2017 IEEE Intelligent Vehicles Symposium (IV)
June 11-14, 2017, Redondo Beach, CA, USA

Analysis of ITS-G5A V2X communications performance in autonomous cooperative driving experiments

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Abstract— **In this paper the performance of ITS-G5A communications for an autonomous driving application is analyzed in a real high-density scenario. The data was collected during the cooperative platooning tests that took place in Helmond in the frame of the Grand Cooperative Driving Challenge 2016. In the competition, between 8-10 autonomous vehicles formed two platoons in different lanes and were required to merge into a predefined competition zone. The performance is characterized using CAM CCDFs which serves as a base for the evaluation of a Cooperative Adaptive Cruise Control application. Two important effects has been identified that affect to the reliability of the communications. Firstly, there is a degradation with the distance that appears to be stronger for cars and more gentle for trucks. This indicates that occlusions heavily affect the connectivity of ITS-G5A. Secondly, the reliability is below expectations and some of the vehicles perform consistently worse than others. Although further investigation is required, a possible explanation for this is that a highly congested channel is making some of the vehicles get stuck and are not able to regularly access the channel.**

I. INTRODUCTION AND RELATED WORK

In the last few years, there has been a continuous increase in the number of Advanced Driver Assistance Systems (ADAS) that reach factory vehicles. Examples of these are the Pedestrian Protection Systems (PPS), Adaptive Cruise Controllers (ACC), Forward Collision Braking (FKW) or lane keeping systems. Commercial vehicles are incorporating more and more sensors every year (radar, ultrasound, cameras). It is only a matter of time that future vehicles will be equipped with advanced systems that allow inter-vehicular communication [1]. Sharing these sensors information could be beneficial for other vehicles on the road, however the communications requirements for cooperative perception and manoeuvring are yet to be understood in detail [2]. More importantly, mixed traffic environments where fully autonomous vehicles find standard vehicles pose a more immediate scenario for collaborative sensing and autonomous communicating vehicles.

In Europe, the ETSI TC ITS has been working over the last few years towards standardizing Vehicular Ad-hoc NETworks (VANETs) communications based on IEEE 802.11p [3]. As a result the ETSI ITS-G5 standardizes V2X communications for different applications. ETSI ITS-G5 operates int the 5.9 GHz band and allocates three different frequency ranges for safety related (G5A) and non safety related applications (G5B and G5C). This standard not only describes the physical and medium access control sub-layers but also the messages to be utilized. Two messages are currently in the standard:

- **Cooperative Awareness Message (CAM):** CAM is intended to inform about the current state of the sending vehicle (position, dynamics, geometry, etc.). Given the dynamic nature of some of the information contained, CAM messages are typically broadcasted as periodical beacons at 1-10 Hz.
- **Decentralised Environmental Notification Message (DENM):** DENMs are used to warn of asynchronous events such as road works, approaching emergency vehicles, accidents, etc.

Most of ADAS applications are safety-related; because of that, the studies about communications performance are also focussed on ITS5-GA and CAM messages. In [4] a very thorough study of communications and application level reliability for CAM messages is presented. The authors propose different tolerance levels for several safety applications and study the performance of the communications in a real environment with 3 vehicles. Their results indicate that the performance of the communications is adequate for their safety applications requirements. However 3 vehicles is a low congestion environment and their minimum temporal window for analysis was 0.3s which can be not enough for some safety applications. In [5] the authors analyse the performance of ITS-G5A on a simulator using a 6-lane highway with different vehicle densities and CAMs frequencies. Their results point to the channel load as a key factor in the performance of the ITS-G5A, reducing the reliability of the communications to intolerable levels when the channel load is high. Similar conclusions were reached in [6] where a cooperative positioning system based on GPS and VANETs was presented. In their simulations, it was observed that for high channel load scenarios the communications degraded to the point that they had to propose a mixed CAM transmission system in which smaller CAM messages with critical information were sent at ”full” rate (10Hz) and standard CAM messages at 2Hz, reducing the channel load to 8.4% from 40%. Other works have explored the posibility of improving the position estimation of vehicles using V2X in urban areas where GPS-based localization is not accurate [7].

Most of the work in performance analysis of ITS-G5 communications is based on simulations of tests with a few vehicles. In this paper we analyze the results of extensive experiments that collected real-world data from between 9

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and 12 vehicles equipped with ITS-G5A compliant V2X communication systems. The data was collected during 7 repetitions of the merging competition during the Grand Cooperative Driving Challenge 2016 (GCDC2016) that was held in Helmond, Holland. Our main objective is to stablish the reliability of the communications and to analize how the autonomous driving capabilities are affected in a real world and highly congested scenario.

