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Cooperative Perception for Connected and Automated Vehicles: Evaluation and Impact of Congestion Control

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ABSTRACT Automated vehicles make use of multiple sensors to detect their surroundings. Sensors have significantly improved over the years but still face challenges due to the presence of obstacles or adverse weather conditions, among others. Cooperative or collective perception has been proposed to help mitigate these challenges through the exchange of sensor data among vehicles using V2X (Vehicle-to-Everything) communications. Recent studies have shown that cooperative perception can complement on-board sensors and increase the vehicle's awareness beyond its sensors field of view. However, cooperative perception significantly increases the amount of information exchanged by vehicles which can degrade the V2X communication performance and ultimately the effectiveness of cooperative perception. In this context, this study conducts first a dimensioning analysis to evaluate the impact of the sensors' characteristics and the market penetration rate on the operation and performance of cooperative perception. The study then investigates the impact of congestion control on cooperative perception using the Decentralized Congestion Control (DCC) framework defined by ETSI. The study demonstrates that congestion control can negatively impact the perception and latency of cooperative perception if not adequately configured. In this context, this study demonstrates for the first time that the combination of congestion control functions at the Access and Facilities layers can improve the perception achieved with cooperative perception and ensure a timely transmission of the information. The results obtained demonstrate the importance of an adequate configuration of DCC for the development of connected and automated vehicles.

INDEX TERMS Cooperative perception, collective perception, cooperative sensing, message generation, CPM, connected automated vehicles, CAV, automated vehicles, autonomous vehicles, V2X, vehicular networks, C-ITS, ITS-G5, congestion control, DCC, ETSI.

I. INTRODUCTION

Automated vehicles use embedded sensors to drive autonomously with low or no human intervention. To this aim, the vehicle's planning system uses perception and localization data to determine the travel path and driving actions (e.g. lane changes, acceleration or braking) that are executed by the vehicle's control platform. For perception and localization, automated vehicles equip multiple exteroceptive sensors (e.g. lidars, radars and cameras) that locally perceive the driving environment [1]. This environment includes static elements (e.g. road shape and curvature, lane marks and trees) and dynamic ones (e.g. other vehicles, bicycles, pedestrians). Sensors for automated vehicles have significantly improved their perception range and detection accuracy over the last years [2]. However, the capabilities of these sensors can still be impaired due to the presence of obstacles, adverse weather conditions, or sensitivity to lighting conditions among other factors [3]. These limitations can negatively influence the safety and efficiency of automated vehicles. V2X (Vehicle-to-Everything) communications can reduce this negative impact and improve the perception or sensing capabilities of Connected and Automated Vehicles (CAVs) by facilitating the exchange of sensor data among vehicles. This process

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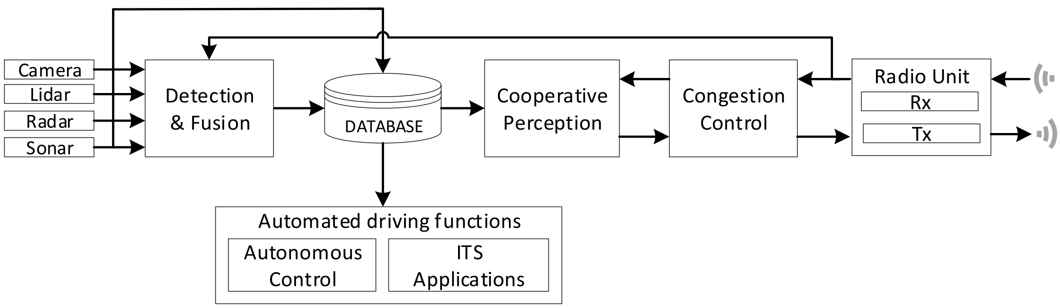

FIGURE 1. Basic architecture of cooperative perception.

is generally referred to as cooperative perception, collective perception or cooperative sensing [4], [5]. Figure 1 depicts the basic architecture for cooperative perception [6]. On-board sensors locally perceive the environment and perform the necessary processing, fusion and detection tasks to support the automated driving functions. The information gathered by the sensors is also used as an input for the cooperative perception component. This component selects the information to be exchanged among vehicles. For example, it decides which detected objects should be included in a cooperative perception message and how often these messages should be transmitted. Congestion control protocols may adapt the rate at which cooperative perception messages are generated and transmitted to control the communications channel load. It should be noted that the received cooperative perception messages are fused with the information obtained from the on-board sensors to improve and extend the vehicles' perception of the driving environment.

Cooperative perception enables vehicles to exchange their sensors' data. This provides vehicles with additional sensor data about the driving environment, including data beyond their on-board sensors' field of view (FoV). Cooperative or collective perception can also help improve the vehicles' sensor detection accuracy and increase the confidence about the detected objects. This is the case because vehicles can correlate and compare the information from their on-board sensors with sensor information gathered from nearby vehicles using V2X communications. Cooperative perception also helps mitigating the negative impact of adverse weather conditions or the negative effect of lighting conditions on the sensitivity.

Cooperative perception relies on V2X communications for vehicles to exchange sensor data. The development of V2X communications was initially focused on the so-called Day One Services [7]. These services include, among others, a basic cooperative awareness service where vehicles regularly broadcast their position, speed and basic status information through CAMs (Cooperative Awareness Messages) based on ETSI (European Telecommunications Standards Institute) standards [8] or BSMs (Basic Safety Messages) based on SAE (Society of Automotive Engineers) standards [9]. This basic cooperative awareness service improves the awareness of vehicles, but the information exchanged is limited and does not exploit the rich sensor data gathered by CAVs. ETSI [4] and SAE [5] have then recently launched activities to define new V2X standards to implement collective or cooperative perception for CAVs to exchange sensor data. ETSI has recently finalized a Technical Report to define the so-called Collective Perception Service (CPS). This service includes the definition of the Collective Perception Message (CPM) format and the generation rules to decide when a new CPM should be generated and what information it should include. These efforts highlight the industrial interest and potential of V2X communications to support the development and deployment of connected and automated vehicles. However, the work is still at its early stages, and has initially focused on drafting a framework to develop cooperative perception and define first CPM messages and generation rules. It is then necessary to better understand the operation of cooperative perception and optimize the related V2X communication protocols to maximize the effectiveness of cooperative perception while ensuring the network's scalability. This is important since exchanging sensor data significantly increases the communication channel load.

This study goes beyond the state-of-the-art and presents a dimensioning study that analyzes the performance and effectiveness of cooperative perception using V2X communications. The study first shows how cooperative perception mitigates the perception limitations of on-board sensors. The study then analyzes the impact of the market penetration rate and different sensor configurations on the operation and performance of cooperative perception. This analysis shows that cooperative perception can significantly increase the communication channel load and activate the operation of congestion control protocols. The study investigates then the impact of these protocols on the performance and operation of cooperative perception. The study is based on ETSI's Decentralized Congestion Control (DCC), one of the most important congestion control frameworks to date that operates across multiple layers of the V2X communication protocol stack. The study demonstrates that using congestion control protocols only at the Access layer augments the latency (or information age) of cooperative perception messages. This negatively impacts connected automated driving that requires low latency for a safe driving. This study demonstrates then for the first time that this challenge can be addressed through the combination of congestion control functions at the Access and Facilities layers. This combination increases the perception and reduces the latency through the dynamic adaptation of the rate at which cooperative messages are generated and transmitted.

II. STATE OF THE ART

Perception of automated vehicles has advanced significantly over the past years [2], [10], [11]. However, there are still relevant perception challenges that need to be solved [3], [11]. For example, the detection accuracy under poor weather and lighting conditions must be improved to reduce uncertainty. This is particularly the case of lidars and cameras. Lidar sensing can be restricted by high refraction and reflection caused by dense fog, smoke and rain [3]. Also, high sun angles may increase the noise level in lidar pulses which will affect the perception. In addition, their detection range depends on the reflectivity of the objects that are reached by the laser beams [2]. Cameras are very good for classifying objects and provide additional information about the environment (color, texture, etc.) [3]. However, cameras also see their performance degrade under adverse weather conditions and are very sensitive to lighting conditions. In addition, they require intensive and diverse training data for their AI-based image processing [10]. Moreover, velocity and distance information to detected objects cannot be directly measured with cameras but must be calculated [3]. Radars perform better than lidars and cameras in poor weather conditions (rain, snow, fog, etc.) [3], and some radars can detect objects at 250 m distance [12]. However, they provide lower resolution than lidars, and their field of view is limited [3]. In fact, the range and speed resolution of a radar is determined by its bandwidth. Products available on the market provide accuracies of 10 cm up to 1% to 5% of the distance to the object [12]. Radars also suffer from multipath fading, which reduces the accuracy of the detected objects [3]. The perception of automated vehicles also needs to be improved in complex urban environments. In particular, it is necessary to improve the accuracy, certainty and reliability of the sensors' perception. This is especially the case due to the presence of occluding objects (e.g. other vehicles or buildings) that can limit the sensor's range [11]. Lidar, radar and cameras can only work under Line-of-Sight (LOS) conditions. All these challenges and constraints limit the perception capabilities of automated vehicles that exclusively rely on their on-board sensors. This can in turn impact their safety and driving efficiency.

Cooperative perception has been proposed to improve the perception capabilities of CAVs. Cooperative perception makes use of V2X communications so that vehicles can exchange sensed data. Most of the studies conducted to date consider that vehicles exchange information about the detected objects (e.g. their position, speed and size). Recent studies have analyzed what information should be exchanged about detected objects in cooperative perception. Günther *et al*. propose in [13] to include in cooperative perception messages not only basic information about detected objects (e.g. their speed and position) but also information about the on-board sensors and the characteristics of the transmitting vehicle. This allows the receiving vehicles to understand the capabilities of the transmitting vehicles and better identify free-space and unknown areas. The authors show in [13] that their proposal allows earlier detection of possible obstructions and hence augment the driver's reaction time in the presence of a potential safety risk. The proposal from [13] was evaluated in [14]. This study compares the perception achieved when the information about the detected objects is attached to existing CAMs or is transmitted in separate messages that are transmitted following the CAM generation rules. Authors of [15] propose a message format to decrease the transmitted information without affecting the accuracy of the perception system. The proposed format includes information about the correlation and higher order derivatives (e.g. the acceleration or yaw rate) of the detected objects, and this information is transmitted less frequently. The work in [16] proposes and evaluates different content control schemes for cooperative perception. The study concludes that cooperative perception should prioritize the transmission of content related to objects that are located farther away from the transmitting vehicle but near the edge of its on-board sensor range in order to optimize the tracking error. The authors show that coupling this proposal with a multiplicative decrease and additive increase transmit rate control can also control the communication channel load and improve the channel utilization.

