sensors. The CPS component implements the periodic and the dynamic CPM generation rules. Two different periodic policies with 10Hz (*T_GenCpm*=0.1s) and 2Hz (*T_GenCpm*=0.5s) have been considered as a baseline in this study. In the dynamic policy, the *T_GenCpm* parameter has been set to 0.1s, so that the maximum CPM rate is 10Hz. The CPM size is dynamically calculated by the transmitting vehicle based on the number of containers in each CPM. The size of each container has been estimated offline using the current ASN.1 definition of the CPM [16]. To this aim, we have generated 10^4 standard-compliant CPMs and Table I reports the average size of containers that is used in this study. In our scenario, each vehicle is equipped with two on-board sensors [16]. Sensor 1 has 65m range and a field of view of ±40 degrees. Sensor 2 has 150m range and a field of view of ±5 degrees. The sensor shadowing effect (sensor masking) is implemented in the XY-plane. We assume that the sensors can detect only the vehicles that are in their Line-of-Sight (LOS) [15] and that the objects detected by the two sensors are fused.

The traffic scenario is a six-lane highway with 5km length and a lane width of 4 meters. We simulate two different traffic densities following the 3GPP guidelines for V2X simulations [18]. The high traffic density scenario (120veh/km) has a maximum speed of 70km/h, while the lower one (60veh/km) has a speed limit of 140km/h. For each traffic density, this study considers different speeds per lane. The speeds have been selected based on statistics of a typical 3-lane US highway obtained from the PeMS database [19]. Vehicles measure 5m x 2m. To avoid boundary effects, statistics are only taken from the vehicles located in the 2km around the center of the simulation scenario. The configuration of the scenario is summarized in Table II.

All vehicles are equipped with an ITS-G5 transceiver (100% penetration) and operate in the same channel. The propagation effects are modeled using the Winner+ B1 propagation model following 3GPP guidelines [18]. The communication parameters are summarized in Table III.

TABLE I. CPM CONTAINERS

CPM Container	Size
ITS PDU header Management Container Station Data Container	121 Bytes
Sensor Information Container	35 Bytes
Perceived Object Container	35 Bytes

TABLE II. SCENARIO

Parameter	Values	
	Low traffic density	High traffic density
Highway length	5km	
Number of lanes	6 (3 per driving direction)	
Traffic density	60 veh/km	120 veh/km
Speed per lane	140 km/h 132 km/h 118 km/h	70 km/h 66 km/h 59 km/h

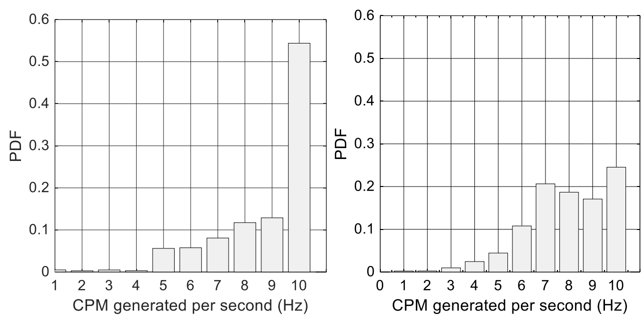
TABLE III. COMMUNICATION PARAMETERS

Parameter	Values
Transmission power	23dBm
Antenna gain (tx and rx)	0dBi
Channel bandwidth/carrier freq.	10MHz / 5.9GHz
Noise figure	9dB
Energy detection threshold	-85dBm
Data rate	6Mbps (QPSK 1/2)

