Generation of Cooperative Perception Messages for Connected and Automated Vehicles

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Abstract— Cooperative or collective perception (or sensing) enables connected and automated vehicles to exchange sensor information to improve their perception of the driving environment. Standards are currently being developed by ETSI to define collective perception message formats and generation rules. These generation rules establish when collective perception messages should be generated and transmitted. This study shows that current collective perception message generation rules generate a high number of messages with information about a small number of detected vehicles. This results in an inefficient utilization of the communication channel that reduces the effectiveness of collective perception. This study proposes a novel algorithm that modifies how the information of detected vehicles is organized in collective perception messages. The proposed algorithm improves the V2X (Vehicle to Everything) reliability and the perception compared to current ETSI solutions for collective perception or cooperative sensing.

Index Terms— Collective perception, cooperative sensing, message generation, CPM, connected automated vehicles, CAV, V2X, vehicular networks, autonomous vehicles, C-ITS, ITS-G5, C-V2X, ETSI.

I. INTRODUCTION

A utomated vehicles utilize onboard sensors to perceive the surrounding environment and drive autonomously. The perception capabilities of these sensors can be limited for example due to the presence of obstacles (including other vehicles) or adverse weather conditions. Collective perception or cooperative sensing aims to improve the perception capabilities of Connected and Automated Vehicles (CAVs) by wireless exchanging sensor information between vehicles and between vehicles and infrastructure. Vehicles can use the exchanged information to improve their perception and knowledge of the surrounding environment even beyond their onboard sensors’ detection range [1].

First collective or cooperative perception studies analyzed the advantages and disadvantages of exchanging raw sensor data, processed metadata or compressed data [2]. Exchanging raw sensor data would require large communication bandwidths that cannot be provided by existing technologies such as DSRC (Dedicated Short-Range Communications), ITS-G5 or C-V2X. Recent studies have focused on the exchange of basic information about detected objects including their position, speed and size. For example, the study in [3] compares the perception achieved when the information about the detected objects is attached to existing awareness messages (Cooperative Awareness Messages or CAMs [4]) or is transmitted in separate messages with equal or lower priority than CAMs. Other studies try to control or optimize the sensor information exchanged between vehicles. In [5], authors propose that each vehicle should transmit the information about a detected object only if this information is valuable enough for its neighboring vehicles. Accurately estimating the value of this information is a complex challenge. The exchange of collective perception or cooperative sensing messages can increase significantly the load on the V2X (Vehicle to Everything) communications channel. The study in [6] analyzes different congestion and content control schemes. These schemes dynamically decide whether to report or not about certain detected objects based on their distance to the sender vehicle and their impact on position tracking errors. The study determines that message content should focus on detected objects that are located farther away from the sender, but near the edge of onboard sensor detection range. These studies clearly show the need to control the amount and size of cooperative sensing messages without degrading the perception of connected and automated vehicles.

ETSI (European Telecommunications Standards Institute) has started the standardization of collective perception with the definition of the so-called Collective Perception Service (CPS) [7]. The current version of the ETSI Technical Report defines the Collective Perception Message (CPM) and the CPM generation rules1. A CPM is made of one common header and multiple containers with information about the vehicle that generates the CPM, its onboard sensors (range, field of view, etc.), and the detected objects (position, speed, size, etc.). The CPM generation rules identify when a new CPM needs to be transmitted and the information it should contain. These rules have a clear impact on the effectiveness of collective perception and on the channel load generated by the transmission of these new CPM messages. The study presented in [8] showed that current ETSI CPM generation rules result in the frequent transmission of CPMs that include information about a small number of detected objects. This

1 The CPS standard has not yet been approved, so the current CPM message format and generation rules are still a proposal.

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results in an inefficient use of the communication channel due to the frequent transmission of protocol headers and data about the transmitting vehicle. These inefficiencies reduce the probability of receiving CPM messages, and therefore the effectiveness of cooperative perception. This paper proposes to tackle these inefficiencies by modifying the current ETSI CPM generation rules so that less CPMs are transmitted and each CPM includes data about a higher number of detected objects. This study demonstrates that the proposed solution improves the reliability of V2X communications and the perception capabilities of CAVs compared to the current ETSI CPS implementation.

