Demonstration and Evaluation of Precise Positioning for Connected and Automated Mobility Services

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***Abstract*—Cooperative, Connected and Automated Mobility (CCAM) services require precise and reliable localization services able to infer and track the position of a vehicle with lane accuracy. The H2020 5GCroCo project, which trials 5G technologies in the European cross-border corridor along France, Germany and Luxembourg, as well as in five small-scale trial sites, considers different technologies to enhance vehicle localization, including GPS-Real Time Kinematic (GPS-RTK), Ultra-WideBand (UWB) and Inertial Sensors (INS). This paper presents a compact prototype, which integrates these localization technologies with 5GCroCo's On-Board Unit (OBU) equipment, and its evaluation within the scope of the Anticipated Cooperative Collision Avoidance (ACCA) Use Case demonstrated in Barcelona small-scale trial site.**

I. Introduction

The seamless delivery of Cooperative, Connected and Automated Mobility (CCAM) services along different countries requires innovative solutions that support such a challenging multi-operator, multi-telco-vendor, and multi-car-manufacturer environment. The H2020 5GCroCo project[1] aims at validating advanced 5G features in cross-border scenarios, such as New Radio, MEC-enabled distributed computing, Predictive QoS, Network Slicing, and improved positioning systems, to enable innovative use cases for CCAM. 5GCroCo defines three use cases: Tele-Operated driving (ToD), High-Definition (HD) map generation and distribution for autonomous vehicles, and Anticipated Cooperative Collision Avoidance (ACCA)[1].

The ACCA use case aims to anticipate certain road hazards in order to reduce the probability of collisions, particularly in situations when these hazards are out of the field of view of the vehicle sensors. For this purpose, vehicles upload a set of information such as their vehicle status or detected events, which are processed by a service deployed in a distributed backend including MEC and public Internet hosting. It allows to build a situational awareness of the road in quasi real-time manner, and to notify vehicles about collision risks [1].

Enhanced precise positioning is a key feature to enable CCAM services such as ACCA, where lane accuracy is needed to provide an accurate situational awareness to the vehicles. Although a combination of Global Navigation Satellite System (GNSS) and Inertial Navigation Systems (INS) can satisfy most of the minimum requirements of the different use cases, in some locations where satellites cannot be easily tracked, like urban or rugged areas, it could lead to inaccuracies of several meters and significant latencies. In this sense, 5GCroCo analyzes three positioning solutions to enhance vehicle's location: 5G NR side-link, 3GPP GPS Real Time Kinematic (GPS-RTK) and Ultra-WideBand (UWB) [2]. This paper presents the evaluation performed in Barcelona small-scale trial site of two of these technologies, GPS-RTK and UWB, by means of a localization prototype connected to the On-Board Unit (OBU) equipment of the vehicles.

This paper is organized as follows. Section 2 introduces the ACCA cross-border deployment in the Barcelona small-scale trial site. Section 3 details the localization technologies that have been considered in this evaluation and the proposed approach. Section 4 describes the implementation carried out, which is evaluated in Section 5. Finally, Section 6 concludes the paper.

II. 5GCroCo Barcelona Trial Site

The Barcelona small-scale trial site is composed of a 5G neutral hosting platform deployed in the 22@ district, and a cross-border Internet Exchange Point (IXP) platform deployed in Castelldefels (at CTTC premises), 25 km south from Barcelona, as shown in Fig. 1. Both platforms are connected through a dedicated Ethernet/optical transport network.

