Performance analysis of Vehicle-to-Vehicle communications for critical tasks in autonomous driving

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Abstract— **In this paper we present a series of experiments in order to gain insight about the performance of ITS-G5A V2V communications in critical scenarios for autonomous driving. Critical tasks such T-intersection managing in semi-urban environments or elevation changes in two ways inter-urban roads have been identified as challenging scenarios in which traditional sensor based approaches may fail. For this purpose, we designed a set of experimental tests in real environments with automated vehicles equipped with GPS, ITS-G5 compliant V2V communications, cameras and radars. Cameras and radars range is compared to that of the V2V communications in the designed critical scenarios and conclusions are drown. Packets Delivery Ratios (PDR) and the Complementary Cummulative Distribution Function (CCDF) of the Update Delay (UD) are used as metrics to evaluate the quality of the communications and to analyse the requirements of the possible automated driving applications. The obtained results show that ITS-G5 V2V communications offer better performance than on-board sensors in all cases, only being affected by occlusions with big obstacles such as buses or trucks.**

I. Introduction

Autonomous driving is a blooming topic among car makers and researchers across the globe. Despite the rapid technological development, there are still a number of open issues that have to be addressed before fully autonomous cars can robustly, safely and efficiently circulate mixed with manually-driven vehicles in real traffic. It is a widely accepted belief that cooperative automated driving will be far more robust than standalone self-driving. This cooperative driving can only come from the exchange of information between the driving agents, either active (communications) or passive (using sensors).

The so-called cooperative awareness problem can be solved from two different perspectives. Firstly, using on-board sensors such as cameras, LiDAR or radar. Secondly, endowing vehicles and infrastructure with V2X communications capabilities, sharing information between each other.

Both solutions are different in nature and have their own intrinsic limitations and strengths. On the one hand, sensor based solutions, are very demanding in terms of cost and computational power. The detection range of sensor based solutions is also usually shorter and the computational cost of the inference techniques needed to extrapolate the other driving agents intentions very high. As for the pros, the accuracy of the information is usually higher than those of communications based solutions, due to the redundant sensors and also its reliability, as the information is generated and transmitted inside the vehicle. On the other hand, V2X communications solutions suffer from latency or packet losses problems, compromising the accuracy of the measurements. Also, the reliability of the sources is another important problem. On the pros side, their associated costs are lower, their coverage is usually higher, and the communication may include richer information such as vehicle state, planned trajectory, etc. allowing cooperative driving and intention sharing. However, the communications requirements for cooperative driving are yet to be understood in detail [1] and further experimentation is needed.

Concerning enabling V2V communication technologies, although recent field test studies [2] [3] showed promising results of Cellular V2X radio technologies compared with Dedicated Short-Range Communications (IEEE 802.11p), DSRC/ITS-G5 still represents the most tested and consolidated technology for vehicular communications [4].

In Europe, there has been a considerable effort by the ETSI TC ITS towards the standardization of Vehicular Ad-hoc NETworks (VANETs) communications, based on IEEE 802.11p [5]. The result, ETSI ITS-G5, standardizes V2X communications for safety related (G5A) and non safety related applications (G5B and G5C) in the 5.9 GHz band. This standard describes not only the physical and medium access control sub-layers, but also the messages to be used:

- **Cooperative Awareness Message (CAM):** Typically broadcasted as periodical beacons at 1-10Hz. Contain information about the current state of the sending vehicle (position, dynamics, geometry, etc.).
- **Decentralised Environmental Notification Message (DENM):** Asynchronous warning notifications for events such as road works, accidents, etc.

In this paper we present a series of experiments in order to gain insight about the performance of ITS-G5A V2V communications in critical scenarios for autonomous driving. Critical tasks such T-intersection managing in semi-urban environments or elevation changes in two ways inter-urban roads have been identified as challenging scenarios in which traditional sensor based approaches may fail. For this purpose, we designed a set of experimental tests in real environments, with real vehicles equipped with GPS, ITS-G5 compliant V2V communications, cameras and radars. LiDAR perception was not included in the analysis due to its low resolution at long distances, clearly compromising its performance. Cameras and radars range is compared to that of the V2V communications in the designed critical scenarios and conclusions are drown. Packets Delivery Ratios (PDR)

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and the Complementary Cummulative Distribution Function (CCDF) of the Update Delay (UD) are used as metrics to evaluate the quality of the communications and analyse the requirements of the possible automated driving applications.

