GoT: decreasing DCC queuing for CAM messages

Oscar Amador, Ignacio Soto, Manuel Urueña, and Maria Calderon

***Abstract*—Vehicular networks use Decentralized Congestion Control (DCC) mechanisms to operate effectively, but this mechanism may introduce queuing delays. Freshness of Cooperative Awareness Messages (CAMs) is critical for their usefulness. In this letter we explore how the presence of other types of traffic additional to CAMs, even with lower priorities, has an impact on the freshness of CAM messages due to DCC queuing. Finally, we propose Generate-on-Time (GoT), which is a simple mechanism that reduces DCC queuing delays for CAM messages without introducing any downside in other performance metrics.**

***Index Terms*—Cooperative Awareness, end-to-end delay, ETSI, Intelligent Transport Systems (ITS), vehicular networks.**

I. Introduction

Cooperative awareness (CA) services are one of the cornerstones of Intelligent Transport Systems (ITS). It is through these services that ITS stations learn about the position, heading, speed, and contextual information about their neighbors on the road. The European Telecommunication Standards Institute has defined a standard for a Cooperative Awareness basic service (ETSI EN 302 637-2) [1], which specifies Cooperative Awareness Messages (CAM). A CAM contains information regarding the status (e.g., time, position, activated systems) and attributes (e.g., dimensions, vehicle type and role) of a generating station. CAM messages are generated periodically, and their frequency is affected by changes in the status of the generating station and by channel occupation.

Since the objective of a CA service is to keep neighbors aware of a vehicle's status, the *validity* and *recentness* of the information in CAM messages is paramount. There are factors that affect these two attributes, such as collisions —that lead to messages being received at longer intervals—, and end-to-end delay, which is the time difference between the generation of a CAM in a station and its consumption in the Cooperative Awareness service of a remote neighbor.

Extensive work has been conducted on evaluating the performance of CA services. The bulk of the work has been focused on metrics pertaining losses and collisions, as well as comprehensive performance analyses of the CA basic service. In [2], authors evaluate the performance of ETSI CAM in platooning scenarios and traffic jams. Authors in [3] evaluate the performance of ETSI CAM in winding roads, and propose an addition to the standard generation algorithm to account for curves. However, these two publications use the ETSI Reactive Approach DCC mechanism [4]. Furthermore, they do not consider the coexistence of multiple types of traffic, or the effect of DCC on CAM latency.

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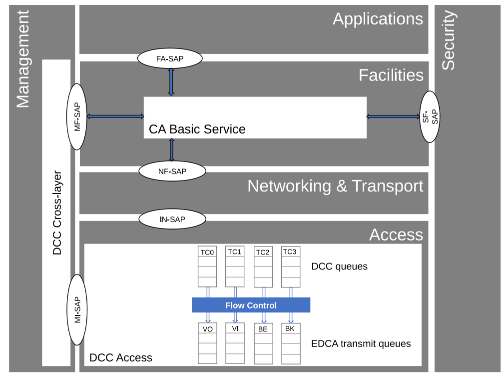


Fig. 1: ETSI ITS Architecture with DCC cross-layer

In the past, several publications [5] [6] have studied the problem of coordination between the different layers at which the DCC mechanism operates. The work in [5] proposes an integrated congestion control solution that takes into account the requirements of CA applications and the experienced channel load. The work in [6] proposes that DCC functionalities should be performed only at the Facilities layer. However, these previous works do not propose how to improve the coordination between Access and Facilities layers in the ETSI architecture as our paper does. On the other hand, several past works have analyzed the performance of congestion control protocols considering the coexistence of distinct V2X ITS services [6]–[8]. Several of these works have considered the coexistence of messages with different priorities (i.e., CAM and lower-priority traffic) [7] [8]; however, they do not analyze how this low priority traffic can impact the freshness of CAMs as our work does.

Our previous work [9] [10] had the aim of evaluating the Adaptive Approach of the ETSI Decentralized Congestion Control mechanism and proposed a variation that improves the performance in rapidly-changing scenarios. In [10], we found an effect of multi-traffic on CAM latency, using scenarios with realistic CAM generation (i.e., based on vehicle dynamics and the rate allowed by DCC) and another type of traffic with lower priority coming from the same station. Since the transmission of different types of traffic is controlled by a single DCC mechanism, following the rules from [1], the transmission of another message might delay the transmission of a CAM that is generated afterwards, making it wait at the DCC queue. Furthermore, this desynchronizes the DCC mechanism at the Access layer and the CA service, leading to further queuing delays.