The remaining of this paper is organized as follows: the experiments are described in Section II-A; then our implementation of ITS-G5A communications is introduced in Section II-B. The performance metrics used to evaluate the communications performance are explained in Section II-C. The results and discussion of the communications performance and its influence in the autonomous driving capabilities of DRIVERTIVE (DRIVErless cooperaTIve VEhicle) is described in Sections III-A and III-B respectively. Finally conclusions and future work are described in Section IV

II. EXPERIMENTAL SETUP

A. *V2X communications at GCDC2016*

The GCDC2016 is a project supported by the European Commission aimed to *'speed up real-life implementation and interoperability of wireless communication based automated driving'*. The focus of GCDC2016 was on cooperative aspects of automated driving, with the introduction of advanced platoon operations (merging of two platoons) [8]. To test such cooperative abilities, two scenarios were designed for GCDC2016: highway and intersection. In the *highway scenario*, two formed platoons in different lanes were required to merge into a predefined competition zone. Distance from other participants, gentleness of manoeuvres, reliability of communications and the ability to cope with unexpected situations were evaluated as part of the judging criteria. Each scenario was repeated several times (heats) and an average of the best performances was used as final technical score ([8] and [9]).

In addition to the standard messages, a non-standard one was introduced in the GCDC2016 to manage the interaction protocols between the vehicles and Road Side Units (RSU) during the competition: the iGame Cooperative Lane Change Message (iCLCM). In order to successfully complete the heats at the GCDC2016 the autonomous vehicles should, not only autonomously drive, but to cooperate with each other. The iCLCMs provided a mean for the vehicles to pair up, ask for permission to merge, declare that a merging was safe, and many other similar indications needed for the competition (see [9]). Due to the strict safety requirements of the GCDC2016 competition, CAM, DENM and iCLCM messages were broadcasted at 25Hz, more than twice the frequency required by the standard (10Hz).

In this paper, we will analyze the communications performance in the platooning scenario, when all the participants were transmitting. The platooning scenario started with two stationary aligned platoons; then one of the platoons started to speed up to 60Km/h. When a signal from a RSU was received the second platoon cached up with the first at a maximum speed of 80Km/h. Once both platoons were aligned they reduced their speeds to 40Km/h and the merging started. Table I summarizes the conditions of the experiments.

TABLE I
EXPERIMENTS CONDITIONS

Length of Highway	5km
Number of Lanes	2
Number of vehicles	8-10
Speeds	40-80Km/h
Mean distance	10m+0,9*speed(m/s)
Channel bandwidth	10MHz
Antenna Gain	9Db
CAM frequency	25Hz
iCLCM frequency	25Hz
DENM frequency	25Hz

B. *DRIVERTIVE's implementation*

The GCDC2016 communications architecture is based on the ITS-G5 V2V standard for V2X communications [10]. This standard uses the GeoNetworking protocol [11] for packet dissemination, the basic transport protocol (BTP) [12] for the transport layer and IEEE 802.11p for the physical layer [13]. This architecture was present in vehicles, as well as in Roadside Units (RSU).

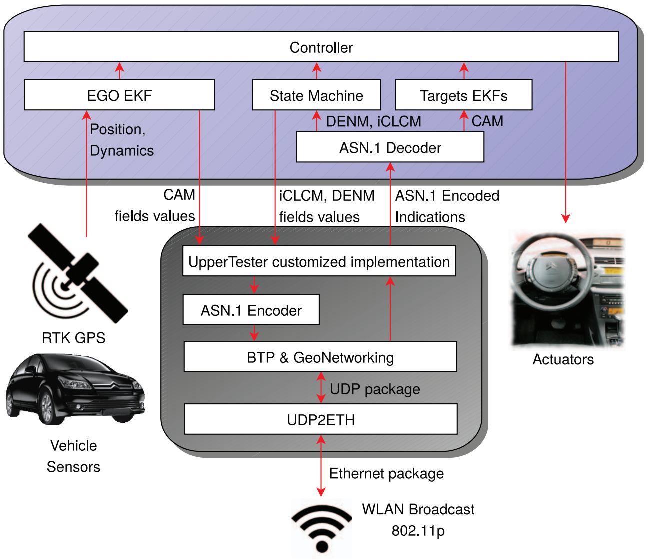


Fig. 1. Communications information flow: the blue box represents the vehicle controller's CPU whereas the black one is the APU1D communications box. Messages were exchanged between the vehicle's controller and the communication box using an UDP socket.