VI. EVALUATION

A. Operation

Before analyzing the performance and efficiency of each CPM generation policy, it is necessary to better understand their operation. To this aim, we focus first on the dynamic policy. Figure 1 represents for this policy the Probability Density Function (PDF) of the number of CPMs transmitted per second per vehicle under the two traffic densities. The number of CPMs generated per vehicle depends on the number of detected vehicles (i.e. traffic density) and on their dynamics (e.g. an object is included in a CPM every 4m). The speed of vehicles is higher for low traffic densities than for higher ones. As a result, vehicles satisfy more frequently one of the 3 conditions specified in Section IV for the dynamic CPM generation rules, and vehicles generate more CPMs per second at low densities (Figure 1a) than at high densities (Figure 1b). However, not all vehicles generate CPMs at the same rate in a given traffic density scenario since the speed limit varies per lane (Table II). It is interesting to analyze with more detail the high traffic density scenario (Figure 1b). As previously mentioned, the higher the density the less CPMs are in general generated per vehicle since they travel at lower speeds. The vehicles that travel in the higher speed lane move at 70km/h or 19.4m/s. They will then change their absolute position by more than 4m every 0.21 seconds. Vehicles that detect this change generate then a CPM at 4.8Hz on average. However, Figure 1b shows that there are vehicles that transmit 6-10 CPMs per second. This is the case because a vehicle generates a CPM as soon as one of the vehicles it detects changes its absolute position by more than 4m. If the detected vehicles change their absolute position by more than 4m at different times, the transmitting vehicle will need to generate different CPM messages. This explains why CPM frequency rates as high as 10Hz are observed in the highest traffic density scenario (Figure 1b). It is also important to emphasize that the frequent transmission of CPMs reporting information about a small number of detected vehicles can result in a loss of efficiency due to a higher number of channel access attempts and redundant headers. Such efficiency might be improved by grouping in a single CPM the information of several detected vehicles in a short period of time.



(a) Low traffic density (b) High traffic density

Figure 1. PDF (Probability Density Function) of the number of CPMs generated per second and per vehicle with the dynamic policy.

Figure 2 represents the PDF of the number of objects included in each CPM for the periodic and dynamic CPM generation policies under the two traffic densities. The figure shows that the periodic CPM generation policies augment the size of CPMs since they include a higher number of detected objects per CPM. This is the case because the periodic policies always include in the CPM all the detected objects, while the dynamic policy selects the detected objects to be included in a CPM based on their dynamics. As the traffic density increases, the number of objects included in each CPM increases with the periodic policies because more objects (i.e. vehicles in our study) are detected. However, Figure 2 shows that the traffic density does not significantly affect the number of objects included in each CPM with the dynamic policy. This is the case because the speed of vehicles decreases with the traffic density. As a result, vehicles change their absolute position by more than 4m less frequently. So even if we detect more vehicles due to the higher traffic density, the status of a detected vehicle needs to be reported in a CPM less frequently. The obtained results clearly show the benefits of the dynamic policy since it can adapt the number of objects included in each CPM to the traffic density and speed.

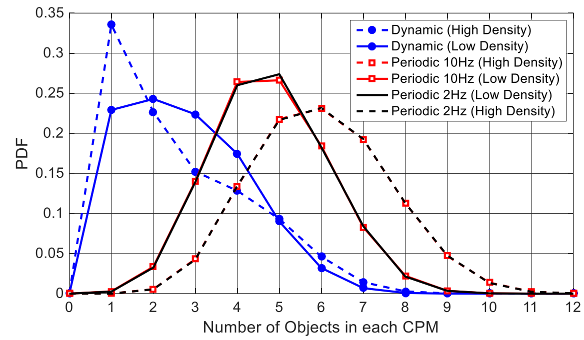


Figure 2. PDF (Probability Density Function) of the number of objects included in each CPM with the dynamic and periodic policies.

B. *Communications performance*

This section evaluates the impact of the CPM generation policies on the communications performance. To this aim, Table IV shows the average CBR (Channel Busy Ratio) experienced when implementing each CPM generation policy under the two traffic densities. The CBR is measured by each vehicle every second. The CBR is a measure of the channel load, and it is defined as the percentage of time that the channel is sensed as busy. A high CBR value indicates that the channel is very loaded and hence risks saturating. If this happens, the communications performance degrades and the packet delivery ratio decreases [20]. Table IV shows that the periodic policy operating at 2Hz is the one generating the lowest channel load. On the other hand, the periodic policy at 10Hz generates the highest channel load. The dynamic policy generates intermediate channel load levels (Table IV) in line with the results depicted in Figure 1 and Figure 2. These results showed that the dynamic policy generates between 4 and 10 CPMs per second, approximately, and reduces the number of objects per CPM compared to the periodic policies. Consequently, the dynamic policy increases the channel load compared to a periodic policy at 2Hz, but decreases it compared to the periodic policy at 10Hz. Table IV shows that the channel load and CBR increase with the traffic density. However, lower increases are observed with the dynamic policy. In particular, an increase in the traffic density augments the CBR experienced by the dynamic policy by a factor of 1.6, whereas it increases by factors of 2.1 (2Hz) and 1.9 (10Hz) for the periodic policies. This is again due to the same trend observed in Figure 2. When the traffic density increases, the speed of vehicles decreases and vehicles change their absolute position by more than 4m less frequently. As a result, vehicles generate less CPM messages, and the CBR degradation with the traffic density is lower for the dynamic policy than the periodic ones.