The main contribution of the present work is a mechanism

— Generate-on-Time (GoT) — to reduce waiting times of CAM messages at DCC queues and, thus, end-to-end delay. GoT delays the generation of CAMs until they can be sent, without altering the rate at which they are transmitted, by synchronizing the cross-layer DCC mechanism. The work is divided as follows: in section II, an analysis of CAM end-to-end delay in multi-traffic scenarios is presented, considering the current ETSI CAM standard [1] and GoT, our proposed solution. Section III presents results of simulations on fixed and dynamic scenarios to evaluate the performance of ETSI CAM and GoT. Finally, conclusions are presented in section IV.

II. End-to-end delay in CAMs

A. Overview of CAM generation rules

As shown in Fig. 1, the CA basic service resides in the Facilities layer. There, it receives and delivers information to other layers [11]. For example, CAM generation rates are limited by by a cross-layer DCC mechanism [4] through the management entity.

Following the rules established by [1], the CAM generation interval is limited within a range from 0.1 s to 1 s by four parameters:

- $T\_Elapsed$ (i.e., time since last CAM generation),
- vehicle dynamics (i.e., shifts in position, acceleration, and heading),
- T_GenCam_DCC (i.e., lower limit of the CAM generation given by the DCC mechanism), and
- T_GenCam (i.e., upper limit for the generation interval).

When $T\_Elapsed \geq T\_GenCam\_DCC$, a CAM generation is triggered by either of two conditions:

1) if vehicle dynamics have exceeded certain thresholds, or
2) if $T\_Elapsed > T\_GenCam$.

Where T_GenCam is $T\_Elapsed$ for the last CAM generated by condition 1. After three CAMs have been generated by condition 2, T_GenCam is set to 1 s.

When an outgoing CAM message reaches the Access layer, it is placed at the DCC queue corresponding to DCC Profile 2 [12] (also known as Traffic Class Identifier 2 (TC2) in recent ITS-G5 standards [13]). There, the congestion control mechanism dequeues messages according to their priority (i.e., TC0 to TC3, with TC0 having the highest priority). When the DCC mechanism reaches the time for the next transmission (i.e., t_{go} from [4]), the message is sent to the lower-layer transmit queues. In the presence of a single type of traffic, t_{go} and T_GenCam_DCC will usually coincide, which means that a generated CAM will not have to wait in the DCC queues and it will only be delayed by the medium access control mechanism (i.e., EDCA) until it is finally transmitted.

B. Analysis of CAM end-to-end delay with multi-traffic

Fig. 2 illustrates how CAM messages are generated, enqueued, and transmitted in a vehicle and received in a remote station when CAM coexists with lower-priority traffic (e.g., multi-hop DENM messages, and other data traffic [13]). The interval at which CAMs are generated is expressed as t_{cam}, and t_{dcc} represents the interval at which DCC allows a vehicle to send traffic. The upper part of the diagram shows the case when CAM messages are generated at rates lower than those allowed by the cross-layer DCC mechanism, and the lower part represents what happens when CAM message rate is restricted by the DCC mechanism (i.e., dynamics trigger a CAM every time DCC allows a generation).

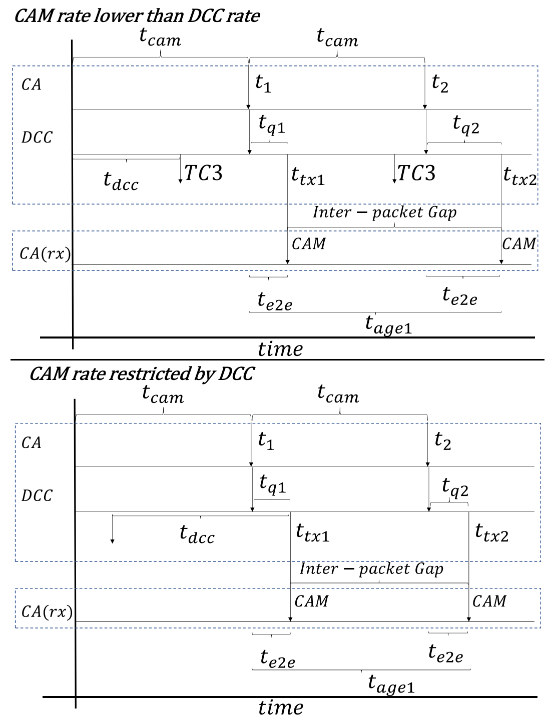


Fig. 2: CAM generation under rules defined in [1]