DRIVERTIVE's implementation of its communications system used an ALIX APU1D board running Voyage Linux as its hardware platform. An open-source implementation of Geonetworking [14] along with a customised version of UpperTester was used to connect the vehicle control-computer to the communications box via UDP (see Fig. 1). All of the information transmitted was encoded using

ASN.1. Our system decoded these messages using the open source ASN.1 compiler asn1c developed by Lev Walkin [15]. Finally, the UDP package generated by Geonetworking was converted to an Ethernet package using Jan De Jongh's udp2eth [16] and transmitted through the 802.11p wireless interface.

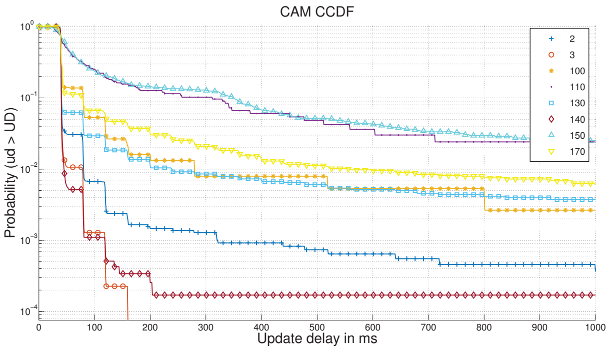
C. Performance metrics

Our main goal is to analyze the impact of Dedicated Short Range Communications (DSRC) performance on autonomous cooperative driving systems. Typical safety applications are based on the awareness about the state of the vehicles in their surrounding. One of the most used performance metric is the so called *update delay* (UD) [17] [18]. The UD measures the reception time difference between consecutive messages which is a good indicator of how updated is your information about the status of the transmitting vehicle. Usually an histogram of the UD is used to compute the Complementary Cumulative Distribution Function (CCDF) which represents the probability of exceeding a maximum update delay value. As many application level systems require a minimum update of the information, CCDF is used to determine the reliability of not exceeding a maximum update value. In addition, many of these applications depend, not only on the up-to-dateness of the information, but on the range at which it is available. There is no use for very updated information if it is only available within a few meters from the transmitter. To show the ranges at which the information is available the UDs are accumulated for different distance bins (in our case bins of 25m) and the mean, maximum and minimum values are shown for the different distances.

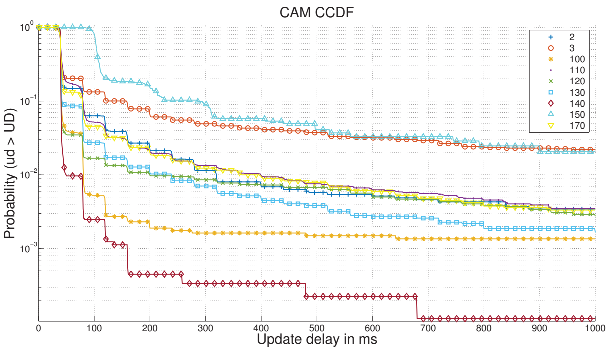
III. RESULTS

A. Communications performance

Fig. 2 shows the CCDF of the received CAMs from all the participants in a real highway scenario with 10 participants. The performance for the different teams is quite uneven: some of them show probabilities below 1% of missing one message, being normally the closest ones (see Table II); for the rest of them this probability is around 10% which is quite high. In Fig. 2a participants 150 and 110 response is not stepped indicating that probably they were not beaconing at the required frequency. There are 2 possible explanations for this degradation. First, the computation load on the vehicle can be interfering with the transmission of the beacons. Second, the Decentralized Congestion Control (DCC) mechanism specified by the ETSI recommends to scale the CAM transmission rate to 2Hz in order to not exceed 60-70% of channel load [6]. In GCDC2016 the CAM and DENM beaconing frequency was increased to 25Hz and a new non-standard message (iCLCM) was also transmitted at 25Hz. It is possible that what we observe is a congested channel that kept some of the participants continuously trying to access the channel, rendering them temporarily invisible to other vehicles [19].