TABLE IV. AVERAGE CBR (CHANNEL BUSY RATIO)

Policy	Traffic density	CBR
Periodic at 2Hz	Low	5.6 %
	High	11.9 %
Periodic at 10Hz	Low	25.6 %
	High	49.6 %
Dynamic	Low	19.2 %
	High	31.7 %

The channel load or CBR has an impact on the PDR (Packet Delivery Ratio). The PDR is defined as the probability of successfully receiving a CPM as a function of the distance between the transmitting and receiving vehicles. Figure 3 plots the PDR of the periodic and dynamic CPM generation policies under the two traffic densities. The degradation of the PDR with the distance is due to the radio propagation effects. The PDR can also be degraded due to packet collisions or interference when the channel load is high. This effect is highlighted in Figure 3 where the arrows indicate the degradation of the PDR as a result of an increase of channel load and packet collisions when the traffic density increases. Table IV already showed how the channel load increases with the traffic density. The resulting PDR degradation observed in Figure 3 is hence a consequence of the trends observed in Table IV. Following these trends, Figure 3 shows that the periodic policy operating at 2Hz achieves the highest PDR and the policy at 10Hz the lowest one. Figure 3 also highlights that the dynamic policy achieves a balance between the two periodic policies. However, it is yet to be seen whether the dynamic policy could improve the network performance and increase the PDR by avoiding the transmission of certain CPM messages without degrading the perception capabilities of vehicles.

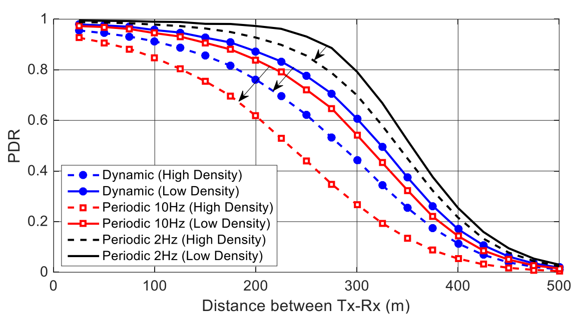


Figure 3. PDR (Packet Delivery Ratio) as a function of the distance between transmitter and receiver.

C. *Perception capabilities*

This section analyzes the perception capabilities of vehicles as a result of the different CPM generation policies. To this aim, we define the Object Awareness Ratio as the probability to detect an object (vehicle in this study) through the reception of a CPM with its information in a time window of one second. We consider that an object is successfully detected by a vehicle if it receives at least one CPM with information about that object per second. Figure 4 depicts the average Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM. The results are shown for the periodic and dynamic policies and the two traffic densities. The results obtained show that all policies achieve a high object awareness ratio (higher than 0.989) up to 350m. Beyond 350m, the awareness ratio degrades under higher densities for the dynamic policy and the periodic policy at 10Hz as a result of the higher CBR (Table IV) and lower PDR levels (Figure 3). On the other hand, Figure 4 shows that from 350m a higher degradation of the awareness ratio is observed for the periodic policy at 2Hz under low traffic densities. This is due to the fact that at such distances the propagation effect becomes dominant when the traffic density is low (there are less packet collisions). All CPM generation policies experience the same degradation due to the propagation since it is not dependent on the channel load. However, propagation loses affect more negatively the Object Awareness Ratio for the periodic policy at 2Hz since this policy transmits less CPMs.

The value of collective perception or cooperative sensing depends on how timely or fresh is the information received about the detected objects. A vehicle cannot base its driving decision on outdated information. Figure 5 plots the time difference between received CPMs with information about the same object or vehicle. The metric (referred to as the time between object updates) is represented as a function of the distance between the object and the vehicle receiving the CPMs for the low traffic density scenario. It is important to emphasize that the CPMs including information about the same object or vehicle might be transmitted by different or multiple vehicles. Figure 5 shows that all CPM generation policies provide object updates below 0.1s up to 200m approximately. This time value is reduced to 0.03s with the dynamic policy that can provide updates nearly as frequently as the periodic policy at 10Hz while better controlling the channel load (Table IV) and improving the communications performance (Figure 3). This is important to ensure the stability and scalability of the vehicular network that supports the implementation of collective perception. Similar trends have been observed under high traffic densities, but with even lower average time between object updates. The obtained results show that in general all CPM generation rules provide very frequent updates about detected objects. However, we have seen in Table IV and Figure 3 that the CPM generation policies can generate non-negligible channel load levels that can degrade the communications performance and impact the network's scalability. It is hence necessary to evaluate whether the current CPM generation policies generate unnecessary redundancy about the detected objects.