As shown in Fig. 2, CAM messages are generated every t_{cam}. At t_1, a CAM is generated (with a timestamp and information corresponding to t_1), but since a TC3 message was transmitted, the CAM waits at the DCC queue (t_{q1}) until it is dequeued and transmitted (t_{tx1}). The message then reaches a remote ITS station, where it is decoded by the CA service. The latency of this message (t_{e2e1}) is mainly dominated by the time it waited in the queues, and when the next CAM is received at t_{tx2}, this delay will add to the inter-packet gap to constitute the information age of the first message (t_{age1}).

Considering a system in steady state with two types of traffic with different traffic classes and priorities (e.g, CAM with TC2 and another type of traffic with TC3), where CAM generations occur at a regular rate (i.e., t_{cam} is practically constant), the total message rate for a vehicle is modeled in equation 1:

$$r_{total} = \frac{1}{t_{dcc}}; r_{cam} = \frac{1}{t_{cam}}; r_{tc3} = r_{total} - r_{cam} \quad (1)$$

where message rates (r) are defined for CAM (r_{cam}) and lower priority traffic (r_{tc3}), that add up to the total message rate for the vehicle (r_{total}). If t_{cam} is equal to t_{dcc}, r_{tc3} approaches zero and $r_{total} = r_{cam}$. However, if t_{cam} is larger than t_{dcc}, TC3 finds gaps to be transmitted, becoming a source for desynchronization between the interval provided by DCC to the CA service and the actual time a CAM will be dequeued. Both cases are exemplified in Fig. 2.

The DCC mechanism at the Access layer dequeues a message according to the rate defined by channel occupation. After a message is transmitted (i.e., at t_{tx} in Fig. 2), the time at which the next message is dequeued (i.e., t_{go}) is updated to t_{tx} plus a time between 25 and 1000 milliseconds (i.e., t_{dcc}), as indicated in [4] Annex B. The transmission of a lower priority message can potentially delay higher priority traffic. An example can be illustrated when a CAM generation occurs instants after a TC3 message was transmitted, which will cause the CAM to wait for the next gate opening at the DCC queues.

Another source of delays at the DCC queues can emerge when $t_{cam} = t_{dcc}$ and the feedback from DCC at the CA service is not synchronized with t_{go} (lower part of Fig. 2), and thus a generated CAM must wait until DCC allows its transmission. This waiting time at the queue (t_q) is carried over to the end-to-end delay metric (t_{e2e}). This effect, even when not considering losses in the channel, adds to the age of the information a vehicle has about their neighbors, leading to undesirable ramifications such as tracking errors.

The information provided to the CA service by DCC through the Management Entity [1] consists only of the allowed message rate, but it does not specify the instant when the next transmission will occur, and thus a CAM can be generated at any time between two consecutive transmissions. Due to this desynchronization, t_q can be of any length from zero to t_{dcc}, and the relation between this waiting time at the queue and the time interval provided by DCC is a uniform distribution as expressed in equation 2:

$$T_q \sim U(0, t_{dcc}) \therefore \overline{t_q} = \frac{t_{dcc}}{2} \qquad (2)$$

This becomes an issue when t_{dcc} is high. Besides affecting the end-to-end delay (t_{e2e}), the waiting time at the queue affects another related metric: the information age (t_{age}) of CAM messages at remote stations. Information age is the time difference between the generation time-stamp in the most recent CAM received from a neighbor and the time a new message is received. In a channel with no losses, the minimum age of the information of the last CAM at the moment of the reception of a new one is expressed in equation 3:

$$t_{age(n-1)} = t_{q(n)} + t_{cam(n)} \qquad (3)$$

where $t_{q(n)}$ is the waiting time for the CAM being received, and $t_{cam(n)}$ is the time elapsed between two CAM generations (i.e., the intended time between updates). Longer times waiting at the queues have an effect on information age, since time offsets can be as high as $2 \cdot t_{dcc}$.