(a) CCDF for the participants in heat 1



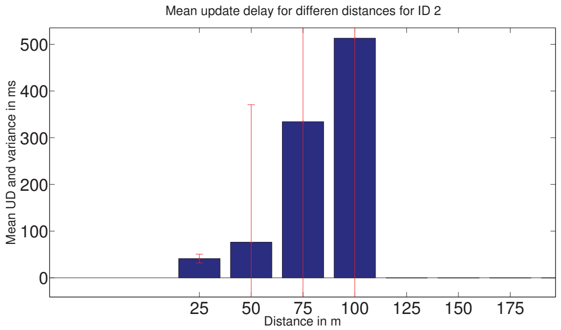
(b) CCDF for the participants in heat 2

Fig. 2. CAM CCDF for two heats of the GCDC2016. Participants 100 and 110 were trucks

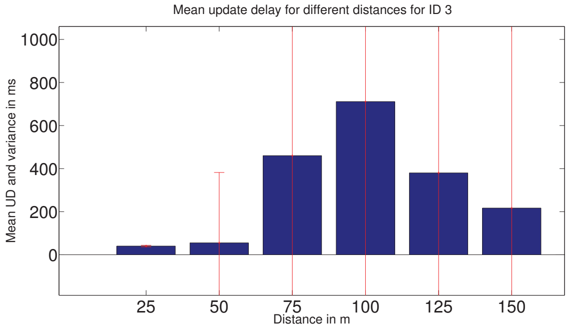
TABLE II
MEAN DISTANCE TO PARTICIPANTS

Participant ID	Heat 1	Heat 2
2	25.6m	57.46m
3	36.6m	38.9m
100	228.4m	66.6m
110	214m	113.1m
120	na	18.3m
130	124.9m	26.4m
140	20.6m	35.7m
150	133.8m	33.7m
170	29.5m	32.6m

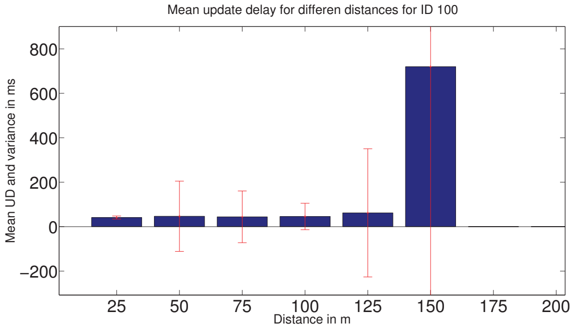
The CDDF alone does not illustrate the effect that distance had on the UD. To analyze this effect the UD has been accumulated into distance bins of 25 meters for the different participants and the mean and variance of the UD for the different beans computed. Fig. 3 shows the variation of the UD with distance for two cars (3a and 3b) and two trucks (3c and 3d). Trucks in the competition (ID's 100 and 110) carried the antennas at about 3 metres height while in the cars they were at about 1.5 metres. The UDs in Figure 3 for the cars show a high degradation of the reception as the distance increases, while for the trucks this effects appears further and smaller. One possible explanation is that occlusion introduces very high losses in the communications system, and the extra height of the truck's antenna allowed us to receive their signal free of occlusions up to a higher range.



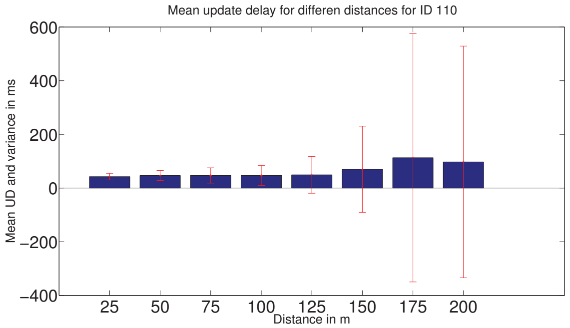
(a) UD Mean and variance at different distances for ID 2 (car)



(b) UD Mean and variance at different distances for ID 3 (car)



(c) UD Mean and variance at different distances for ID 100 (truck)



(d) UD Mean and variance at different distances for ID 110 (truck)

Fig. 3. UD Mean and variance at different distances for different IDs

In general, the performance of the communication systems was poor showing high probabilities of missing messages (see Fig. 2). However, this performance was not only heavily affected by the kind of vehicle (car or truck) and the distance. Some of the vehicles were consistently received with much higher reliability. One possible explanation for this is that the DCC in a highly congested channel is making some of the vehicles get stuck in *Restrictive* state [19] and are not able to regularly access the channel.