II. Related Work

Although a considerable number of works have been proposed concerning V2V-related applications [6], in this paper we only refer to those ones based on ITS-G5 technology and including experimental validation beyond simulation. Considering low-density traffic scenarios, in [7] the non-line-of-sight propagation was characterized at urban intersections. They found a reception rate above 50% for distances of 50m to intersection. In [8], reliable communications ranges were quantified at four different urban intersections under non-line-of-sight conditions using commercial interface cards which meet the ITS-G5 specifications. The achieved effective reliable communication ranges were found to be between 85m and 115m. In [9] highway merging lane scenarios were also tested. The effect of vegetation on the communication link in summer and winter seasons was studied in [10]. The effect of heavy traffic in a urban congestion environment was analyzed in [11]. Considering high-density scenarios, in [12], [13] the performance of ITS-G5A communications for autonomous driving applications was analyzed within the context of the second Grand Cooperative Driving Challenge (GCDC). Considerable limitations were found in both performance and reliability.

In this work, we will study what communications technologies can bring to autonomous driving in challenging scenarios, were traditional sensors may fall short.

III. Experimental Setup

A. Measurement Equipment

In the tests, two vehicles were used: A commercial Citröen C4 modified for autonomous driving (DRIVERTIVE) equipped with a Velodyne HDL-32E Lidar mounted on the roof, two high-speed FHD+ Bayer cameras (front and rear view), an ARS-308 Continental long-range radar mounted on the front of the car, two SRR-208 Continental wide-range radars mounted on the front lateral sides and a Trimble NetR9 Geospatial RTK DGNSS with an MPU6050 IMU (Fig. 1) [13] [14].

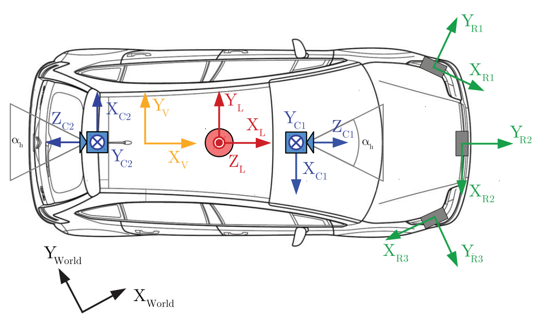


Fig. 1. DRIVERTIVE vehicle. In green the radars position, in blue the cameras position, in red the Lidar position and in yellow the RTK GPS position.

The second one is a commercial Toyota Prius equipped with Toyota Safety Sense package (ACC and LKAS) and access to CANbus (BANDIT) (Fig. 2). Both vehicles used ECO9-5500 omni-directional antennas mounted on their roof at approximately 1.5m above the ground. Its nominal gain is 9dBi and the transmission power was configured to 23 dbm.

Fig. 2. BANDIT vehicle.

The communications modules are based on ALIX APU1D boards running Voyage Linux. The wireless cards use Atheros AR9462 chipset. BANDIT's communications module logged the vehicle position from a Navilock NL-302U GPS. Drivertive's position was logged using an Extended Kalman Filter based on RTK and IMU fusion [13]. Using a modified Linux driver based on ath5k we configured the wireless cards to operate at 5.9 GHz in a 10 MHz channel using the OCB mode defined in 802.11p and needed for ITS-G5A [5]. Both communications boxes use GeoNetworking [15] protocol for packet dissemination, Basic Transport Protocol (BTP) [16] as transport layer and IEEE 802.11p for the physical layer [17]. Geonetworking was implemented using an open-source project [18] along with a customized version of UpperTester to connect the vehicles to the communications systems. All the transmitted information is encoded using open-source ASN.1 encoder by Lev Walking [19]. A flow diagram of the communications implementation is shown in Fig. 3.