Controlling the channel load is critical for the performance of V2X communications and hence for the effectiveness of cooperative perception. Recent studies have then focused on optimizing the exchange of information about detected objects in cooperative perception. For example, the work in [17] proposes the concept of value-anticipating networking so that an object is included in a cooperative perception message and transmitted only if the transmitter estimates that it could have value for potential receivers. This approach reduces the transmission rate of less valuable information and can help control the channel load in congested scenarios. The challenge is to obtain an accurate estimation of the value of the information. This challenge has been partially addressed in a recent study by the same authors in [18] where they propose the use of deep reinforcement learning to select the data to transmit. A similar concept was proposed in [19] where authors present a method for each vehicle to dynamically adapt the message transmission rate taking into account the area covered with their sensors and that is not covered by nearby vehicles. In [20], authors evaluate the impact of congestion control on cooperative perception. To this aim, authors consider the Reactive approach that is part of ETSI's DCC framework at the Access layer, and evaluate the impact of considering different DCC Profiles (or DPs) for the collective perception messages. This study was one of the first to consider the impact of congestion control.

The authors demonstrate that congestion control does impact the performance and operation of cooperative perception, and should hence be carefully designed. This should include the congestion control functions at the Access layer that were the focus of the study in [20]. However, it should also consider those functions that control and adapt the generation rate of cooperative perception messages, since the message rate has a notable impact on the communication channel load. The same authors recently proposed in [21] message generation rules for cooperative perception based on the dynamics of vehicles. These generation rules decide when a new cooperative perception message should be created and what should be its content. The message generation rules proposed in [21] have been adopted within the ETSI Technical Report[1] for collective perception [4]. These generation rules were evaluated in detail in [22] where authors found that they can frequently generate messages with a small number of objects. This increases the channel load since packets with a small payload create a relatively high overhead due to the message headers. The study also found that the ETSI generation rules for cooperative perception can significantly increase the number of updates received per second about the same object. It is unclear whether this really benefits perception while it significantly increases the communication channel load. Similar conclusions were reached by authors of [23], [24] and [25] that also argue for the need to control the information exchanged with cooperative perception in order to avoid exceeding the communication channel capacity.

Existing studies demonstrate the industrial interest and potential of cooperative perception to improve connected automated driving. However, a more comprehensive understanding of cooperative perception is necessary for its correct dimensioning and configuration. This is exactly the objective of this study that first looks into the impact of the type of sensors and market penetration rate on cooperative perception. This study analyzes then in detail the impact that V2X congestion control has on cooperative perception. This is important since congestion control protocols modify the transmission of messages, and this can significantly impact the effectiveness of cooperative perception. The study demonstrates for the first time how a careful combination of congestion control functions at different layers of the protocol stack can improve the performance of cooperative perception.

III. COLLECTIVE PERCEPTION SERVICE

ETSI has recently approved the Technical Report [4] that proposes the Collective[2] Perception Service (CPS) and that will serve as a baseline for the Technical Specification TS 103 324. The following subsections describe the current Collective Perception Message (CPM) format and the CPM generation rules defined in [4] and that are used in this study.

A. COLLECTIVE PERCEPTION MESSAGE

The CPM is a broadcast message that includes an ITS (Intelligent Transport System) PDU (Protocol Data Unit) header and 5 types of containers: a Management Container (MC), a Station Data Container (SDC), a Sensor Information Container (SIC), a Perceived Object Containers (POC) and a Free Space Addendum Container (FSAC). It also contains a data element that specifies the current number of perceived objects. This number does not necessarily match with the number of objects included in the CPM because all objects are not included in all CPMs, as explained in the next subsection. The main containers and data elements are next described.

1) ITS PDU HEADER

The ITS PDU header was specified in [26] and includes data elements such as the protocol version, the message ID and the station ID.

2) MANAGEMENT CONTAINER

The MC is mandatory in the CPM and contains basic information about the transmitter, including its type (e.g. vehicle or RSU) and position. The MC also includes an optional container to inform about whether the data of a CPM has been split up into multiple messages due to message size constraints.

3) STATION DATA CONTAINER

The SDC is optional and includes additional information about the originating vehicle or RSU. The SDC can include the Originating Vehicle Container (OVC) or the Originating RSU Container (ORC) depending on whether a vehicle or RSU generates and transmits the CPM. The OVC describes the vehicle data elements, such as the heading, speed and angle, and its size. The ORC includes information such as the Intersection Reference ID or Road Segment ID. This information is useful for the receiver to match the received objects to the defined intersection or road segment.

4) SENSOR INFORMATION CONTAINER

The SIC is optional and describes the sensing capabilities of the transmitter. The SIC is used by the receiver to derive the areas that are currently sensed by the transmitter. For each sensor, the SIC includes data elements such as the sensor ID, sensor type (e.g. radar, lidar or a sensor fusion system) and its detection area. The SIC can optionally specify for each sensor its Free Space Confidence, which is the isotropic free space confidence that can be assumed for its entire detection area. When sensor fusion is not used, the SIC includes the capabilities of each of the on-board sensors; the CPM can report about up to 128 sensors. When using sensor fusion, all the sensors capabilities are combined and reported in the SIC as a single sensor.

[1] This Technical Report has been recently approved and will be used as a starting point for the ETSI Technical Specification of collective perception.

[2] ETSI generally refers to cooperative perception as collective perception. We will then maintain the term collective perception in this section and when referring to ETSI content or discussions.

5) PERCEIVED OBJECT CONTAINER

The POC is set optional and describes the dynamic state and properties of the detected objects. The POC contains information about up to 128 detected objects. For each object, the following data elements are included in the POC: (1) the object ID that identifies the object and can be used for tracking purposes; (2) the Time of Measurement that provides the time difference between the message generation time and the object measurement time[3]; (3) the IDs of the sensors that have detected the object; (4) the position, speed, acceleration and size of the object (among other fields); (5) the confidence associated to the object; (6) and its classification (vehicle, person, animal, other). These and other data elements provide a detailed description of the detected object and enable the receiver to coordinate and track the detected object in a three-dimensional space.

6) FREE SPACE ADDENDUM CONTAINER

The FSAC is optional and describes the free space areas within the sensor detection areas. In addition, it includes their associated confidence levels. This information can be used by the receiver to better estimate the free space areas around the transmitting vehicle.

B. CPM GENERATION RULES

The CPM generation rules define how often a vehicle should generate a CPM and what information should be included in each CPM. A vehicle should check every *T_GenCpm* if a new CPM should be generated. *T_GenCpm* should be set between 100 ms and 1000 ms. It is important to highlight that the DCC can adapt *T_GenCpm* based on the channel load as we will describe in detail in the next section. A vehicle should generate a new CPM if it has detected a new vehicle, or if any previously detected vehicles satisfy any of the following conditions:

- its absolute position has changed by more than 4m since the last time its data was included in a CPM;
- its absolute speed has changed by more than 0.5m/s since the last time its data was included in a CPM;
- its absolute velocity has changed by more than 4° since the last time its data was included in a CPM;
- the last time it was included in a CPM was 1 (or more) seconds ago.

A vehicle includes in a new CPM all new detected vehicles and those previously detected vehicles that satisfy at least one of the previous conditions. The CPM generation rules prioritize then the transmission of information about the detected vehicles that are moving faster or have higher acceleration. These vehicles are included in CPMs more frequently so that other vehicles can have an accurate and updated knowledge of the driving environment.

We should note that a vehicle generates a CPM every second even if none of the detected vehicles satisfy any of the previous conditions. In this case, the CPM will not contain the Perceived Object Container, but only the Management Container, the Station Data Container, and the Sensor Information Containers. In addition, the SIC is only included in a CPM once per second since the sensor information does not change.

[3]This information is useful to accurately compute the information age for each object at the receiver.

IV. DECENTRALIZED CONGESTION CONTROL

Cooperative perception relies on the V2X exchange of information about detected objects. Its effectiveness depends on the correct reception of the exchanged V2X messages. The performance of V2X communications is highly influenced by the communication channel load since high channel load levels increase the risk of packet collisions. Vehicular networks integrate congestion control algorithms to control the channel load and avoid channel congestion [27]. These protocols can modify the rate or the power at which messages are transmitted and even drop packets. Congestion control algorithms can then alter the transmission of V2X messages and could then impact the effectiveness of cooperative perception. This paper studies this impact in detail using the Decentralized Congestion Control (DCC) solution defined by ETSI. This is one of the most complete solutions to control congestion in vehicular networks since it defines DCC components and functions at all relevant layers of the protocol stack.

A. ITS COMMUNICATIONS ARCHITECTURE

DCC is implemented over the ITS Communications Architecture defined by ETSI [28] and illustrated in Figure 2. This architecture follows the principles of the OSI (Open System Interconnection) model and is divided in different layers. The Access layer covers the PHY (Physical) and MAC (Medium Access Control) layers of the protocol stack. It controls the access to the radio channel and enables the wireless transmission and reception of information. The Transport & Network layer is used to multiplex messages from different services and route them from source to destination nodes. The Facilities layer includes components and services, such as the Collective Perception Service, that are used to support V2X applications. Applications are implemented on the top and are abstracted from the underlying protocols. The transversal

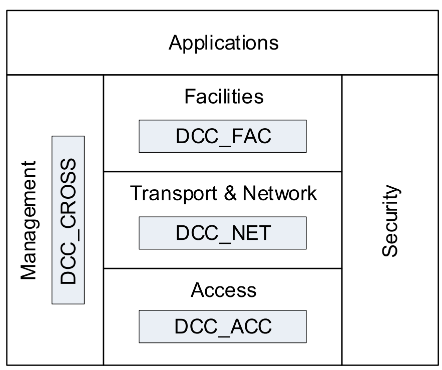

FIGURE 2. ETSI ITS Communications Architecture with DCC components.

Management layer is in charge of the management of the communications and the protocol stack. The Security layer provides the necessary security services, such as privacy or encryption.