Equation 3 does not consider some additional contributions to end-to-end delay: 1) waiting time in the EDCA queue, regulated by the IEEE 802.11 medium access control mechanism; 2) the packet transmission time; and 3) propagation delay. The sum of these delays has a value close to 1 ms (see [10]) and is, therefore, negligible compared with the delays we are analyzing in this letter.

C. Generate-on-Time (GoT)

We propose the use of another parameter in combination with the ones defined in the rules established by [1]. Using

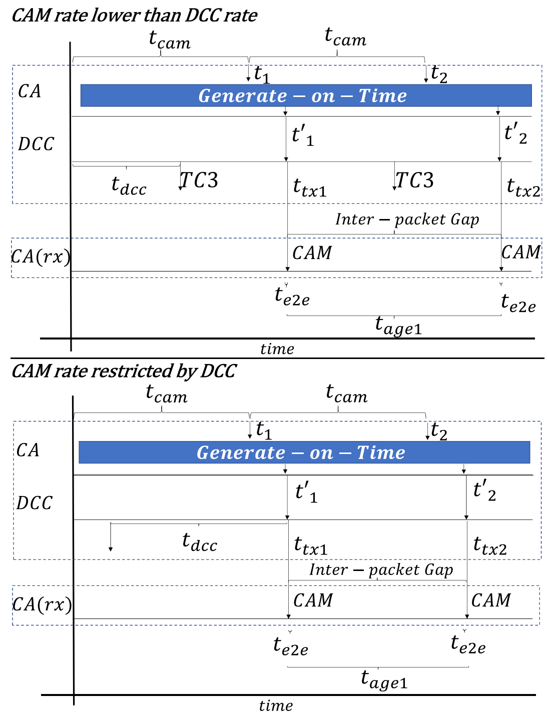


Fig. 3: CAM generation with GoT

the existing architecture [11], the interface to the Management Entity will provide, besides the message rate t_{dcc}, the time the next transmission will occur (t_{go}). Then, when conditions 1 or 2 would trigger a CAM generation in the CA service, another condition is checked: if $((t_{go} - t) - \varepsilon) \leq 0$, where t is the current time and ε is greater than the time required to create a CAM message. If this condition is not met, the CAM is not generated at this instant, but the current time is stored (t), along with the current values for position, acceleration, and heading (i.e., D, for dynamics). The CA service will wait for the time provided by the Management Entity (e.g., sleeping for $(t_{go} - t) - \varepsilon$). After this wait, when t_{go} allows for the CAM to be generated at the instant t', it will include the most recent values for dynamics (D'). However, the next CAM generation will be referred to the stored values (i.e., t_{cam} will be calculated using t instead of t', and shifts in dynamics will be compared to D instead of D'), keeping average t_{cam} within the values it would have had with the standardized CAM generation rules. CAM messages using GoT, time-stamped with t' and including D', will update neighbors using the most recent information from the vehicle data provider.

The advantages of delaying CAM generation depend on the ability of obtaining updated location information in the vehicle. Global Navigation Satellite Systems (GNSS) have a minimum time between measurements. However, because the CAM generation is not synchronized with the GNSS measurements, even small delays can allow obtaining an updated location position. Moreover, the use of additional sensors (inertial sensors) for tracking functionality enables a continuous reading of vehicle position between GNSS measurements.