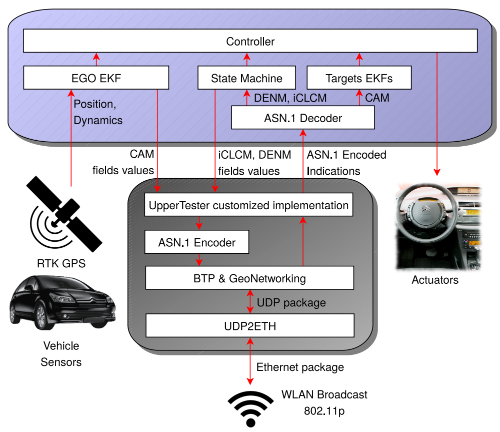


Fig. 3. Flow diagram of the communications system [12].

During the experiments, CAMs broadcast frequency was fixed to 10Hz which is the recommended by the standard.

B. Measurement Scenarios

Two critical tasks were identified were communications could complement or even substitute traditional sensors for autonomous driving.

*1) **Scenario 1 - Uncontrolled T-intersection with/without line-of-sight**:* In this scenario we analyze the required detection range for a safe and comfortable merge into the traffic at an uncontrolled T-intersection (Fig. 4). This is a challenging situation, specially at inter-urban environments where the incoming speeds are higher.

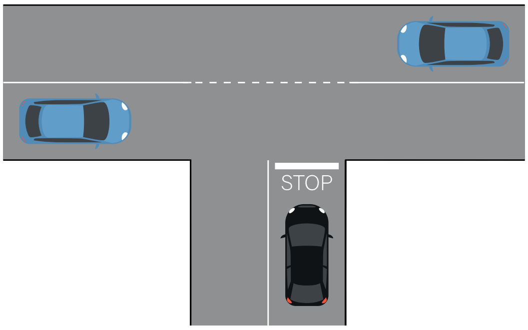


Fig. 4. Scenario 1: Uncontrolled T-intersections in inter-urban or semi urban environments.

Assuming line-of-sight, lateral high aperture radars usually have an effective detection range of approximately 50 m, which can be insufficient for this situations.

Figure 5 shows the distance run by two vehicles 50 meters apart. The first one starts 50 meters ahead of the second and drives with a constant acceleration ranging from $0.5m/s^2$ to $2m/s^2$ (the limit of $2m/s^2$ has been selected based on the maximum acceleration that DRIVERTIVE can deliver [13]). The shadowed area represents the distance run by the second vehicle starting at 0 meters and with a constant speed of between 20 and 50 Km/h (shadowed area).

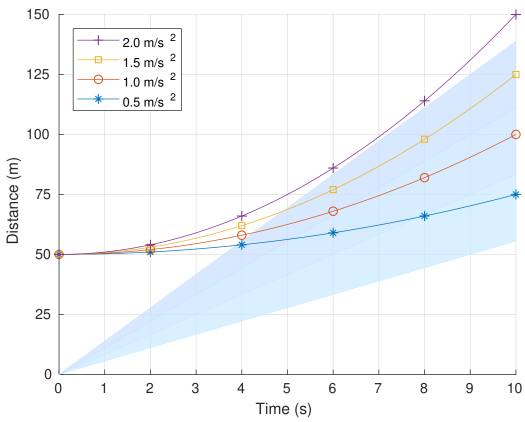


Fig. 5. Analysis of a T-intersections management. The shadowed area represents the distance run by a vehicle moving at constant speed of 20-50 Km/h. The lines represent the distance run by a second vehicle 50m ahead of the first one with a constant acceleration of 0.5-$2m/s^2$.

As can be seen, for incoming traffic at speeds above 30 Km/h the manoeuvre needs more than 50m of detection range for a safe and comfortable merging, even in this advantageous situation, where no merging manoeuvre is considered and the two cars start aligned.

*2) **Scenario 2 - High slope road with non-line-of-sight**:* Elevation changes in two-way roads are always a risky situation, even for human drivers. It is one of the most obvious situations in which V2V communications can provide an improved awareness of the incoming traffic. ITS-G5A works in the 5.9 GHz band which heavily suffers from non-line-of-sight losses. In this scenario our goal is to evaluate the improvement that V2V communications can provide (if any) over traditional sensors that also need line-of-sight such as radar or vision.