CPMs are generated by the Collective Perception Service at the Facilities layer and sent down to the lower layers for their transmission. At the Transport & Network layer, CPMs make use of the BTP (Basic Transport Protocol) that multiplexes messages from different applications/services. In the same layer, the GeoNetworking protocol configures the transmission of the CPM in broadcast mode to all 1-hop neighboring nodes. At the Access layer, CPMs can be transmitted using the ITS-G5 [29] radio access technology. ITS-G5 is an adaptation of IEEE 802.11p, which was specifically designed for vehicular environments. IEEE 802.11p uses OFDM (Orthogonal Frequency Division Multiplexing) with a channel bandwidth of 10 MHz. It supports data rates from 3 to 27 Mbps using coding rates of 1/2, 2/3 or 3/4 (convolutional coding) and BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying), 16-QAM (16-Quadrature Amplitude Modulation) or 64-QAM modulations. The basic radio channel access method of IEEE 802.11p is known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In CSMA/CA, a node must sense the radio channel before transmitting a packet. If the channel is sensed as idle, the node can start its transmission. If the channel is sensed as busy, the node defers its transmission until the end of the current transmission. At the end of the channel busy period, the node waits for a random backoff time. This backoff is used to minimize collisions between multiple nodes that also deferred their transmission since they also detected the channel as busy. The node decreases the backoff time when it senses the channel as idle and can start its transmission when its backoff time reaches zero. To provide different channel access times to different types of packets, IEEE 802.11p makes use of EDCA (Enhanced Distributed Channel Access) that differentiates 4 access categories. Each category has different channel access parameters (e.g. backoff times).

B. DCC FRAMEWORK

The generation and transmission of messages using the ITS Communications Architecture is controlled by DCC. DCC is a cross-layer function that spans over multiple layers of the protocol stack. In particular, ETSI has defined DCC_ACC, DCC_NET, DCC_FAC and DCC_CROSS components (see Figure 2). The DCC_ACC [30] component is in the Access layer and has been the target of most of the research conducted to date. It operates as a gatekeeper to control the traffic that is effectively transmitted by each vehicle. DCC_NET [31] is optional and implemented at the Networking & Transport layer. It enables vehicles to exchange information about the channel load they sense so that each vehicle is aware of the channel load experienced by its one-hop and two-hop neighbours. The Technical Specification that defines DCC_FAC [32] is still a draft and has not been approved yet. In the current draft, DCC_FAC is defined as optional and is implemented at the facilities layer when considered. It controls the number of messages generated by each application/service within each vehicle. The control takes into account the messages' traffic classes or DCC profiles (DPs). Thus, DCC_FAC distributes access to the channel among the different applications/services within each vehicle.

DCC_CROSS [33] defines the necessary management support functions for DCC and the required interface parameters between the DCC management entity and the DCC entities in the Facilities, the Networking & Transport and the Access layers. For all DCC components, the upper limits of the maximum transmission duration and minimum time interval between two consecutive transmissions are defined in ETSI EN 302 571 [34]. In this study, we analyze the impact of DCC_ACC and DCC_FAC on cooperative perception since they contain the main mechanisms that control congestion and that can affect the V2X communications performance.

C. DCC ACCESS

The DCC_ACC component is located in the Access layer. It controls the traffic at the Access layer and acts as a gatekeeper. To this aim, it adapts the amount of time that each vehicle can access the channel as a function of the channel load. The channel load used as input for the algorithm can be the one locally measured by a vehicle or the one provided by DCC_NET if vehicles share their channel load measurements. ETSI defines in [30] the DCC_ACC component for ITS-G5. It makes use of Prioritization, Queuing and Flow Control, as described below.

Prioritization: The packets that are received by the DCC Access component from the upper layers are first classified according to their traffic class. The traffic class is defined by the Facilities layer to provide different priority levels to different types of messages. Four different traffic classes are differentiated by DCC Access and mapped to four DCC profiles (DPs): DP0, DP1, DP2 and DP3, where DP0 has the highest priority. At the lower layers, these DCC profiles are mapped to the EDCA access categories of ITS-G5 [35].

Queuing: DCC Access implements 4 different queues, one for each traffic class or DCC profile. Each queue follows a first-in-first-out (FIFO) scheduling policy so that the packet that has been waiting longer in the queue is transmitted first. The DCC Access queuing mechanism drops those packets that have been waiting in the queue for a time longer than their lifetime. When a queue is full, no more packets are accepted.

Flow control: Flow control is applied to de-queue packets from the DCC queues and send them to the lower layers for their radio transmission. Packets with higher priorities are de-queued first. A packet is only de-queued if there is no packet with a higher priority waiting in its corresponding queue. As a result, lower priority packets can suffer from starvation and never be transmitted.

DCC Access defines in [30] two approaches to control the rate of packets transmitted per vehicle: Reactive and Adaptive. Both approaches adapt the time between consecutive packet transmissions based on the channel load or CBR (Channel Busy Ratio). The CBR is defined as the percentage of time that the channel is sensed as busy. These two approaches are described below.

1) REACTIVE APPROACH

The Reactive approach makes use of a state machine for flow control. Each state is mapped to a range of CBR values and to a time T_{off}. T_{off} is the minimum time interval allowed between message transmissions for each vehicle and is different for each state. Therefore, T_{off} is the inverse of the maximum message transmission rate allowed per vehicle in each state. When the CBR changes, the Reactive approach switches to the corresponding state, changing the minimum T_{off} and maximum message rate allowed per vehicle. As a result, vehicles dynamically adapt their message rate to the CBR.

The Restrictive state is the state associated with the highest CBR and the Relaxed state is associated to the lowest one. A number of intermediate states called *Active states* can also be defined. Each state can only be reached by a neighbouring state. Table 1 shows the mapping of CBR values to states and T_{off} reported as Informative Annex in [30]. This table is derived considering that the packet duration T_{on} is below 0.5 ms. Other configurations are possible but we have used the one shown in Table 1 because it is the one adopted by the C2C-CC (Car-to-Car Communication Consortium) [36].

TABLE 1. Mapping of CBR values to states and T_{off} for T_{on} < 0.5 ms [30].

State	CBR	Packet rate	T_{off}
Relaxed	< 30%	20 Hz	50 ms
Active 1	30% to 39%	10 Hz	100 ms
Active 2	40% to 49%	5 Hz	200 ms
Active 3	50% to 65%	4 Hz	250 ms
Restrictive	> 65%	1 Hz	1000 ms

2) ADAPTIVE APPROACH

The Adaptive approach uses a linear control process for flow control. The process is designed so that each vehicle adapts its packet transmission rate in order for the channel load to converge to a target value $CBR_{target} = 68\%$. To this aim, every 200 ms each vehicle adapts the parameter δ that represents the maximum fraction of time that a vehicle is allowed to transmit. The parameter δ is updated based on the difference between the current CBR sensed and the target CBR using the following equation:

$$\delta = (1-\alpha)\cdot\delta + \delta_{offset} \tag{1}$$

where

$$\delta_{offset} = \beta \cdot \left(CBR_{target} - CBR\right) \tag{2}$$

and

$$G^{-}_{max} \leq \delta_{offset} \leq G^{+}_{max} \tag{3}$$

The values of the parameters are defined in [30] as $\alpha = 0.016$, $\beta = 0.0012$, $G^{-}_{max} = -0.00025$ and $G^{+}_{max} = 0.0005$.

The protocol computes then the time between packet transmissions (T_{off}) after every transmission. To this aim, it takes into account the duration of the current packet (T_{on}) and the fact that $0.025\text{s} \leq T_{off} \leq 1\text{s}$:

$$T_{off} = \frac{T_{on}}{\delta} \tag{4}$$

It is also recommended to update T_{off} when δ is updated. Different studies have demonstrated that the Adaptive approach is able to converge to a stable solution in steady state [37].

D. DCC FACILITIES

DCC Access controls the total amount of messages that a vehicle can transmit per second. DCC at the Facilities layer (DCC_FAC) controls the number of messages that each application/service can generate [32] to satisfy the DCC Access limit imposed to each vehicle. To this aim, the DCC_FAC makes use of the DCC Access limit, the message size and the message interval from each application/service. The current ETSI draft that defines the DCC_FAC component calculates the minimum interval $T_{off\ min\ ij}$ for each application/service with index j and traffic class with index i. Based on this minimum interval, each vehicle proportionally distributes the channel resources to each application/service and traffic class. Distributing the channel resources with ITS-G5 is equivalent to distributing the channel access time. To perform this distribution, each vehicle estimates for each application/service j and traffic class i, the average message duration $\overline{T_{on\ ij}}$ and the average message interval $\overline{T_{off\ ij}}$ from the latest messages. The average message duration can be simply calculated as the ratio between the average message size of each application/service j and traffic class i and the data rate (by default, the data rate is set to 6 Mbps [35]). Then, the average channel resources consumed by each application/service can be estimated as:

$$\overline{CRE}_{ij} = \frac{\overline{T_{on\ ij}}}{\overline{T_{on\ ij}} + \overline{T_{off\ ij}}} \tag{5}$$

Using equation (5), the total channel resources CR_i from all applications/services of traffic class i can be calculated as:

$$CR_i = \sum_j \overline{CRE}_{ij} \tag{6}$$

The channel resources CBR_a that the vehicle can use depends on the current channel load and the specific DCC Access algorithm. For the Adaptive approach, $CBR_a = \delta$, i.e. the maximum fraction of time that a vehicle is allowed to transmit. However, for the Reactive approach, $CBR_a = 1/T_{off}$, i.e. the maximum number of messages that the vehicle can transmit per second. CBR_a is used by DCC Facilities as an input to distribute the available channel resources among the different traffic classes. The traffic class with the highest priority is TC_0, so the available channel resources for this traffic class ACR_0 is set equal to CBR_a. If traffic class TC_0

does not consume all the available channel resources for the vehicle, the remaining resources are assigned to the next traffic class. As a result, ACR_i for traffic class i is calculated as:

$$ACR_i = \max(0, ACR_{i-1} - CR_{i-1}) \quad (7)$$

Equation (7) can be applied to both Reactive and Adaptive approaches at the DCC Access, but ACR_i represents a fraction of time for Adaptive and a message rate for Reactive since they use a different CBR_a.