II. COLLECTIVE PERCEPTION STANDARDIZATION

ETSI is currently working on the standardization of the Collective Perception Service (CPS). Current developments are described in the Technical Report in [7] and will serve as a baseline for the specification of CPS in ETSI TS 103 324. The Technical Report describes the CPM format and the CPM generation rules. CPM messages include an ITS (Intelligent Transport Systems) PDU (Protocol Data Unit) header and 4 containers: Management Container, Station Data Container, Sensor Information Containers (SICs), and Perceived Object Containers (POCs). The ITS PDU header 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, e.g. its position. The position is used to reference the detected objects. The Station Data Container is optional and includes additional information about the transmitting vehicle (e.g. its speed, heading, or acceleration). The CPM can include up to ten SICs. These containers describe the capabilities of the sensors embedded in the transmitting vehicle. Finally, the POCs provide information about the detected objects (e.g. the distance between the detected object and the transmitting vehicle), the speed and dimensions of the object, and the time at which these measurements were done. A single CPM can include up to 255 POCs.

The CPM generation rules define how often a vehicle should generate and transmit a CPM and the information (detected objects and sensors information) to be included in each CPM. The current ETSI CPM generation rules [7] establish that a vehicle has to check every \( T\_GenCpm \) if a new CPM should be generated and transmitted. A vehicle should generate a new CPM if it has detected a new object, or if 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 its data was included in a CPM.
2. Its absolute speed has changed by more than 0.5m/s since the last time its data was included in a CPM.
3. The last time the detect object was included in a CPM was 1 (or more) seconds ago.

A vehicle includes in a new CPM all new detected objects and those objects that satisfy at least one of the previous conditions. The vehicle still generates a CPM every second even if none of the detected objects satisfy any of the previous conditions. The information about the onboard sensors is included in the CPM only once per second.

III. MOTIVATION

We first analyze the current ETSI CPM generation rules to motivate our proposal. We consider a highway scenario (Figure 1a). Without loss of generality, we suppose that the ego vehicle is equipped with a sensor that has a Field of View (FoV) of 360º. The vehicle generates CPMs following the current ETSI CPM generation rules. The ego vehicle checks the conditions to generate a CPM every \( T\_GenCpm = 0.1s \). Let’s first consider that all vehicles in the scenario move at 70km/h (19.4 m/s). In this case, all vehicles detected by the ego vehicle satisfy condition 1 described in Section II every 205ms. The ego vehicle then includes each detected vehicle in a CPM every 300ms. Let’s suppose an ideal scenario where the ego vehicle detects all neighboring vehicles in Figure 1a at the same time. The ego vehicle generates then 3 CPMs per second, and each CPM includes the information of the 6 detected vehicles. It is though very unlikely that an ego vehicle can detect all its neighboring vehicles at the same time. In a realistic scenario, vehicles constantly enter and leave the detection range of an ego vehicle at different times. The ego vehicle will then include the detected objects (i.e. vehicles in this study) in different CPMs as illustrated in Figure 1b. This figure illustrates an example in which the ego vehicle detects neighboring vehicles at different times. In particular, the figure represents a scenario in which the ego vehicle detects two different neighboring vehicles every \( T\_GenCpm = 0.1s \). In this case, the ego vehicle ends up transmitting 9 CPMs per second instead of 3 like in the ideal scenario. Each CPM includes now information about two detected objects instead of six, like in the ideal scenario where all vehicles were detected at the same time. Transmitting more CPMs per second consumes more bandwidth since each CPM includes the ITS PDU Header, and the Management and Station Data containers of the ego vehicle (Section II). In addition, each CPM implies additional protocol headers from the Transport, Network, MAC (Medium Access Control) and PHY (Physical) layers. A similar effect is observed if we consider a scenario where vehicles move at different speeds. The ego vehicle still checks the conditions to generate a CPM
every $T_{GenCpm}=0.1s$. However, since each vehicle moves at different speeds, they satisfy condition 1 in Section II at different time instants, and the ego vehicle will include their data in different CPMs. This can again result in the frequent transmission of CPMs with data about a small number of detected objects. We have analyzed and quantified this trend by means of simulations using the network simulator ns3 and the road mobility simulator SUMO.