Fig. 3 models the behavior of GoT, which acts as a layer that registers when a CAM needs to be generated, but completes

TABLE I: Simulation parameters

Parameter	Values
Access layer protocol	ITS-G5 (IEEE 802.11p)
Data rate	6 Mbit/s
Transmit power	126 mW
Channel bandwidth	10 MHz at 5.9 GHz
Path loss model	Two-Ray Interference Model
Sensing range	750 m
DCC mechanism	ETSI Adaptive Approach DCC
Packet Size (including certificates)	CAM: 335 Bytes, TC3: 332 Bytes
GoT ε	15 ms

the generation once t_{go} approaches, using a time buffer (ε) to guarantee the message will be ready to be dequeued by the DCC mechanism. A new t_{cam} will be calculated taking t_n as a reference. When comparing Fig. 2 and Fig. 3, it is shown that CAM messages triggered at t_n will not be dequeued until t_{tx} for both approaches. However, GoT delays the fulfillment of this trigger in order to compensate for t_q, improving t_{e2e} and t_{age}. Regardless of the mechanism being used, transmissions will occur at the same time (t_{tx}), and neighbors will receive CAM messages not only at the same rate, but also at the same time (i.e., Inter-packet gaps are equal for both approaches), but GoT guarantees that the information in CAM messages is the most up to date possible.

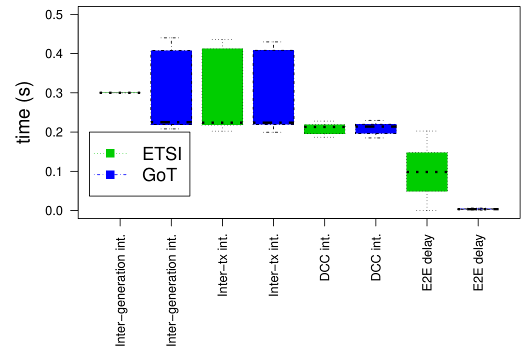
TC3 traffic is not the only source of desynchronization, for example, for cases where there is traffic with higher priority than CAMs (e.g., high-priority DENM messages), CAMs triggered with GoT or ETSI rules are equally affected: a TC0 or TC1 message will update t_{go} and delay the dequeuing of a CAM or, in the case of GoT, it can possibly delay its generation. For both cases, the next CAM will be sent the next time t_{go} allows it. However, GoT synchronizes the next CAM generation with the DCC gate opening. This is an important property of GoT, since in ETSI CAM, any event that creates desynchronization will not be corrected until $t_{cam} > t_{dcc}$ and no other type of traffic is transmitted.

III. Simulation Results

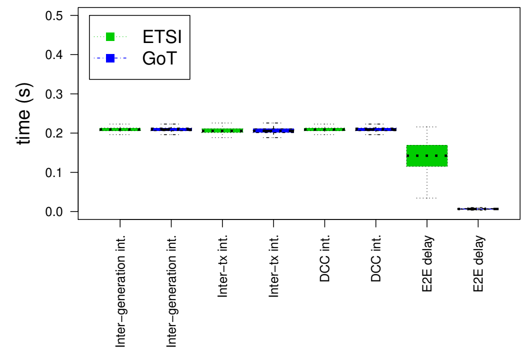
In order to evaluate the performance of ETSI CAM and GoT, we performed two types of experiments: 1) a static scenario where CAM generation is triggered at fixed rates (0.1 and 0.3 s), but restricted by feedback from DCC at the Facilities layer; and 2) a highway with five vehicle densities ranging from 10 to 50 vehicles/km per lane. Simulations are performed on Artery [14], with the parameters shown in Table I. The value we used for ε was 15 ms, which is a conservative value that allows for the construction of a CAM and which can be adjusted accordingly in real implementations.

A. Static Scenario

The static scenario consists of 300 vehicles deployed equidistantly within 200 meters of each other, well into communication range. To evaluate cases of multi-traffic coexistence, one where TC3 traffic is allowed to be transmitted and one where it is not, we generate traffic at two different rates: one case with CAM messages attempting to be generated every 100 ms and another with 300 ms between generations. In both



(a) CAM generation triggered every 300 ms



(b) CAM generation triggered every 100 ms

Fig. 4: Comparison between ETSI CAM and Generate-on-Time in a static scenario

cases, CAM generations are restricted by the feedback from DCC Facilities, e.g., a CAM generation would be triggered every 100 ms, but it will be limited by the t_{dcc} parameter.

To evaluate the case where $t_{dcc} < t_{cam}$, CAM traffic was triggered every 300 ms, well above the 200 ms inter-generation interval allowed by DCC. Fig. 4a shows that there is a greater variation between CAM generations with GoT, where the values for inter-generation intervals (i.e., the time between two CAM arrivals at the DCC queues) range from approximately 200 to 400 ms, while ETSI CAM generations are at a fixed rate of 300 ms. However, when CAM messages go down the stack, actual transmissions occur at the same time for both approaches: every 200 or 400 ms for both algorithms, following a bimodal distribution.