B. Application level: Cooperative Adaptive Cruise Control (CACC)

DRIVERTIVE's CACC allowed our vehicle to automatically follow one or more leading vehicles at a desired distance. In our experiments the GCDC2016 organization defined the desired distance as a fixed safety distance (r) plus a variable distance which depended on the speed of the host vehicle. This variable distance was defined as a constant (headway time th) multiplied by the speed of the host vehicle (v_h):

$$d = r + th \cdot v_h \tag{1}$$

Considering that the maximum speed was 80Km/h and the maximum allowed deceleration was $-4m/s^2$ we can simulate a worst case scenario in which both the leading and the host vehicle are driving at 80Km/h and the leading vehicle brakes with the maximum deceleration. In such scenario DRIVERTIVE would start braking at $-4m/s^2$ after the update delay time and the brakes activation delay time which includes processing and mechanical activation of the brakes. This brakes activation delay has been experimentally calculated to be around $400ms$.

Figure 4 shows the ratio between real distance and the desired distance (Eq. 1). A ratio greater than 1 means that DRIVERTIVE is able to brake and still maintain the desired distance. A ratio between 0 and 1 means that the desired distance is violated but there is no collision. A negative ratio means that DRIVERTIVE is not able to avoid the collision.

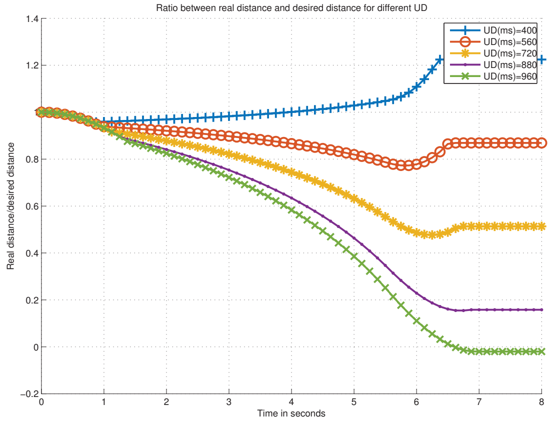


Fig. 4. Ratio between the real distance and the desired distance in an emergency braking situation for different update delays.

As shown in Figure 4 for UDs up to 400ms DRIVERTIVE is able to maintain the desired distance after a transitory violation. For UDs between 400 and 880ms the collision is avoided but the desired distance is violated. If the UD is above 880ms DRIVERTIVE would not be able to brake in time. Looking into Fig. 2 for the CCDF of the different heats we can find a minimum reliability for our CACC to be safe. Considering that for the critical situation ($UD > 880ms$) the probabilities are in the order of $[10^{-2}\,10^{-3}]$ we can conclude that the reliability in the application level is not enough for our particular CACC application. From an experimental point of view DRIVERTIVE successfully performed several CACC based only on communications information but only when 4 or less vehicles were transmitting. In the platooning scenarios the missing packets were too many to perform a gentle CACC and the information from a frontal RADAR had to be used to compensate for the packet loss.

IV. CONCLUSIONS AND FUTURE WORK

In this paper the performance of ITS-G5A for autonomous driving applications is analyzed in a real high-density scenario. The data was collected during the cooperative platooning tests that took place in Helmond in the frame of GCDC2016. First, the performance is characterized using CAM CCDFs which serves as a base for the evaluation of a CACC application. Two important effects have been identified that affect to the reliability of the communications. Firstly, there is a degradation in the UD with the distance that appears to be stronger for cars and more gentle for trucks. This indicates that occlusions heavily affect the connectivity of ITS-G5A. Secondly, the reliability is below expectations and some of the vehicles perform consistently worse than others. Although further investigation is required, a possible explanation for this is that the DCC in a highly congested channel is making some of the vehicles get stuck in *Restrictive* state and are not able to regularly access the channel.

In addition, the effect of this performance in a CACC application has been studied theoretically and confirmed with experiments. The reliability obtained from the experiments in the high-density scenarios is not enough to allow for the CACC system to work only relying on communications. However when the number of transmitting vehicles is reduced to 4 the CACC is able to work, indicating that the channel load is responsible for the low reliability.

ACKNOWLEDGMENT

This work was supported by Research Grants SEG-VAUTO S2013/MIT-2713 (Autonomous Community of Madrid), DPI2014-59276-R (Spanish Ministry of Economy), SPIP2015-01774 'Cooperative UAH Car' (General Traffic Division of Spain) and by MAPFRE Foundation under the research project 'Estrategias Cooperativas entre Vehículos Autónomos para la Reducción de Riesgos'.

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