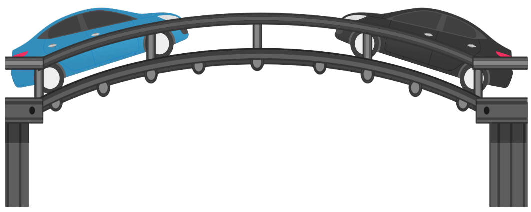


Fig. 6. Scenario 2: High slope road with non-line-of-sight.

In this scenario, additionally to an increase in the range of detection, V2V communications offer the advantage of providing richer information about the vehicles current and future trajectories in possible drifting into the opposing lane.

C. Experiments results

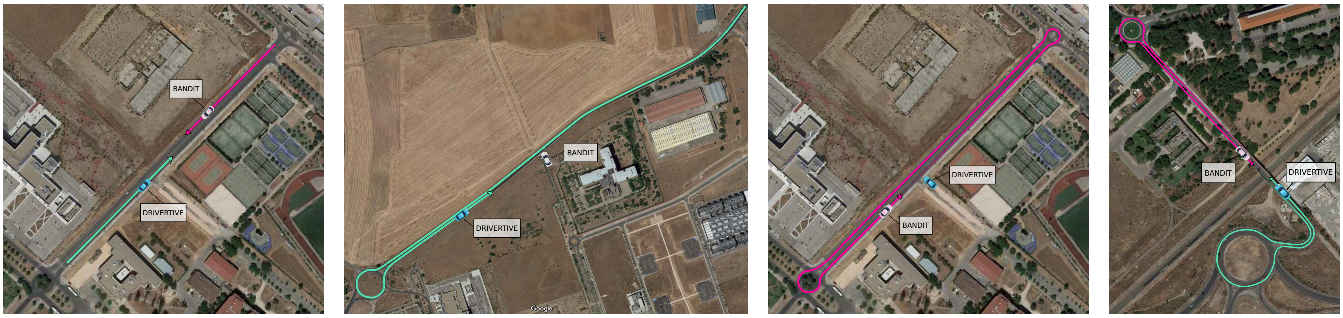
To evaluate the performance of V2V communications and compare it to radar and vision, four different experiments were performed:

*1) **Experiment 1 (baseline)**:* this experiment took place on a 350 m straight two-way street with a roundabout at each end (Fig. 7(a)). Both vehicles started stopped at one end of the street and drove towards the other side, crossing with the other vehicle in the process. This was repeated a total of 6 times in groups of 2 at speeds of 20, 40 and 60 Km/h. The purpose of this experiment was to evaluate the detection range of the different systems in close to ideal circumstances at different speeds. For the camera detections a YoloV3 [20] with a minimum confidence of 75% was used (Fig. 12). Table I shows the detection distances for the baseline scenario.

TABLE I
DETECTION DISTANCES FOR THE BASELINE SCENARIO

Experiment 1	Camera	Radar	V2V
20 Km/h	126.22 m	140.5 m	388.58 m
40 Km/h	110.78 m	145.22 m	368.78 m
60 Km/h	117.41 m	131.5 m	408.46 m

As expected, V2V communications shows the higher range with consistent detections along the whole scenario. The only

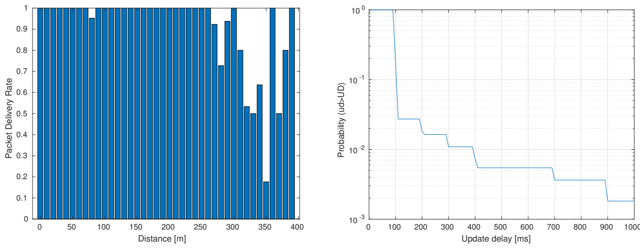


(a) Experiment 1 (Baseline) (b) Experiment 2 (c) Experiment 3 (d) Experiment 4

Fig. 7. Google Maps overlaid trajectories for the different experiments.

losses were produced when the line-of-sight was lost in the roundabouts. Maximum detection ranges for cameras and radars are approximately 120m and 140m respectively.