DCC Facilities then identifies the channel resources ACR_{ij} that each application/service j belonging to the same traffic class i can use. To this aim, it takes into account the average channel resources consumed by each application/service calculated with equation (5):

$$ACR_{ij} = \frac{\overline{CRE_{ij}}}{CR_i} \times ACR_i \quad (8)$$

For the Adaptive approach, the minimum interval $T_{off\ min\ ij}$ for each application/service with index j and traffic class with index i can be then calculated as follows:

$$T_{off\ min\ ij} = \overline{T_{on\ ij}} \times \frac{1 - ACR_{ij}}{ACR_{ij}} \quad (9)$$

For the Reactive approach, ACR_{ij} is a message rate and the minimum interval $T_{off\ min\ ij}$ can be directly computed as[4]:

$$T_{off\ min\ ij} = \frac{1}{ACR_{ij}} \quad (10)$$

$T_{off\ min\ ij}$ is then used to adapt the minimum time interval between message generations of each application/service. To this aim, the time interval used to check the message generation rules of each application/service (e.g. *T_GenCpm* for CPMs or *T_GenCam* for CAMs) is set equal to its corresponding $T_{off\ min\ ij}$. As a result, the time interval between consecutive messages of each application/service is dynamically adapted to satisfy the DCC Access limits imposed to each vehicle.

We now illustrate the operation of DCC Facilities with an example in a scenario where vehicles transmit CAMs and CPMs with the same DCC profile. The average message size at the facilities layer is 200 Bytes for CAMs and 300 Bytes for CPMs, including the ITS PDU header and the payload at the Facilities layer. Additionally, 80 Bytes of headers are added by the corresponding protocols: 4 Bytes are added by the Basic Transport Protocol (BTP) [38], 40 Bytes by the GeoNetworking protocol [31], [39], 30 Bytes by the Medium Access Control (MAC) and 6 Bytes by the PHY layer of IEEE 802.11p [29]. The average message interval is 0.2 s for CAMs and 0.1 s for CPMs. Let's assume that DCC Facilities is combined with the Adaptive approach at DCC Access and that the total available channel resources per vehicle is $CBR_a = \delta = 0.005$. In this case, each vehicle can use 0.5% of the channel access time when using IEEE 802.11p or ITS-G5. We consider that vehicles transmit at a data rate of 6 Mbps. The average channel resources consumed by CAM and CPM messages can be estimated using equation (5) and are equal to $CRE_{CAM} = 0.0019$ and $CRE_{CPM} = 0.05$ respectively. We can then compute the total consumption of channel resources CR using equation (6): $CR = 0.0069$. Using equation (8), we can estimate the available channel resources for CAM ($ACR_{CAM} = 0.0013$) and CPM ($ACR_{CPM} = 0.0037$) messages. Finally, the minimum interval can be computed for CAMs as $T_{off\ min\ CAM} = 0.2763$s and for CPMs as $T_{off\ min\ CPM} = 0.1383$s following equation (9). We then adapt the generation rate of CPMs and CAMs at the Facilities layer so that $T\_GenCpm = T_{off\ min\ CPM}$ and $T\_GenCam = T_{off\ min\ CAM}$. A different solution would be obtained in this example if DCC Facilities was combined with the Reactive approach at DCC Access. The feedback provided by the Reactive approach is the maximum number of messages that the vehicle can transmit per second. Let's assume in this example that $CBR_a = 10$Hz. If we follow the same procedure to compute the minimum interval for CAMs and CPMs using equation (10) instead of (9), we obtain $T_{off\ min\ CAM} = 0.3706$s and $T_{off\ min\ CPM} = 0.137$s.

V. SCENARIO AND PARAMETERS

This study uses the network simulator ns-3 and the road mobility simulator SUMO. The ns-3 simulator implements the ITS-G5 V2X standard based on IEEE 802.11p. We extended ns-3 with a DCC Access module, a DCC Facilities module, a CPS component and different on-board sensors. The DCC Access module used in this study is described in [40] and publicly available. The CPS component implements the ETSI CPM generation rules defined in [4] and described in Section III. By default, all vehicles in the scenario are equipped with an ITS-G5 transceiver except when we analyze the impact of the Market Penetration Rate (MPR) on the effectiveness of cooperative perception. Vehicles transmit CAMs and CPMs. The CAM size is set equal to 350 bytes [41] and CAMs are generated following [8]. By default, the *T_GenCpm* parameter has been set to 0.1 s so the maximum CPM rate is 10 Hz. The CPM size is dynamically computed by the transmitting vehicle based on the number of containers in each CPM, the size of the containers reported in Table 2 and the number of objects included in a CPM.[5] Vehicles transmit messages using the 6 Mbps data rate (i.e. QPSK modulation with 1/2 code rate) and always use the same channel. The transmission power is set to 23 dBm and the packet sensing threshold to −85 dBm. Radio propagation is modeled using the Winner+ B1 propagation model following the 3GPP V2X guidelines [42]. This model was used for the simulation studies conducted during the V2X standardization process of the 3GPP. Other propagation models could have been used (e.g. [43]) but similar conclusions would

[4] This is currently not specified in the current draft of ETSI TS 103 141 but it is a change needed to combine the DCC Facilities algorithm with the Reactive approach at DCC Access.

[5] The Free Space Addendum Container is optional and has not been considered in this study.

TABLE 2. CPM containers.

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

TABLE 3. Communication parameters.

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

be obtained since our study is comparative in nature and a different model would affect similarly all configurations being tested.

Table 3 summarizes the main communication parameters. Unless specified, DCC is not enabled by default. When enabled, DCC Reactive and Adaptive are analyzed at the Access layer. We consider a queue length of 2 following [44] and different DCC profiles for the CPM since the standards have not specified them yet. The DCC profile for CPMs is set to DP2 or DP3 and the DCC profile of the CAM is set to DP2 following [45]. The DCC profile has an impact on the priority of the packets at the access layer. We have also implemented the current DCC Facilities defined by ETSI[6] and described in Section IV.

We implement three different sensor configurations shown in Table 4. In the forward sensors configuration, vehicles are equipped with two forward facing sensors following [4]. The 360° sensor configuration considers a single circular shape sensor with 360° field of view following [4]. The Tesla sensors configuration follows [46] and equips vehicles with seven sensors. In all sensor configurations, we assume that the sensors can detect only the vehicles that are in their line-of-sight. To this aim, we implemented in ns-3 a 2D sensor shadowing effect in the XY-plane that considers the occlusion caused by nearby vehicles. By default, this study assumes that the information about objects detected by multiple sensors is fused.

We consider a highway scenario with 5 km length and two driving directions. We simulated three traffic densities: low, medium and high as presented in Table 5. The low and medium traffic densities follow the 3GPP guidelines for V2X simulations [42] considering 6 lanes (3 in each direction) and a different speed per lane following statistics of a typical 3-lane US highway [47]. The high traffic density considers 8 lanes (4 in each direction) and a maximum speed of 50 km/h [47]. To avoid boundary effects, statistics are only taken from the vehicles located in the 2 km around the center of the simulation scenario.

[6] This implementation could be subject to modification since the standard has not been finalized yet.

TABLE 4. Sensor configurations.

Sensor	Specification	Range (m)	FOV (°)
Forward	Mid-range radar	65	±40
	Long-range radar	150	±5
360°	Circular radar	150	360
Tesla	Narrow forward camera	250	±15
	Radar	160	±15
	Main forward camera	150	±22
	Forward side cameras	80	±25-115
	Wide forward camera	60	±60
	Rear view camera	50	±115-180
	Rearward side cameras	100	±150-180

TABLE 5. Traffic scenarios.

Parameter	Traffic density scenarios		
	Low	Medium	High
Number of lanes	6	6	8
Vehicles per km	60veh/km	120veh/km	240veh/km
Speed per lane	140km/h 132km/h 118km/h	70km/h 66km/h 59km/h	50km/h for all lanes

VI. EVALUATION OF COOPERATIVE PERCEPTION

We first evaluate the perception capabilities of different sensor configurations without using cooperative perception. In this case, perception is limited by occluding objects. Figure 3 compares the object perception ratio experienced with the three sensor configurations under low and high traffic densities. The object perception ratio is defined as the probability of successfully detecting an object at a given distance. Sensors do not correctly detect a vehicle if their line-of-sight is occluded by other vehicles. Figure 3 shows that occluding vehicles can significantly degrade the perception

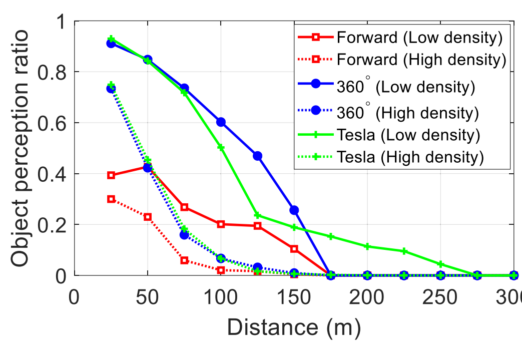

FIGURE 3. Object perception ratio achieved with different sensor configurations under low and high traffic densities.

capabilities, and the degradation increases with the distance and the traffic density. This is the case because both factors augment the probability that a vehicle blocks the sensors' line of sight. Figure 3 shows that the perception capabilities augment with the sensors' FoV and range. In this case, using forward sensors alone reduces the object perception ratio since these sensors cannot detect vehicles in all directions.

Cooperative perception can mitigate the occlusion problems illustrated in Figure 3 and increase the perception capabilities of connected automated vehicles. This is shown in Figure 4 that compares the average object perception ratio with and without using cooperative perception for the three different sensor configurations. When using cooperative perception, the metric is defined as the probability to successfully detect a vehicle within a time window thanks to the exchange of CPMs. We consider that a vehicle successfully detects an object if it receives at least one CPM with information about that object during the time window. The time window was set to 200 ms for the low traffic density scenario and to 300 ms for the rest of the scenarios. These values were chosen since they correspond to the time required by the CPM generation rules for a vehicle to send an update about a detected object considering the speed of the vehicles in each scenario. The metric is represented in Figure 4 as a function of the distance between the detected object and the vehicle receiving the CPM. Results in Figure 4 were obtained assuming 100% penetration rate of cooperative perception and that DCC is disabled. This is done so that Figure 4 focuses on the effect of the sensor configuration on the effectiveness of cooperative perception. We also assume that the vehicles fuse the information received from their multiple sensors. In this case, if multiple sensors detect the same object, the vehicle will only transmit once the information about the detected object.