The 5G neutral hosting platform can deploy multiple virtual mobile network operators (vMNO) emulating a typical cross-

[1] https://5gcroco.eu/

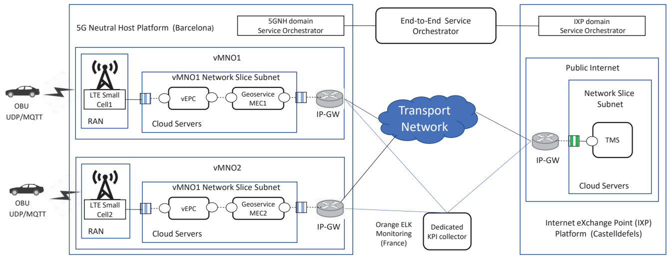

Fig. 1. Cross-border ACCA scenario in Barcelona trial

border scenario. It is based on ETSI NFV and Network Slicing and empowered by the intelligent combination of underlying controllers such as OpenSourceMano, OpenStack, and a proprietary Radio Access Network (RAN) controller. Each vMNO provides cellular connectivity to vehicles by means of three lampposts equipped with LTE small cells at 3.5 GHz (Band 42), and MEC services to host the edge part of ACCA backend software (i.e., Edge Geoservice).

Vehicles are connected to any of the two vMNOs deployed to emulate a cross-border scenario. The vehicles used in the Barcelona small-scale trial are equipped with an OBU which can be used as communications control unit in any vehicle or as vehicle emulator. Two different protocols are considered for the vehicles' communication with the backend: UDP (User Datagram Protocol) carrying ETSI-ITS encoded messages, and MQTT (Message Queuing Telemetry Transport) either also with ETSI-ITS payload or with JSON encoded messages.

The street cabinet is equipped with a MEC platform allowing to deploy the Edge Geoservice software (i.e., edge part of the ACCA backend) and the virtualized EPC (vEPC) for each vMNO. The Edge Geoservice is deployed by two applications, the Geoserver and the MQTT broker. The main task of the Geoserver is to gather awareness, perception and sensor information from vehicles and other IoT devices, consolidate them and evaluate potential hazards. The Geoserver manages directly hazard-related information from vehicles using UDP. It also connects to the Edge MQTT broker to synchronize hazard related data between different types of services (MQTT or UDP), and to the Central Geoservice to transmit and receive wider scope hazard-related data.

The cross-border IXP platform provides the physical infrastructure through which multiple vMNOs can exchange data traffic. The interconnection among the different vMNO operators, and the cloud servers is done through a software defined networking (SDN)-enabled switch. It is also offering public cloud services, deploying both virtual machines and containers. On top of the SDN orchestrator, we deploy an NFV service platform that interfaces with the SDN controller and the cloud controllers. The IXP platform deploys Central Geoservice applications, representing the centrally hosted part of the ACCA backend. This part includes services that do not need to be hosted at the edge and enables communication between edge servers in cases when they cannot directly communicate, as can be initially assumed for MECs operated by different MNOs. The Central Geoservice deploys the Traffic Management System (TMS) application, which is a complex distributed application that enables the monitoring, management and operation of large infrastructures.

The cross-border nature of the Barcelona pilot requires service orchestration procedures that allow to instantiate and operate end-to-end services across a multi-operator environment. It is performed by the 5GCroCo Cross-border service orchestration platform.

Finally, precise positioning is also implemented at the vehicle side and sent in the ETSI-ITS encoded messages to feed the ACCA services. Details of the positioning solution are provided in the following Sections.

III. Localization/Positioning techniques

Enhanced vehicular services such as ACCA require precise and reliable localization systems able to infer and track the position of a vehicle with lane accuracy. In this section, we detail the technologies that have been selected in 5GCroCo to be demonstrated in the Barcelona pilot [2].

A. Inertial Navigation System

INS is a relative positioning system. It does not require a specific infrastructure or a previous knowledge of the area where it is going to be used. INS is a sub-type of Dead Reckoning solutions [3], which only uses inertial sensors. Inertial Measurement Units (IMU) are composed by accelerometers and gyroscopes (to detect angular velocity) and, in some cases, magnetometers. The localization is performed by integrating the sensors' measurements over time and the target position is computed relative to the initial point (known position). The errors coming from the kinematic model and from the uncertainties of the sensor accumulate and grow with time, making the system drift. Therefore, INS is not suitable for long-distance operations. For this reason, it is usually integrated with other technologies such as GPS or UWB [4].