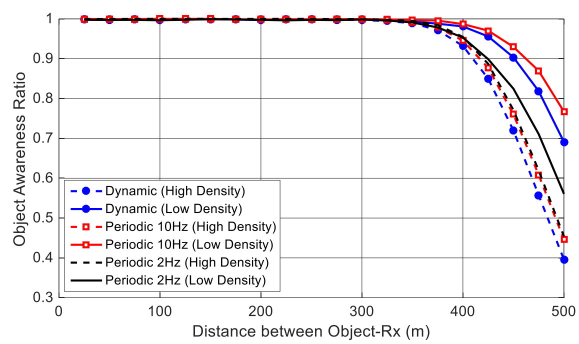


Figure 4. Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

Figure 6 illustrates the number of updates received per second about the same object through the reception of CPMs. This metric is referred to as detected object redundancy and is depicted in Figure 6 as a function of the distance between the object and the vehicle receiving the CPM. The degradation observed in Figure 6 with the distance is a direct consequence of the PDR degradation reported in Figure 3. Figure 6 shows that the periodic policy at 10Hz provides around 51 updates per second of the same object at short distances. The dynamic policy can reduce this value to around 30 updates per second and object without degrading the Object Awareness Ratio (Figure 4). In addition, the dynamic policy can reduce the channel load (Table IV) and improve the communications performance (Figure 3). Despite the gains observed with the dynamic policy, it is yet an open issue whether the still high redundancy levels observed in Figure 6 are necessary for a safe connected and automated driving or not. The dynamic policy could be modified to further decrease the redundancy and increase the robustness and scalability of the vehicular network as it is a key component to achieve the expected benefits of connected and automated driving.

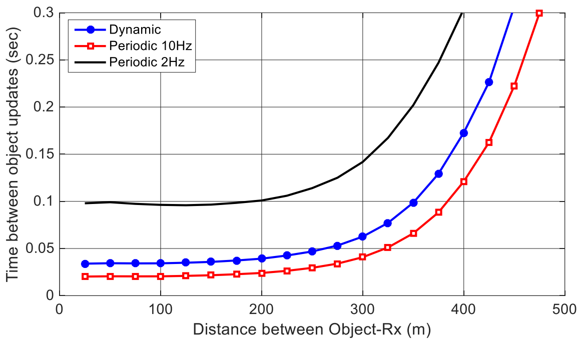


Figure 5. Average time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM for the low traffic density scenario.

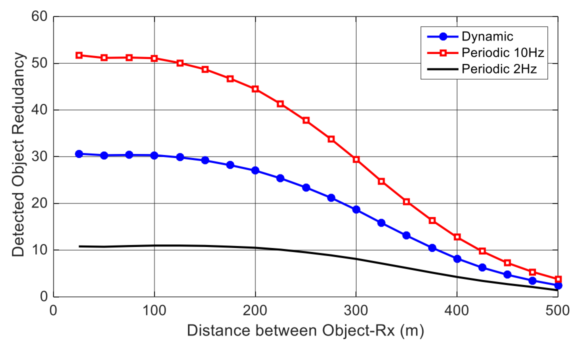


Figure 6. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM for the low traffic density scenario.

VII. Conclusions

Collective perception or cooperative sensing can provide significant benefits to a safer connected and automated driving by improving the vehicles' perception of the environment through the exchange of sensor information. ETSI is now defining the standards to implement collective perception based on the exchange of information about the detected objects. This paper provides an in-depth evaluation of the operation, communications performance and perception capabilities of the different message generation rules under discussion. These rules define which objects should be transmitted in a CPM, and how often they should be transmitted. The obtained results show the existing trade-off between perception capabilities and communications performance (and network scalability). The conducted analysis has shown that the CPM generation policies that improve the perception capabilities generate higher channel load levels and hence have a higher risk to saturate the communications channel and render the network unstable. While some redundancy could benefit the detection of nearby objects, unnecessary redundancy could severely impact the performance of vehicular networks. The dynamic policy achieves an interesting balance between perception capabilities and communications performance. However, it is yet an open discussion whether the observed levels of redundancy are necessary or whether they could be further optimized to reduce any potential negative impact of the implementation of CPM in the stability and scalability of future V2X networks. These networks are fundamental to support connected and automated driving services.

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