Figure 4 clearly shows that cooperative perception significantly increases the perception capabilities of CAVs. In particular, it increases the distance at which objects can be detected compared to when only using the on-board sensors. Figure 4 shows that in these scenarios the sensor configuration does not significantly affect the object perception ratio when utilizing cooperative perception compared to when not utilizing it (Figure 3). In fact, the Tesla and 360° sensor configurations achieve similar perception rates, and the perception with the forward sensor configuration only slightly degrades at medium to large distances for low traffic densities (Figure 4a). This is the case because cooperative perception compensates the perception limitations of sensors. For example, a vehicle that uses only forward sensors can detect objects behind when using cooperative perception thanks to the CPMs received from other vehicles that detect these objects. We should note that the slight perception degradation observed in Figure 4 with the forward sensor configuration is reduced for higher traffic densities. This is the case because at higher densities more vehicles detect each object and cooperative perception can better compensate the limitations of the forward sensors.

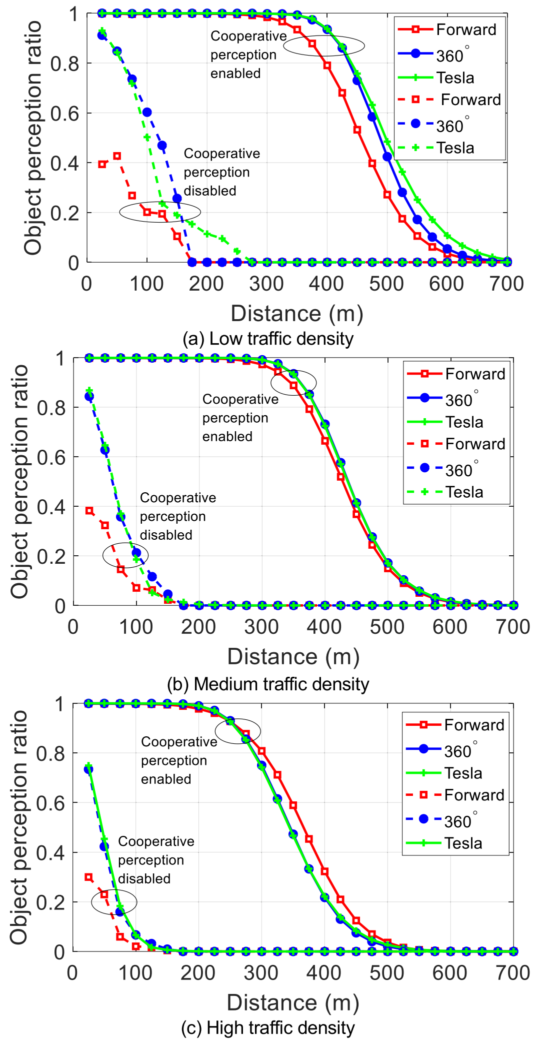

FIGURE 4. Object perception ratio under different traffic densities. When using cooperative perception, the x-axis represents the distance between the detected object and the vehicle receiving the CPM. When cooperative perception is not used, the x-axis represents the distance between the detected object and the vehicle detecting it with its sensors.

Figure 4 also reveals that the object perception ratio significantly decreases when the traffic density increases. This degradation is due to the increase in channel load and interferences at higher traffic densities. The interferences augment the packets losses due to packet collisions and degrade the PDR (Packet Delivery Ratio) as it can be observed in Figure 5. This figure also shows that the highest PDR under the highest traffic density is achieved with the forward sensor configuration. This is the case because each vehicle detects a lower number of vehicles than with the 360° or Tesla configurations and thus transmits less information. In fact, the sensor configuration can have an important impact on the channel load. Table 6 shows that the 360° and Tesla sensor configurations can increase the CBR by around 40% compared with the forward sensor configuration. Thanks to the lower channel load generated, the forward sensor configuration is able to provide higher cooperative perception ratios than the 360°

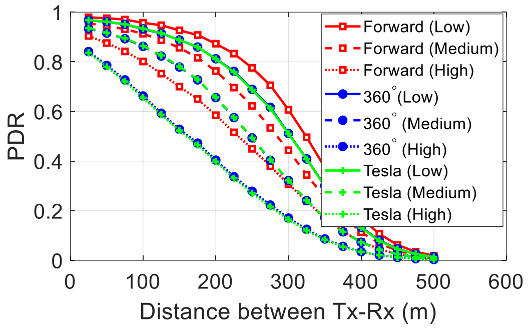

FIGURE 5. PDR (Packet Delivery Ratio) under different traffic densities (low, medium and high) and sensor configurations.

TABLE 6. Average CBR (Channel Busy Ratio).

Traffic density	Sensor configuration		
	Forward	360°	Tesla
Low	19.2%	27.6%	27.6%
Medium	31.8%	44.4%	44.4%
High	52.4%	71.3%	71.6%

and Tesla sensor configurations for the high traffic density scenario (Figure 4c).

Figure 4 has been obtained considering 100% penetration rate of cooperative perception, i.e. all vehicles in the scenario are CAVs and transmit CPMs. The effectiveness of cooperative perception depends on the number of vehicles that detect objects and share their information. Figure 6 shows the impact of the MPR (Market Penetration Rate) of cooperative perception. The figure shows that the object perception ratio increases with the MPR for low and medium traffic densities. However, when the traffic density is high, the perception ratio decreases for MPRs above 40% (Figure 6c). This degradation is again due to the significant increase of channel load at high traffic densities and the consequent increase in packet loses due to collisions. Figure 6 also shows that the sensor configuration does have an important effect on the perception when the MPR is low. In particular, the 360° and Tesla sensor configurations achieve significantly higher perception ratios than the forward sensor configuration, especially for low MPR. This is the case because cooperative perception cannot compensate well the perception limitations of the forward sensor configuration when there are few vehicles and not all vehicles can detect objects and share their information. However, all the sensor configurations provide similar perception ratios for MPR above 80%.

Figure 6 has shown that the sensors configuration has a strong impact on the perception that can be achieved with cooperative perception when the market penetration is low. The sensor configuration also has a high impact on the channel load generated. In fact, the sensor configuration has a strong impact on the amount of information shared with cooperative perception. This is the case because the sensor configuration affects the number of objects detected by each vehicle.

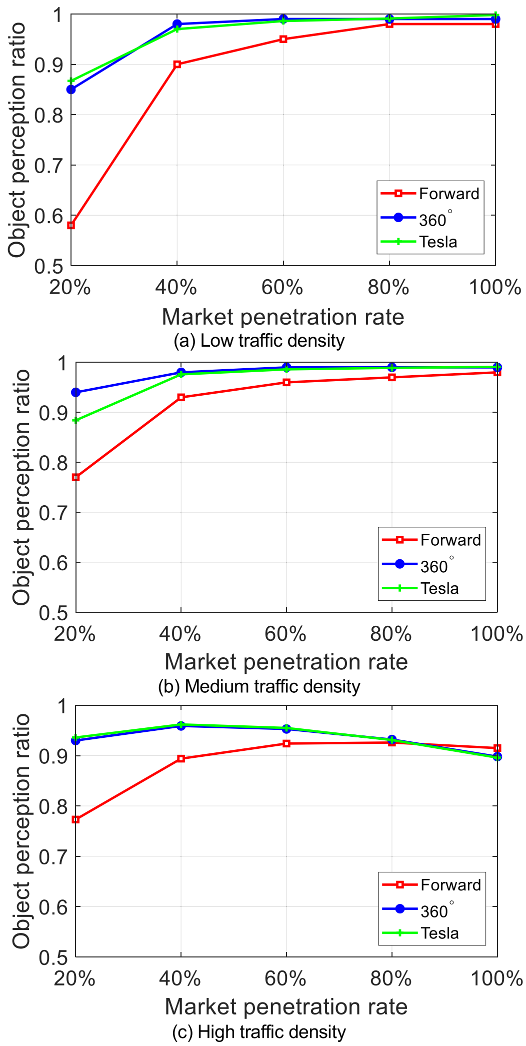

FIGURE 6. Object perception ratio under different traffic densities for different market penetration rates and for distances up to 350m.

As a consequence, the sensor configuration influences the amount of information transmitted by each vehicle. This changes the number of updates about the same object received by a vehicle under the observation time window. This number is referred to as detected object redundancy, and is depicted in Figure 7 as a function of the distance between the object and the vehicle receiving the CPM. Figure 7 corresponds to a 100% MPR.[7] The figure shows that the 360° and Tesla sensor configurations generate a significantly higher amount of redundancy compared to the forward sensor configuration. Despite the trends observed in Figure 7, all sensor configurations provide a similar object perception ratio up to around 300m for low and medium densities and up to around 200m for the high density (see Figure 4). This means that the higher redundancy and number of objects detected by the 360° and Tesla sensor configurations do not improve the perception

[7]Different redundancy values are observed with lower MPRs. However, the trend is maintained, i.e. sensors with wider FoV and larger ranges are characterized by higher redundancy levels.

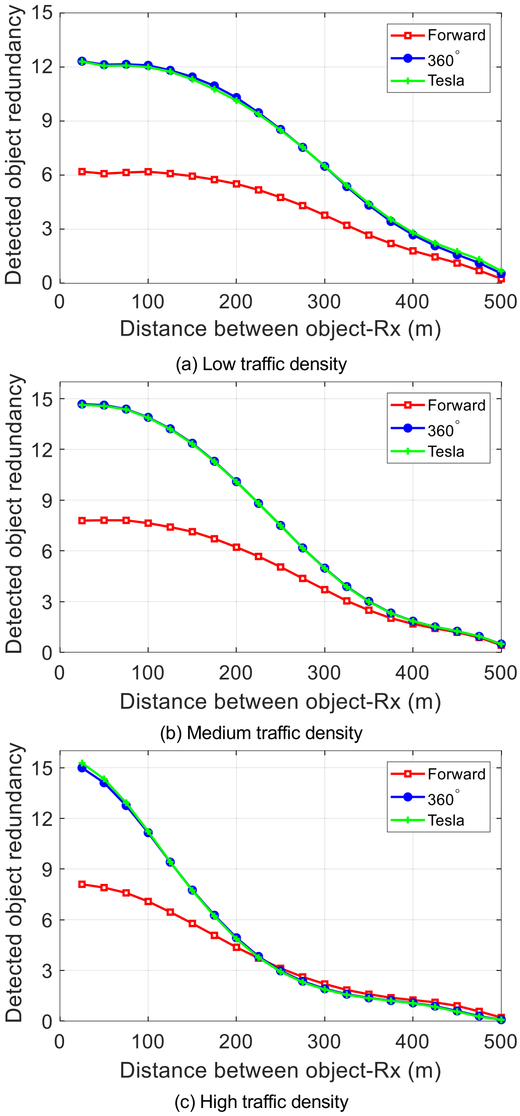

FIGURE 7. **Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities.**

achieved with cooperative perception. Instead, they significantly increase the channel load as shown in Table 6.