Simulations have been conducted for a 5km long six-lane highway scenario. We simulated two traffic densities following the V2X simulation guidelines in [9]: 120veh/km and 60veh/km. We configure in SUMO the speed of vehicles at each lane using statistics from the PeMS database for a typical 3-lane US highway [10]. Different speed configurations are selected for the two traffic densities. All vehicles communicate using ETSI’s ITS-G5 standard (based on IEEE 802.11p) over the same channel. V2X communications are simulated in ns3 [11]. The propagation effects are modeled using the Winner+ B1 propagation model following [9]. The transmission power is set to 23dBm and the packet sensing threshold to -85dBm. All vehicles transmit using the 6Mbps data rate (i.e. they utilize QPSK modulation with $\frac{1}{2}$ code rate). The ns3 simulator has been extended with a CPS component implemented by the authors. The component creates CPM messages based on the ETSI CPM message format [8]. CPM messages are generated following the ETSI CPM generation rules (Section II) with $T_{GenCpm}=0.1s$. Vehicles can be configured with forward or 360º sensors following [7] and [8]. In the first configuration, vehicles are equipped with two forward sensors. The first sensor has a 65m range and a FoV of $\pm40^\circ$. The second sensor has a 150m range and a $\pm5^\circ$ FoV. In the second configuration, vehicles are equipped with a single sensor with 150m range and a 360º FoV.

Figure 2a depicts the Probability Density Function (PDF) of the number of CPMs generated per vehicle per second when using the forward sensors (similar trends were observed with the 360º sensors). Figure 2b represents the PDF of the number of detected objects included in each CPM. Both figures are obtained using the current ETSI CPM generation rules. Figure 2a clearly shows that the current rules result in that CPMs are mostly generated every 0.1s (i.e. at 10Hz) independently of the sensor configuration and traffic density. These CPMs contain information only about a small number of detected objects (Figure 2b). The number of objects included per CPM is actually smaller than the total number of detected objects per vehicle. This is actually visible when comparing Figure 2b with Figure 3 that represents the PDF of the total number of detected objects per vehicle. The transmission of frequent and small CPM messages adds significant channel overhead since each CPM needs to transmit the ITS PDU Header, and the Management and Station Data containers. In addition, each CPM generates additional overhead from the protocol headers at the Transport, Network, MAC and PHY layers. All this overhead increases the channel load, and can reduce the reliability of V2X communications. This can compromise the exchange of CPM messages and reduce the perception of CAVs. This study proposes a novel algorithm that modifies the ETSI CPM message generation rules. The algorithm is designed to avoid the frequent transmission of CPMs with a small number of detected objects, and ultimately improve the perception of CAVs.

![Image](image_url)

(a) PDF of the number of CPMs generated per vehicle per second

![Image](image_url)

(b) PDF of the number of detected objects included in each CPM

Figure 2. Performance of ETSI CPM implementation with forward sensors.

![Image](image_url)

Figure 3. PDF of the number of detected objects per vehicle (forward sensors).

IV. PROPOSAL

The algorithm is designed to improve the perception or sensing capabilities of CAVs compared to the current ETSI CPM proposal. The algorithm is based on the current ETSI CPM generation rules. In particular, vehicles check the conditions to generate a new CPM every $T_{GenCpm}$. The algorithm computes for each detected object the variation of absolute position ($\Delta P$), the variation of speed ($\Delta S$) and the time elapsed ($\Delta T$) since the last time the detected object was included in a CPM. A new CPM is generated if at least one of the conditions specified in Section II is satisfied following the current ETSI CPM generation rules. If it is the case, the CPM must include the information about the detected objects that satisfy $\Delta P>4m$ or $\Delta S>0.5m/s$ or $\Delta T>1s$. The pseudo-code for this process is reported in lines 1-8 of Algorithm I.

Our algorithm extends the ETSI CPM generation rules as follows. The algorithm estimates every time a new CPM must be generated (following the ETSI CPM generation rules) if any of the detected objects that are not included in this new CPM would be included in the next CPM if their current speed and acceleration was maintained. To this aim, the algorithm estimates the following parameters:
\[ \text{Next } \Delta P = \Delta P + S \cdot T_{\text{GenCpm}} \]  
\[ \text{Next } \Delta S = \Delta S + A \cdot T_{\text{GenCpm}} \]  
\[ \text{Next } \Delta T = \Delta T + T_{\text{GenCpm}} \]

where \( S \) and \( A \) are the current speed and acceleration of the detected object. Our algorithm includes in the current CPM those detected objects that satisfy \( \text{Next } \Delta P > 4 \text{ m} \) or \( \text{Next } \Delta S > 0.5 \text{ m/s} \) or \( \text{Next } \Delta T > 1 \text{ s} \). Their information (\( \Delta P \), \( \Delta S \) and \( \Delta T \)) is transmitted in the current CPM instead of the next CPM. Anticipating the transmission of their information is proposed to avoid transmitting many CPMs with information about a small number of detected objects. The following section demonstrates that this approach actually improves the perception compared to the current ETSI approach. The pseudo-code of the proposed extension to the ETSI CPM generation rules is described in lines 9-16 of Algorithm I.