Differences can be seen in the end-to-end delay, where values for the ETSI CAM algorithm follow a uniform distribution with an average value of $\frac{t_{dcc}}{2}$, while GoT keeps average delay to a minimum, close to ε, due to the mechanism's behavior. This means that, even when messages are generated at a constant rate by the ETSI CAM algorithm, they are transmitted at different intervals, while GoT tries to synchronize generation and transmission instants, in order to avoid waiting times at the DCC queues and thus lowering end-to-end delay. To explore the case where $t_{dcc} = t_{cam}$ (i.e., when the t_{dcc} parameter delays generations), CAM traffic was triggered every 100 ms. However, it was not allowed to be transmitted until the interval given by DCC Facilities allowed the generation (on average, $t_{dcc} = 200\,ms$). Fig. 4b once again shows that messages

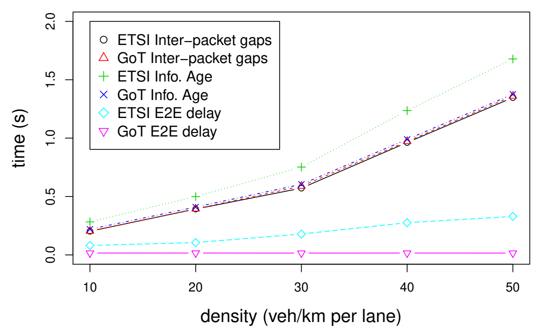


Fig. 5: Comparison between ETSI CAM and Generate-on-Time in a road scenario ($d \leq 400m$)

generated using GoT maintain low values for end-to-end delay.

B. Road Scenarios

The road scenarios are deployed on an a 7.75 km oval road with eight lanes — four in each direction — that has both long straight stretches and curves at the edges. Vehicle densities range from 10 to 50 vehicles/km per lane, and measurements are taken on the center of a straightaway. While the sensing range is around 750 m, only measurements from cars within 400 m of each other are considered. This distance was chosen because it is longer than the safety distance for a driver to react to danger.

Fig. 5 shows that, even when GoT changes the CAM generation pattern, CAM messages are transmitted at the same rate and at the same time than CAM messages generated following the current ETSI rules. Average inter-packet gaps (IPG) are the same for both approaches, and they perform similarly on this metric at different densities, achieving the same performance due to the fact that transmissions happen at the same time, but ETSI CAM messages wait longer at the DCC queues. This waiting time is reflected on the Information Age metric, that shows the effect end-to-end delay has on the accuracy of the information a vehicle has about its neighbors. Furthermore, even the smaller differences in end-to-end delay seen at the two lowest densities (63 and 89 ms for densities of 10 and 20 veh/km per lane, respectively) give a better chance for the GNSS to provide a newer reading, even without position augmenting functions. Higher differences in end-to-end delay translate to errors that can affect safety, since the average end-to-end delay at the highest density is 302 ms, which for this scenario (with an average speed of 14.27 m/s) translates to an error of 4.3 m, above the required position accuracy of many safety applications [15].

IV. Conclusion

We presented an analysis of the effect of multi-traffic on the end-to-end delay and information age metrics of CAM messages, by providing an analytical model and empirical results. In the simulations, we used CAM generation following the rules established by ETSI, and CAM messages coexisted with lower-priority traffic. Due to the desynchronization between the CA service and t_{go}, caused by the transmission of different types of messages, the DCC mechanism causes CAM traffic to wait in the queue after being generated and before being transmitted, adding to both the end-to-end delay of a message and the age of the information neighbors have about a station.

To deal with this effect, we proposed GoT, an addition to the CAM generation algorithm where the Management entity from the ETSI ITS-G5 protocol stack provides the time of the next dequeuing event (i.e., t_{go}), in order to generate CAMs when the DCC mechanism allows their transmission. We demonstrated that the use of GoT lowers end-to-end delay and information age to a minimum, while keeping the frequency at which CAM messages are transmitted at the same rate as the ETSI standardized CAM generation algorithm.

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