Figure 7 also shows an interesting effect produced by the increase of the traffic density. When the traffic density increases, more vehicles transmit information about the same detected object and thus higher redundancy levels would be expected. However, such increase of the object redundancy is only produced at short distances. At medium and long distances, the degradation of the PDR (Figure 5) due to packet collisions reduces the detected object redundancy for medium and high traffic densities.

The previous results have been obtained considering that vehicles implement sensor fusion. In this case, if several sensors detect the same object, their information is fused and the object is reported only once in each CPM. If sensor fusion is not used, an object detected by multiple sensors is reported

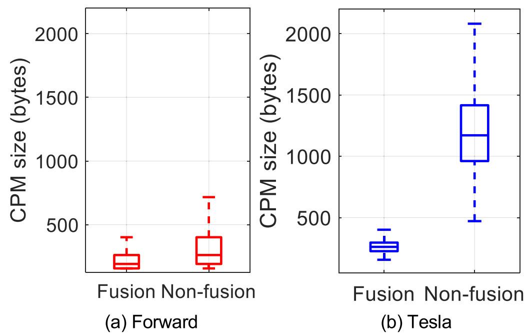

FIGURE 8. **CPM size for medium traffic density and the forward and Tesla sensor configurations. Similar trends have been observed with low and high traffic densities for both sensor configurations.**

multiple times in each CPM. This increases the message size as shown in Figure 8. This figure compares the CPM size with and without sensor fusion for the low traffic density scenario and the forward and Tesla sensor configurations. The results are presented as a box plot with the bottom and top edges indicating the 25th and 75th percentiles and the mark in the middle representing the median. Vertical lines show the most extreme data points that are not considered outliers. The results obtained show that the CPM size significantly increases when sensor fusion is not used, especially for the Tesla sensor configuration since it has more on-board sensors. In fact, the generated payload sizes of the Tesla non-fusion configuration exceed the maximum payload size [39]. In this case, the CPMs would have to be segmented and this could increase the risk of delaying the reception of the information about certain detected objects. Another main concern related with the increasing message size is that it significantly augments the channel load and the interference, and degrades the PDR (Figure 9) without providing additional relevant information to the receiving vehicles. Reducing the PDR degrades the effectiveness of cooperative perception since it reduces the probability to correctly receive CPM messages. This is actually visible in Figure 10 that depicts the object perception ratio when using sensor fusion and when not using

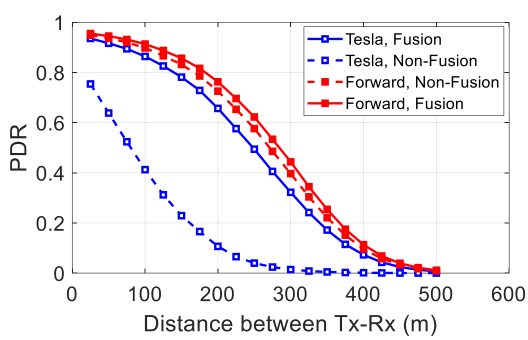

FIGURE 9. **PDR (Packet Delivery Ratio) for medium traffic density and the forward and Tesla sensor configurations. Similar trends have been observed with low and high traffic densities for both sensor configurations.**

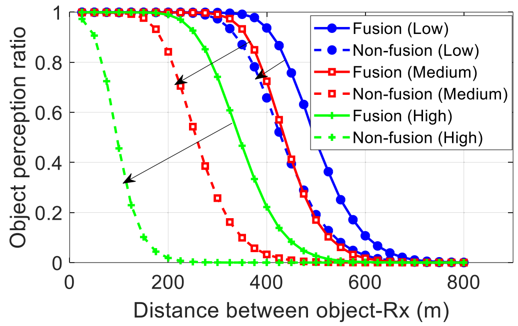

FIGURE 10. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities (low, medium and high). These results correspond to the Tesla sensor configuration.

it. The figure clearly shows how the object perception ratio degrades when sensor fusion is not applied. The degradation is particularly relevant when the traffic density increases. The perception degradation observed in Figure 10 when not using sensor fusion is exclusively due to the degradation of the PDR (i.e. the V2X communication performance) since each vehicle can detect exactly the same number of objects when implementing sensor fusion and when not implementing it.

VII. IMPACT OF CONGESTION CONTROL ON COOPERATIVE PERCEPTION

The previous results have been obtained disabling the DCC mechanisms for congestion control. This was done to focus first on the impact of the sensors and market penetration rate on the perception and effectiveness of cooperative perception. The previous analysis has shown that cooperative perception can increase the channel load quite significantly under certain scenarios and configurations. Increasing the channel load can degrade the PDR, and ultimately the performance of V2X communications and the network scalability. To prevent this, an increase of the channel load above certain threshold activates the DCC mechanisms for congestion control. DCC can alter the performance and operation of collective perception. This can occur for example if the DCC queues CPM messages. Queuing would increase the information age and alter the regular reception of object updates. The DCC could also drop CPMs when the CPM generation rate is higher than the maximum transmission rate allowed by DCC Access. This could also significantly impact the effectiveness of cooperative perception. It is also important highlighting that CPM messages might have to coexist with other messages in the same channel. This increases the risk that DCC is activated and impacts the operation and effectiveness of cooperative perception. In this context, this section analyses the impact of DCC on cooperative perception. We focus first on the impact of DCC at the Access layer and then DCC at the Facilities layer. These are the two DCC components that mostly affect the transmission of CPM messages.

The scenario considered in this section is the high traffic density scenario described in section V, with 240 veh/km, a 100% MPR of cooperative perception and the 360° sensor configuration. We also assume that all vehicles transmit CAMs and CPMs in the same channel. This scenario is chosen to make sure DCC is activated and we can then study its impact on cooperative perception.

A. DCC ACCESS

In the considered scenario, the CBR experienced is equal to 75% when DCC Access is not applied. The use of DCC Access can significantly reduce the CBR as shown in Table 7. These results show that the Reactive approach reduces more aggressively the channel load and maintains the CBR around 37%. The Adaptive approach is designed to converge to the target CBR of 68% and this results in higher CBR levels. Table 7 also shows that nearly the same CBR is achieved independently of the DCC profiles of the messages.

TABLE 7. Average CBR (Channel Busy Ratio) with DCC Access for the high traffic density scenario.

DCC profile	DCC Access	
	Reactive	Adaptive
Different (CAM=DP2 and CPM=DP3)	36.9%	62.1%
Same (CAM=CPM=DP2)	37.8%	61.9%

One interesting effect that cannot be observed in Table 7 is the message transmission rate that DCC Access tolerates. When DCC is not applied, the average rates at which CAMs and CPMs are generated and transmitted are 3.3 Hz and 9.6 Hz, respectively. When DCC Access is enabled, the message transmission rates are reduced due to message dropping as shown in Table 8. Table 8 shows that the transmission rates of CAMs and CPMs are lower than the generation rates when both messages have the same DCC profile. When they have different DCC profiles, only CPMs are dropped because CAMs have higher priority.[8] Table 8 also shows that the Reactive and Adaptive approaches present nearly the same message transmission rate despite experiencing a very different CBR as shown in Table 7. This is the case because with the Reactive approach vehicles tend to synchronize with each other. This synchronization results in that vehicles change their state (and thus their T_{off}) nearly at the same time.

[8]This is the case because CAMs are prioritized since they are the basic awareness messages for active traffic safety applications.

TABLE 8. Average CAM and CPM transmission rates with DCC Access.

DCC profile	CAM		CPM	
	Reactive	Adaptive	Reactive	Adaptive
Different (CAM=DP2 and CPM=DP3)	3.3 Hz	3.3 Hz	3.9 Hz	4.0 Hz
Same (CAM=CPM=DP2)	2.7 Hz	2.1 Hz	5.6 Hz	6.0 Hz

A change to a more relaxed state, immediately allows the transmission of messages that were waiting in their queues. As a result, vehicles transmit nearly at the same time [48], which provokes that the Reactive approach generates a significant amount of packet collisions. Packet collisions reduce the channel load (and CBR) because when packets collide they overlap in time.

DCC Access can reduce the CBR and improve the PDR at the radio level, i.e. the ratio between the received and transmitted packets. This is particularly the case with the Adaptive approach as shown in Figure 11. This figure represents the PDR at the radio level when CAMs and CPMs are configured with the same DCC profile. The figure also shows that the Reactive approach actually degrades the PDR at the radio level despite reducing the CBR. This is due to the high probability of packet collisions for the Reactive approach due to the synchronization problem previously explained. Similar results are obtained when analyzing the PDR at the radio level when CAMs and CPMs have different DCC profiles.

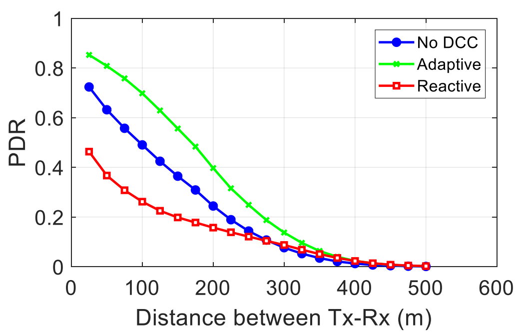

FIGURE 11. **PDR (Packet Delivery Ratio) at the radio level as a function of the distance between transmitter and receiver without and with DCC Access when CAMs and CPMs have the same DCC profile.**

To better understand the effect of DCC Access on the performance of collective perception, Figure 12 plots the PDR for CPMs at the radio and application levels for Reactive and Adaptive approaches. At the application level, the PDR is defined as the ratio between the received and generated CPMs. Thus, a CPM generated at the Facilities layer but dropped by DCC Access is considered as a packet lost when computing the PDR at the application level.[9] Figure 12 shows that DCC Access degrades the performance at the application level due to packet dropping. This degradation is observed for both Reactive and Adaptive approaches. However, the Reactive approach shows a significantly lower PDR at the application level than the Adaptive one due to its lower PDR at the radio level. The figure also shows that this degradation produced at the application level due to packet dropping is particularly relevant when CAMs and CPMs have different DCC profiles. In this case, CPMs are the only messages dropped by DCC since they have lower priority than CAMs.