The performance of the V2V communications is shown on Fig. 8. The PDR was practically 100% up to 275 m where the PDR starts to drop due to non-line-of-sight in the roundabout. The probability of an UD higher than 200 ms (two consecutive packets loss) is slightly above 1 %, but again this is due to the packets lost at long distances with non-line-of-sight. We can conclude that for the baseline scenario the performance of the V2V is completely reliable.



(a) PDR (b) CCDF of the UD

Fig. 8. Packet Delivery Rate and Complementary Cumulative Distribution Function of the Update Delay for Experiment 1 (Baseline).

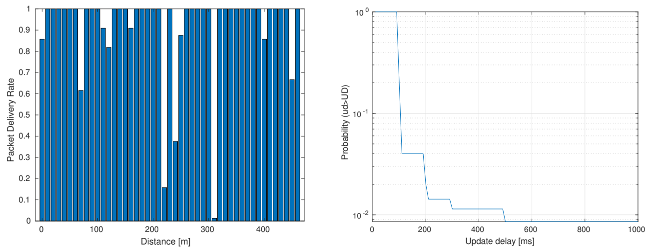
*2) **Experiment 2 (Scenario 1)**:* this experiment took place on an uncontrolled T-intersection on an interurban road (Fig. 7(b)). BANDIT was waiting to merge into the main road while DRIVERTIVE was driving towards the intersection at approximately 60 Km/h. This was repeated 2 times in each direction. BANDIT has only a forward looking Radar and camera, so no information about its ranges could be collected in this experiment.

TABLE II

DETECTION DISTANCES FOR THE SCENARIO 1 INTER-URBAN

Experiment 2	Camera	Radar	V2V
Left-Right 60 Km/h	n/a	n/a	468.81 m
Right-Left 60 Km/h	n/a	n/a	308.99 m

The detection range of the communications is practically the line-of-sight which is approximately 500 m to the left and 300 m to the right. When looking at the communications performance in Fig. 9 we can see that the PDR remains close to 1 as long as there is no interruption on the line-of-sight. The small valleys in 9(a) are due to vehicles blocking the line-of-sight. Similarly to the baseline experiments the UD for two consecutive packets loss is slightly above 1 %, but again due to the packets lost with non-line-of-sight. These results indicate that as long as there is line-of-sight, V2V communications are very reliable.



(a) PDR (b) CCDF of the UD

Fig. 9. Packet Delivery Rate and Complementary Cumulative Distribution Function of the Update Delay for Experiment 2 (Scenario 1).

*3) **Experiment 3 (Scenario 1)**:* this experiment took place on an uncontrolled T-intersection on an urban road (Fig. 7(c)). DRIVERTIVE was waiting to merge into the main street while BANDIT was driving towards the intersection. This was repeated 3 times in each way at speeds of 20, 40 and 60 Km/h respectively. In this case we can compare the V2V range detection with the short range radars mounted on DRIVERTIVE. The distance from the merging point to the roundabouts was approximately 180 and 230 m.

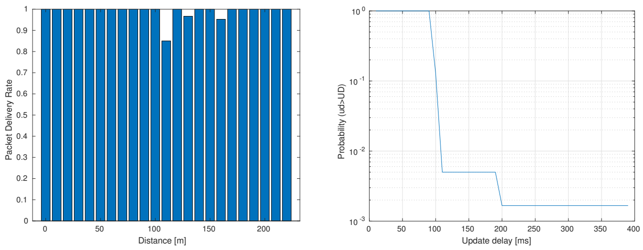
As can be seen from the results in Table III the ranges for the V2V communications practically matches the distances to the roundabouts, so it can be said that V2V communications covered the whole experiment distances. Short range radars performed as expected, given that their detection range is 50 m. As for cameras, and extrapolating from the baseline scenario we can see that for a line-of-sight scenario like this one they would have detected the vehicle at about 120 m in perfect circumstances. Again the range of V2V clearly overcomes any other sensor.