**ALGORITHM I.**

**Input:** Detected objects  
**Output:** Objects (if any) to include in CPM  
**Execution:** Every \( T_{\text{GenCpm}} \)

1. Set \( \text{flag} = \text{false} \)
2. For every detected object do
3. Calculate \( \Delta P \), \( \Delta S \) and \( \Delta T \) since the last time included in a CPM
4. If \( \Delta P > 4 \text{ m} \) or \( \Delta S > 0.5 \text{ m/s} \) or \( \Delta T > 1 \text{ s} \) then
5. Include object in current CPM
6. Set \( \text{flag} = \text{true} \)
7. End If
8. End For
9. If \( \text{flag} = \text{true} \) then
10. For every detected object not included in current CPM do
11. Calculate \( \text{Next } \Delta P \), \( \text{Next } \Delta S \) and \( \text{Next } \Delta T \)
12. If \( \text{Next } \Delta P > 4 \text{ m} \) or \( \text{Next } \Delta S > 0.5 \text{ m/s} \) or \( \text{Next } \Delta T > 1 \text{ s} \) then
13. Include object in current CPM
14. End if
15. End For
16. End If

**V. EVALUATION**

The performance of the proposed algorithm is analyzed using the simulation set-up described in Section III. We consider that \( T_{\text{GenCpm}}=0.1 \text{ s} \), and analyze the performance for both traffic densities and the two sensor configurations. Figure 4 compares the PDF of the number of CPMs generated per vehicle per second with the ETSI CPM generation rules and with our proposal. The results obtained show that the proposed algorithm significantly reduces the number of CPMs generated per second compared to the current ETSI rules. This reduction is achieved for all traffic densities and sensors’ configuration. Table I shows that our proposal reduces the average number of CPMs generated per vehicle and per second by 34%-43% compared to the current ETSI proposal.

Our proposal reduces the number of CPMs transmitted per second by increasing the number of detected objects included in each CPM. This is actually observed in Figure 5. This figure compares the PDF of the number of objects included in each CPM with ETSI’s solution and with our proposal. Figure 5 shows that our proposal increases the number of detected objects included per CPM and reduces the number of CPMs that only include information about 1 or 2 detected objects.

Augmenting the sensors’ field of view increases the number of detected objects per CPM since more objects can be detected. A similar effect is observed when the traffic density increases. However, when the traffic density increases, the detected objects need to be included in a CPM less frequently since vehicles move at lower speeds. Figure 5 shows that our proposal only generates some CPMs with a small number of objects under high densities. These CPMs are generated when...
a vehicle detects for the first time new neighboring vehicles.

The results reported so far clearly show that our proposal generates less CPMs per second than the current ETSI solution. This is done by increasing the number of detected objects reported per CPM. Transmitting less CPMs per second reduces the number of channel access attempts and the number of times the ITS PDU header and the Management and Station Data containers of a vehicle are transmitted. This is visible in Table II that reports the average CPM bytes generated per second and per vehicle with ETSI’s implementation and our proposal. The table also reports the difference of CPM bytes transmitted with our proposal compared to the current ETSI implementation. Table II shows that our proposal reduces the transmission of headers and containers related to the transmitting vehicle (referred to as HC in the table) by 34%-43% compared to the current ETSI implementation. On the other hand, our proposal augments the number of times a detected object is reported in a CPM (and hence the corresponding POC bytes) between 12% and 21% depending on the scenario. This increase results from the reorganization of how detected objects are reported in CPMs.