[9]This packet loss would not be counted in the PDR at the radio level since the packet was never transmitted.

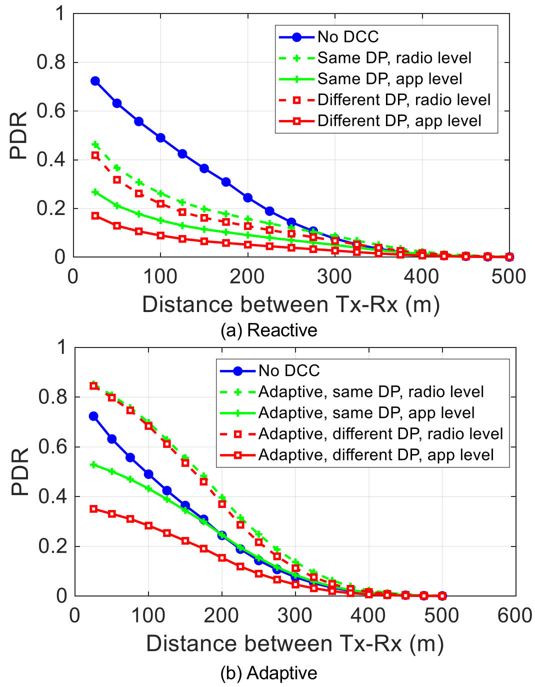

FIGURE 12. **PDR (Packet Delivery Ratio) for CPMs at the radio and application levels as a function of the distance between transmitter and receiver without DCC and with DCC Access when CAMs and CPMs have the same or different DCC profile.**

The PDR at the radio and application levels affect the object perception ratio. However, the differences observed in the PDR of Figure 12 are not directly transferred to Figure 13. Figure 13 depicts the object perception ratio as a function of the distance between the object and the vehicle receiving the CPM. Figure 13a shows that the object perception ratio significantly degrades with the Reactive approach following the trend observed in Figure 12a where Reactive significantly degrades the PDR at the application level. This once again clearly proves that the Reactive approach degrades the performance of cooperative perception despite reducing the channel load. Figure 13b shows the perception achieved with the Adaptive approach. For distances below 200m, the higher PDR achieved at the application level without DCC does not result in a significant improvement of the object perception ratio. This is the case because the object perception ratio is already close to 1 at distances below 200m when DCC is applied. Therefore, without DCC the perception ratio cannot be significantly improved despite its higher PDR at distances below 200m. However, DCC Adaptive improves the object perception ratio for distances beyond 200m when CAMs and CPMs have the same DCC profile. A higher perception is achieved despite having nearly the same PDR at the application level than when DCC is not used. This effect is produced due to the different nature of packet errors with and without DCC. When DCC is not applied, more packet collisions are produced due to the higher channel load. When two (or more) packets collide, more than one packet can be lost due to such collision. Therefore, when

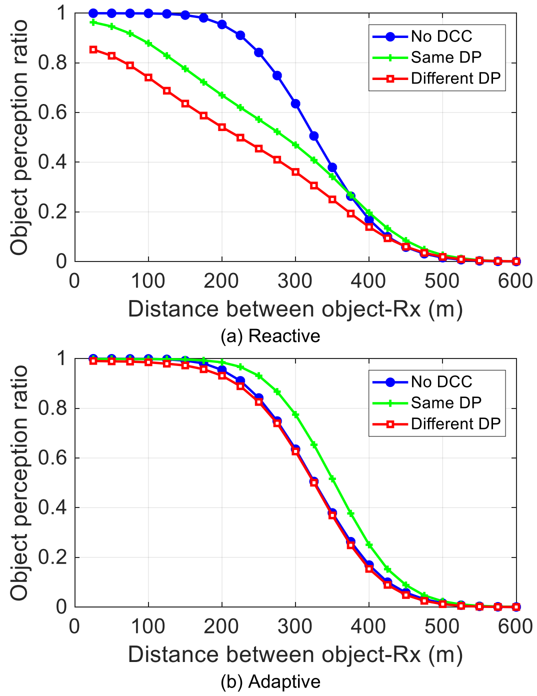

FIGURE 13. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM without DCC and with DCC Access.

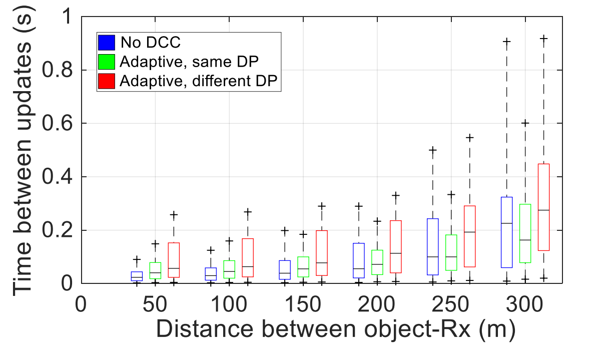

FIGURE 14. Time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM.

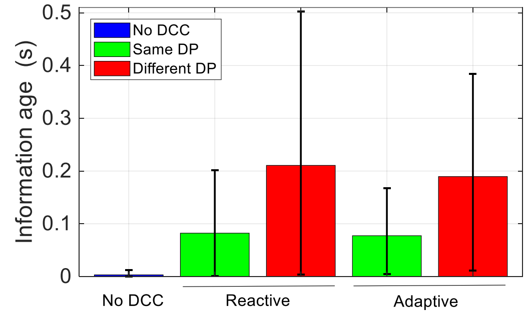

FIGURE 15. Average information age for CPMs received with and without DCC Access. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles.

DCC is not applied, consecutive packet loses are produced with higher probability. This effect is not produced with the packets dropped by DCC, since one packet drop does not affect the reception of other packets. Consequently, packet collisions can increase the time between consecutive object updates. This effect can be observed in Figure 14 that plots the time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM in bins of 50 m. The time between updates shown in Figure 14 corresponds to that measured with the Adaptive approach.[10] Results are presented using box plots with the bottom and top of each box representing the 25th and 75th percentiles. The median is represented inside each box with the black horizontal line. The vertical lines plotted above and below each box represent the 5th and 95th percentiles. Results in Figure 14 reveal that there is higher variability in the time between consecutive updates when DCC is not applied due to the higher probability of consecutive packet loses due to collisions. For example, the 95th percentile of the time between updates is around 0.9 s at 300 m without DCC, and around 0.6 s with DCC when CAM and CPM have the same profile. However, the variability also increases with DCC when CAM and CPM have different profiles for distances higher than 200 m since CPMs have lower priority than CAMs.

The previous results show that DCC Access has an impact on the probability of receiving information about an object through CPMs and therefore on the object perception ratio. However, they do not quantify if the information received is outdated. This is important because connected automated driving requires updated data and low transmission latencies. However, queuing at DCC Access can significantly delay the transmission of messages. To analyze the impact of DCC Access on the freshness of the received information, we measure the information age that is defined as the difference between the time the CPM is generated and the time the CPM has been received. Figure 15 represents the information age obtained without DCC and with DCC (Reactive and Adaptive) when CAMs and CPMs are configured with the same and different DCC profiles. The bars represent the mean values and the vertical lines correspond to the 5th and 95th percentiles. The distance between the transmitter and receiver does not have a significant impact because the propagation delay is negligible. The results obtained show that DCC significantly increases the information age when compared with the scenario without DCC. When DCC is not used, all the generated CPMs are immediately transmitted. However, with DCC, the generated CPMs must often wait in the queue before transmission. This waiting time causes the received information to be outdated by up to 0.4s (Adaptive) or 0.5s (Reactive) when CAM and CPM have different DCC profiles. This provokes a tracking error of up to around 5 m when CAM and CPM have different DCC profiles. This

[10]Similar trends are obtained with the Reactive approach, but with higher times between updates (approximately 2x increase).

is a non-negligible error that can degrade the effectiveness of cooperative perception when implementing DCC. This is despite the possibility to achieve a higher object perception ratio (Figure 13) since detecting more objects is not useful if the information about the detected objects is outdated or not sufficiently fresh.

B. DCC FACILITIES

DCC Facilities is optional as defined in the current Technical Specification draft. However, it can help mitigate the increase of the information age caused by DCC Access and improve the perception capabilities as we demonstrate in this section. DCC Facilities is being designed so that messages are generated at the Facilities layer at the maximum rate tolerated by DCC Access. This is done to reduce the queuing time at the Access layer and limit packet drops. To this aim, DCC Facilities distributes the resources among the different services that generate messages with the same DCC profile. We have therefore considered in this section that both CAMs and CPMs have the same DCC profile, DP2.

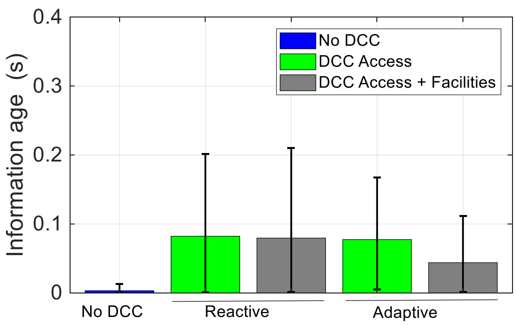

FIGURE 16. **Average information age for CPMs received when CAMs and CPMs have the same DCC profile. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles.**

Figure 16 compares the information age obtained without DCC, with DCC Access only and with the combination of DCC Access and DCC Facilities. The bars represent the mean value and the vertical lines show the 5th and 95th percentiles. As it can be observed, DCC Access significantly increases the information age as we previously showed. However, the combination of DCC Access and DCC Facilities significantly reduces the information age, especially when considering the Adaptive approach. This improvement is achieved because DCC Facilities controls the generation following the limits provided by DCC Access so that messages are not generated if they are going to be queued. The reduction of the information age when DCC Access and DCC Facilities are combined decreases the tracking error below 1.5 m with the Adaptive approach. This error was under 2.3 m with DCC Access (Adaptive) when CAM and CPM have the same profile and below 0.17 m when DCC is not used. The information age is not improved when the Reactive approach is used. This is the case because the channel load variations do not allow DCC Facilities to accurately track the packet transmission rate allowed by the Reactive approach (Table 1) and hence to reduce the queuing time.