TABLE III

DETECTION DISTANCES FOR THE SCENARIO 1 URBAN

Experiment 3	Camera	Radar	V2V
Left-Right 20 Km/h	n/a	46.4 m	228.86 m
Right-Left 20 Km/h	n/a	48.0 m	187.53 m
Left-Right 40 Km/h	n/a	49.9 m	181.08 m
Right-Left 40 Km/h	n/a	45.0 m	161.24 m
Left-Right 60 Km/h	n/a	49.9 m	208.84 m
Right-Left 60 Km/h	n/a	45.0 m	206.90 m

Analysing the communications performance, Fig. 10 shows again that the PDR practically remains at 1 with the exception of some occlusions. The UD for two consecutive packets loss is approximately 1 %, but again due to the packets lost with non-line-of-sight.



(a) PDR (b) CCDF of the UD

Fig. 10. Packet Delivery Rate and Complementary Cumulative Distribution Function of the Update Delay for Experiment 3 (Scenario 1).

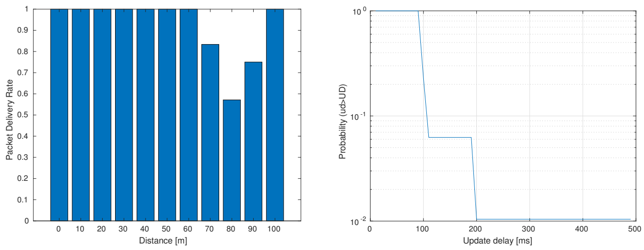
*4) **Experiment 4 (Scenario 2):*** this experiment took place on a rounded arched road bridge with non-line-of-sight (Fig. 7(d)). Each vehicle started at one side of the bridge and drove towards the other side, crossing with the other approximately at the top. This was repeated a total of 3 times at an approximate speed of 30 km/h. The detection ranges are shown at Table IV. In this experiment, DRIVERTIVE's frontal radar results are used as the detections occurred earlier than in BANDIT's radar. In this scenario, V2V communications also suffer from non-line-of-sight, but still can deliver long detection ranges, twice the detection range of the cameras. Radar detections are highly affected by the elevation change in the road, drastically reducing its detection range.

TABLE IV

DETECTION DISTANCES FOR THE SCENARIO 2 INTER-URBAN

Experiment 4	Camera	Radar	V2V
Pass 1	37.82 m	15.6 m	86.25 m
Pass 2	42.31 m	21.4 m	80.95 m
Pass 3	46.8 m	5.4 m	84.17 m

In this scenario, the communications performance shown on Fig. 11 was also very reliable, with a decrease in the range due to the elevation change of the road, but still outperforming the range of any of the other sensors. The range of the V2V communications was computed in a conservative way, although, as can be seen in Fig. 11(a), there are received packets above 100m. The UD for two consecutive packets loss is very similar to the other scenarios, approximately 1 % and again produced at longer distances.



(a) PDR (b) CCDF of the UD

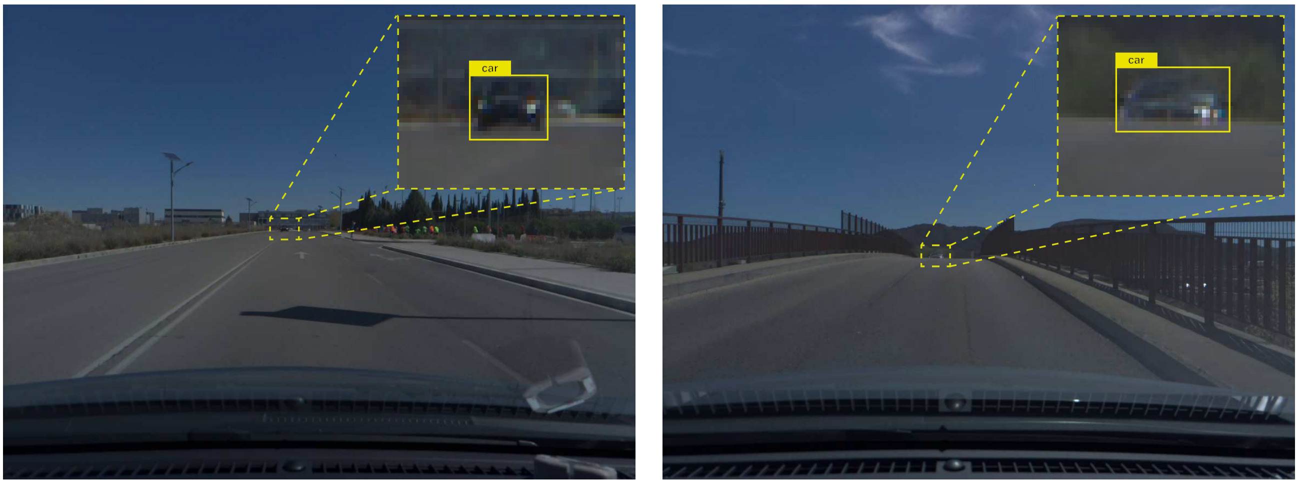
Fig. 11. Packet Delivery Rate and Complementary Cumulative Distribution Function of the Update Delay for Experiment 4 (Scenario 2).