Despite this increase, Table III shows that our proposal reduces the channel load compared to the current ETSI implementation. The channel load is estimated in terms of the average CBR (Channel Busy Ratio) that is defined as the percentage of time that the channel is sensed as busy. Table III shows that our proposal reduces the CBR by 10%-23% compared to the ETSI implementation. These reduction levels are higher than the reduction of average total CPM bytes reported in Table II. This is the case because transmitting less CPMs per second not only reduces the average CPM bytes transmitted per vehicle and per second (Table II), but also the protocol headers generated by the lower layers when a packet is transmitted. This explains why our proposal achieves higher average CBR gains compared to the ETSI proposal (Table III) than gains in terms of average total CPM bytes (Table II). Higher reduction levels are obtained with forward sensors because these sensors detect a lower number of objects. In this case, the Management, Station Data and Sensor Information containers represent a larger proportion of the total bits transmitted over the communication channel. Similarly, our proposal achieves higher CBR reduction levels compared to the ETSI implementation when the traffic density increases. This shows that our proposal has a positive impact on the scalability of vehicular networks.

Reducing the CBR and channel load reduces the packet collisions and improves the PDR (Packet Delivery Ratio). This is actually shown in Table IV that reports the distance up to which a PDR equal or higher than 0.9 is guaranteed. Table IV shows that our proposal increases this distance compared to the current ETSI CPM solution. The increase is around 9%-11% under low traffic density and 35% under high traffic density. These results demonstrate that our proposal increases the reliability of V2X communications.

We also analyze the object perception ratio to demonstrate that our proposal also achieves higher perception capabilities of CAVs compared to the current ETSI implementation. The object perception ratio is defined as the probability to detect an object (i.e. vehicle in this study) in a given 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 considered time window. The CPMs can be transmitted by different vehicles in the scenario. Figure 6 plots the average object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM. The results have been obtained considering a time window of 0.1 seconds. Figure 6 shows that our proposal improves the object perception ratio compared to the current ETSI approach. This is due to two main reasons. The first one is the fact that our proposal increases the PDR and therefore the probability to correctly receive CPM messages increases. The second reason is that our proposal reorganizes the transmission of detected objects in CPMs. This reorganization resulted in a lower number of transmitted CPMs and an increase (between 11% and 21%) in the average number of times that a detected object is reported in a CPM. This also has a positive impact on the perception capabilities of CAVs and hence on the object perception ratio. Figure 6 also shows that the object perception ratio decreases with the traffic density. This is the case because higher densities augment the channel load and reduce the PDR. In addition, vehicles move at lower speeds with high traffic densities, and their data is included less frequently in CPMs. The sensor capabilities also have an impact on the object perception ratio. Figure 6 shows that 360° sensors achieve a higher object perception ratio than forward sensors. This is due to the fact that more vehicles report about the same detected object when sensors have a larger FoV.

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3 This distance is considered a V2X performance reference by some standardization organizations such as the 3GPP [9].
The perception achieved with our proposal is also analyzed in terms of how often a vehicle receives updates about a detected object. The updates can be received from any neighboring vehicle that has detected the same object. Figure 7 plots the average distance travelled by an object between updates as a function of the average distance between the object and the vehicle receiving the CPMs. The shortest the travelled distance the more frequent a vehicle receives updated information about a detected object. Figure 7 shows that our proposal and ETSI’s implementation can provide updates about detected objects every 4m (or less) up to distances between 350 and 400m. 4m is considered as a target reference following the ETSI CPM generation rules. Figure 7 also shows that our proposal generates updates about the detected objects at least as frequently as the current ETSI solution. In fact, our proposal generates more frequent updates for large distances between the detected object and the vehicle receiving the CPMs. This shows once more that our proposal improves the perception of CAVs compared to the current ETSI implementation.

VI. CONCLUSIONS

Cooperative or collective perception will enable connected and automated vehicles to exchange sensor information to improve their perception of the surrounding environment. ETSI is currently defining standards for collective perception message formats and rules that identify when these messages should be generated and transmitted. This study shows that the current ETSI message generation rules for collective perception tend to generate frequent and small CPM messages that only report about a few detected objects. This results in an inefficient use of the communications channel that reduces the V2X reliability and the perception capabilities of CAVs. This paper proposes a novel algorithm that modifies the ETSI CPM message generation rules and reduces the number of CPM messages transmitted per second. This is achieved by reorganizing how information about detected objects is transmitted. Our proposal improves the reliability of V2X communications, and increases the perception capabilities of connected and automated vehicles.

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