DCC Facilities controls the generation of CPMs based on the possibility to transmit them at the DCC Access. This significantly reduces the percentage of CPMs dropped. The percentage of CPMs dropped with DCC Access only is 41.6% for Reactive and 37.5% for Adaptive. The combination of DCC Access and DCC Facilities reduces the CPMs dropped to 12.8% for Reactive and 8.7% for Adaptive. This effect is produced because DCC Facilities reduces the packet generation rate at the Facilities layer following the limits provided by DCC Access. This reduction is shown in Figure 17 that shows the PDF of the number of CPMs generated at the Facilities layer per second per vehicle. The figure also shows that DCC Access generates the same number of CPMs than the scenario without DCC (irrespective of whether using the Reactive or Adaptive approach). This is the case because DCC Access controls messages at the access layer and does not modify the way CPMs are generated at the Facilities layer. When DCC Access is combined with DCC Facilities, the number of CPMs generated per second is reduced. As a consequence, each CPM includes information about a larger number of detected objects. This is the case because the time interval between CPM generations is longer, and thus more objects satisfy the conditions to be included in a CPM since the last time a CPM was generated. This increase of the number of objects in each CPM with DCC Facilities can be observed in Figure 18. Despite the variation observed in the number of CPMs generated per second and the number of objects contained in each CPM, DCC Facilities is designed to generate the load admitted by DCC Access, but not more. The obtained results demonstrate that this goal is achieved with the Adaptive approach. This is the case because the combination of DCC Access and DCC Facilities is able to maintain the CBR around 61.9% when the Adaptive approach is considered. It is the same CBR than the one achieved in the scenario where only DCC Access is used (Table 7). However, the percentage of packet drops is significantly lower when DCC Facilities is used (7.5%) than when it is not used (37.2%).

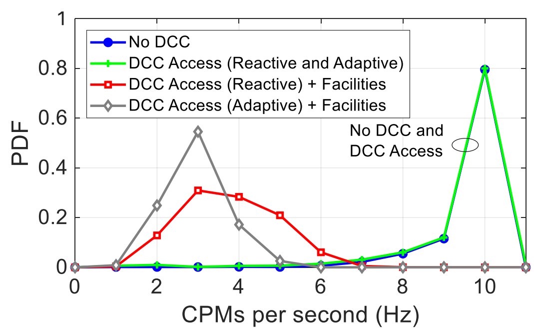

FIGURE 17. **PDF of the number of CPMs generated at the Facilities layer per second per vehicle when CAMs and CPMs have the same DCC profile. When DCC Access is used alone, the same results are obtained for Reactive and Adaptive approaches since DCC Access does not modify the generation of CPMs.**

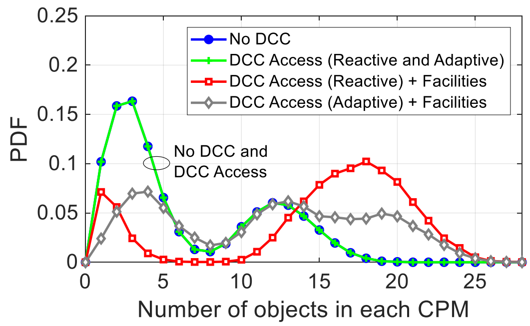

FIGURE 18. **PDF of the number of objects included in each CPM when CAMs and CPMs have the same DCC profile. When DCC Access is used alone, the same results are obtained for Reactive and Adaptive approaches.**

The use of DCC Facilities with the Reactive approach has a different effect on the CBR. It increases the CBR to 46.7% compared to the scenario when only DCC Access is used (37.8%). This increase is produced because DCC Facilities mitigates the synchronization problem that characterizes the Reactive approach and that has been previously explained. DCC Facilities mitigates the synchronization problem because it allows each vehicle to generate (and transmit) messages with different time intervals based on their past generated messages. Mitigating the synchronization problem increases the CBR because there are less packet collisions and thus packets do not overlap in time. Consequently, the implementation of DCC Facilities significantly increases the PDR. This can be observed in Figure 19a for Reactive and in Figure 19b for Adaptive. The PDR at the radio level is especially improved with the Reactive approach due to

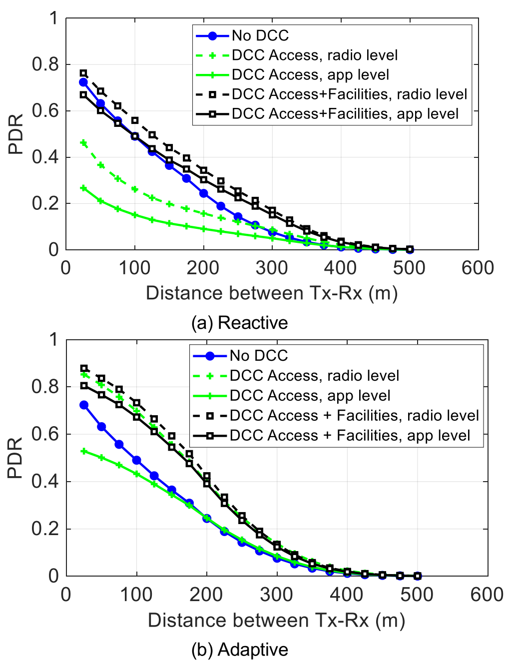

FIGURE 19. **PDR (Packet Delivery Ratio) for CPMs at the radio and application levels as a function of the distance between transmitter and receiver when CAMs and CPMs have the same DCC profile.**

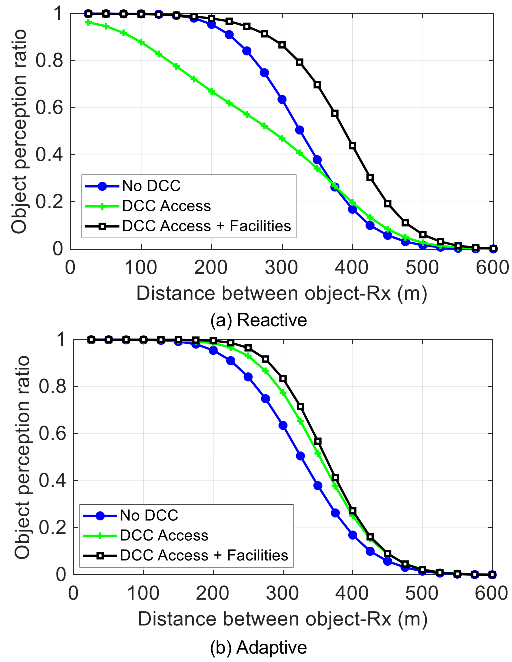

FIGURE 20. **Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs when CAMs and CPMs have the same DCC profile.**

the mitigation of the synchronization problem. It is nearly maintained for Adaptive since the same CBR is achieved. The PDR at the application level is significantly improved for both Reactive and Adaptive. This is due to the low number of packets dropped by DCC when DCC Access and DCC Facilities are combined. Thanks to the improvement of the PDR, the combination of DCC Access and DCC Facilities improves the object perception ratio. This is visible in Figure 20 that compares the object perception ratio when not using DCC, when using DCC Access only and when combining DCC Access and DCC Facilities. Figure 20 reports the object perception ratio for the Reactive and Adaptive approaches. The improvement produced by DCC Facilities is particularly relevant for the Reactive approach given the high PDR increase. In fact, the Reactive approach slightly outperforms the Adaptive one for distances beyond 300m. This improvement is produced due to the higher PDR at the application level of the Reactive approach at such distances (Figure 19) due to its lower CBR and thus lower packet collisions. All these results clearly show that the combination of congestion control functions at the Access and Facilities layers can significantly improve cooperative perception. This is the case because it augments the object perception ratio, reduces the information age, and improves the PDR compared with the scenario with DCC Access only.

VIII. CONCLUSION

This paper analyzes in detail the effectiveness and operation of cooperative perception in connected automated driving. The study shows that cooperative perception significantly improves the perception compared to scenarios in which vehicles exclusively rely on their on-board sensors. The effectiveness of cooperative perception is analyzed for different sensor configurations and market penetration rates. The study shows that very high perception levels can be achieved with penetration rates of only 40%. The perception achieved with cooperative perception strongly depends on the sensors' field of view and range when the market penetration rate is low. However, the impact of the sensors' characteristics on the performance of cooperative perception decreases with the market penetration rate.

Cooperative perception can increase the channel load in the network, which has the risk to reduce the V2X communication performance and degrade the network's scalability. V2X networks control the channel load using congestion control protocols. This study has then also analyzed the impact of congestion control on cooperative perception. To this aim, the study has focused on the DCC algorithm and has evaluated the impact of congestion control functions at the access and facilities layers. At the access level, the study compares for the first time the performance achieved with the Reactive and Adaptive solutions for cooperative perception. The study demonstrates that the Adaptive approach significantly improves the perception achieved but can increase the information age (or freshness) of the exchanged messages compared to scenarios where DCC is not used. This reduces the value of cooperative perception since latency is critical in connected automated driving. This study demonstrates then for the first time that this challenge can be partially addressed through the combination of DCC Access and DCC Facilities. We demonstrate that the combination of DCC Access and DCC Facilities increases the perception and reduces the information age when compared with the DCC Access configuration. This is achieved by dynamically adapting the rate at which messages are generated. This reduces the probability to drop cooperative perception messages (and hence information about the detected objects) and the channel load, which ultimately benefits the V2X network and the effectiveness of cooperative perception. This study therefore demonstrates how critical is the configuration of DCC Access and the importance of DCC Facilities for the development of CAVs. This is particularly relevant for DCC Facilities since it is still a draft that is considered optional and that has not yet been adopted by industry organizations like the C2C-CC. The outcome of this study can provide them valuable knowledge towards an efficient and effective V2X configuration and deployment.

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