IV. CONCLUSIONS AND FUTURE WORK

This paper presents an evaluation of ITS-G5A V2V communications reliability and range at critical scenarios for automated driving and compares the results to the most employed sensors such as radar or cameras. Two critical scenarios has been analysed: T-intersection in semi-urban environments and elevation changes in two-way inter-urban roads. To evaluate the scenarios, we designed a set of experimental tests with two automated vehicles equipped with GPS, ITS-G5 compliant V2V communications, cameras and radars. Packets delivery ratios PDR and the Complementary Cummulative Distribution Function (CCDF) of the Update Delay (UD) were used as metrics to evaluate the quality of the communications and analyse the requirements of the possible automated driving applications.

The results show that, for the line-of-sight scenarios V2V communications generally offer a longer range and reliability as expected. Some challenging situations such as merging into an inter-urban road, where the incoming vehicles speed is higher, may be managed with long range radars or cameras with optimal line-of-sight conditions. In these situations V2V communications have proven to be a valid alternative that can provide longer ranges and good reliability. In the elevation change scenario, V2V communications have shown twice the range of cameras and four times the range of radar. In addition, the information provided by V2V is richer in terms of inferring other vehicles future trajectories, which is a clear advantage to managing these elevation changes.

As future work, we plan to evaluate a planner for the automated merging manoeuvres studied in this paper with an without V2V communications. Also, we plan to study a head-on collision warning system based on V2V communications.



(a) (b)

Fig. 12. Yolo detections for Scenarios 1 baseline and Scenario 2 elevation change.

ACKNOWLEDGEMENT

This work was funded by Research Grants SEGVAUTO S2013/MIT-2713 (CAM), DPI2017-90035-R (Spanish Ministry of Economy), and BRAVE, H2020, EC Contract #723021. This project has also received funding from the Electronic Component Systems for European Leadership Joint Undertaking under grant agreement No 737469 (AutoDrive Project). This Joint Undertaking receives support from the European Union Horizon 2020 research and innovation programme and Germany, Austria, Spain, Italy, Latvia, Belgium, Netherlands, Sweden, Finland, Lithuania, Czech Republic, Romania, Norway.

REFERENCES

[1] G. Ozbilgin, U. Ozguner, O. Altintas, H. Kremo, and J. Maroli, "Evaluating the requirements of communicating vehicles in collaborative automated driving," in *2016 IEEE Intelligent Vehicles Symposium (IV)*, June 2016, pp. 1066–1071.

[2] 5GAA, "V2X Functional and Performance Test Report. Tests Procedures and Results," 2018. [Online]. Available: http://5gaa.org/wp-content/uploads/2018/11/P-180106-V2X-Functional-and-Performance-Test-Report_Final_051118.pdf

[3] Z. Amjad, A. Sikora, B. Hilt, and J. Lauffenburger, "Low latency v2x applications and network requirements: Performance evaluation," in *2018 IEEE Intelligent Vehicles Symposium (IV)*, June 2018, pp. 220–225.

[4] B. Masini, A. Bazzi, and A. Zanella, "A survey on the roadmap to mandate on board connectivity and enable v2v-based vehicular sensor networks," *Sensors*, vol. 18, no. 7, p. 2207, 2018.

[5] ETSI ES 202 663 v1.1.0 Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band. [Online]. Available: "http://www.etsi.org/deliver/etsi_es/202600_202699/202663/01.01.00_50/es_202663v010100m.pdf"

[6] J. E. Siegel, D. C. Erb, and S. E. Sarma, "A survey of the connected vehicle landscape-Architectures, enabling technologies, applications, and development areas," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 8, pp. 2391–2406, 2018.

[7] T. Mangel, M. Michl, O. Klemp, and H. Hartenstein, "Real-world measurements of non-line-of-sight reception quality for 5.9 GHz IEEE 802.11p at intersections," in *International Workshop on Communication Technologies for Vehicles*. Springer, 2011, pp. 189–202.

[8] H. Schumacher, H. Tchouankem, J. Nuckelt, T. Kürner, T. Zinchenko, A. Leschke, and L. Wolf, "Vehicle-to-Vehicle IEEE 802.11p performance measurements at urban intersections," in *2012 IEEE International Conference on Communications (ICC)*. IEEE, 2012, pp. 7131–7135.

[9] T. Abbas, L. Bernado, A. Thiel, C. Mecklenbrauker, and F. Tufvesson, "Radio channel properties for vehicular communication: Merging lanes versus urban intersections," *IEEE Vehicular Technology Magazine*, vol. 8, no. 4, pp. 27–34, 2013.

[10] H. Tchouankem, T. Zinchenko, H. Schumacher, and L. Wolf, "Effects of vegetation on vehicle-to-vehicle communication performance at intersections," in *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*. IEEE, 2013, pp. 1–6.

[11] Y. Shui, F. Li, J. Yu, W. Chen, C. Li, K. Yang, and F. Chang, "Vehicle-to-vehicle radio channel characteristics for congestion scenario in dense urban region at 5.9 GHz," *International Journal of Antennas and Propagation*, vol. 2018, 2018.

[12] I. Parra, A. García-Morcillo, R. Izquierdo, J. Alonso, D. Fernández-Llorca, and M. Sotelo, "Analysis of ITS-G5A V2X communications performance in autonomous cooperative driving experiments," in *2017 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, 2017, pp. 1899–1903.

[13] I. Parra, I. Rubén, J. Alonso, Á. García-Morcillo, D. Fernández-Llorca, and M. Á. Sotelo, "The experience of DRIVERTIVE-DRIVERless cooperaTIve VEhicle-team in the 2016 GCDC," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 4, pp. 1322–1334, 2018.

[14] R. Izquierdo, I. Parra, D. Fernández-Llorca, and M. A. Sotelo, "Multi-radar self-calibration method using high-definition digital maps for autonomous driving," in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, Nov 2018, pp. 2197–2202.

[15] "ETSI 102 636-1 v1.1.1 Intelligent Transport Systems (ITS); Vehicular Communications; Geonetworking; Part 1:Requirements." [Online]. Available: http://www.etsi.org/deliver/etsi_ts/102600_102699/10263601/01.01.01_60/ts_10263601v010101p.pdf

[16] "ETSI 102 636-5-1 v1.1.1 Intelligent Transport Systems (ITS); Vehicular Communications; Geonetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol." [Online]. Available: http://www.etsi.org/deliver/etsi_ts/102600_102699/1026360501/01.01.01_60/ts_1026360501v010101p.pdf

[17] "IEEE 802.11p Standard. Part 11: Wireless LAN Medium Access Control and Physical Layer Specification." [Online]. Available: https://www.ietf.org/mail-archive/web/its/current/pdfqf992dHy9x.pdf

[18] A. Voronov. Geonetworking. [Online]. Available: https://github.com/alexvoronov/geonetworking

[19] L. Walking. The ASN.1 C compiler. [Online]. Available: http://lionet.info/asn1c/blog/

[20] J. Redmon and A. Farhadi, "Yolov3: An incremental improvement," *arXiv*, 2018.