B. Global Positioning System

GNSS stands for the generic satellite navigation system, including GPS, Glonass, Galileo and Beidou. All of them provide geo-spatial positioning over the Earth determining information of latitude, longitude, altitude, velocity and time. The arrangement of the satellites ensures the visibility of at least four of them from any point in the planet and the positioning is achieved by trilateration. GPS is the most globally used, however standard GPS positioning provides accuracy ranging from a few meters to 20 meters, which is extremely low. Therefore, GPS is usually combined with INS to enhance its performance [5]. Moreover, current GNSS modules allow the use of multiple constellations, which makes possible to see more satellites and improve accuracy [6]. There are also other solutions, such as GPS-RTK that provide an enhancement of the accuracy.

Real Time Kinematics is a differential GNSS (DGPS) technique [5] that utilizes information from GPS base stations located at known positions to improve its accuracy. The architecture consists of a base station, one or several GPS users, and a communication channel to broadcast information in real time. Like DGPS, corrections are sent from the base station to the user to cancel the main errors. RTK improvements are based on the usage of carrier measurements to compute the range. These have a higher frequency and smaller noise, and therefore provide more precision, achieving centimeter level accuracy. Though RTK improves GPS performance, reaching a good position accuracy of centimeters, signal availability might still be a problem in urban environments, tunnels and in rural roads where satellite visibility cannot be guaranteed [6].

C. Ultra-Wideband

Ultra-Wideband technology is a wireless communication technique characterized by the use of a big bandwidth, low energy consumption and low power requirement. Obtaining this wide spectrum is possible by generating pulses of short duration (from picosecond to nanosecond) with a very low duty cycle. Short duration pulses enable a good precision in the time domain, achieving accurate distance measurements in the order of 10 cm [7]. UWB requires an infrastructure with reference nodes located at known positions (Anchors) and target nodes moving around (Tag). The Tag computes the distance to each of the reference nodes using Time Of Arrival (TOA), Time Differential Of Arrival (TDOA) or Two Way Ranging (TWR). The position is then calculated using trilateration.

TDOA is based on the difference in the arrival times of the signal from the transmitter node (Tag) to the multiple known-position infrastructure nodes (Anchors). It is an adequate solution in terms of scalability, but its implementation is complex for V2X services since it requires very precise clock synchronization between the anchors. TOA measures absolute Time of Flight (ToF) between the transmitter and the receiver, also requiring accurate clock synchronization in all the nodes. To minimize this requirement, TWR approaches are based on Round-Trip Time (RTT) measurements, which are simpler to implement. In this evaluation, an UWB solution based on symmetric double-sided TWR is used, which by exchanging 3 messages reduces the clock drift providing a better ranging accuracy [8].

UWB systems have specially addressed precise positioning in indoor scenarios. However there exists a rising interest for its application in vehicular use cases, motivated by the capabilities of the technology and the emergence of enhanced HW modules in the market (e.g. facilitating Angle of Arrival (AoA) estimations and supporting the IEEE 802.15.4z standard (2020) with improved features regarding integrity and accuracy). Some of these applications are secure keyless interaction, vehicle tracking [9], [10], automated manoeuvres [4] or autonomous driving [11].

[12] describes UWB EU regulation for location tracking purposes. It specifies strong limitation of the maximum value of mean power density and of the duty cycle. These restrictions limit the number of transmissions and therefore the frequency of positioning that could be achieved by stand-alone UWB solutions (which would be in the order or seconds). To improve the positioning rate, most of the existing approaches use it in conjunction with other on-board sensors such as GNSS receivers or INS, among others. The fusion is done by means of a Kalman Filter (KF) or an Extended Kalman Filter (EKF), albeit there are other options. [4] analyses a positioning system based on the fusion of UWB ranging estimates with odometry and INS data. The fusion is done by means of an EKF and has been tested with a Radio Control car (RC car) in an outdoor scenario. [9] presents a UWB/INS EKF loosely coupled solution validated with a real vehicle in a rural area. [10] investigates a tightly coupled GPS/INS/UWB solution with a Robust KF.

D. Our approach

This paper presents a compact prototype that implements three options for vehicle location: UWB stand-alone, UWB/INS with KF and GPS-RTK. UWB/INS with KF is implemented in a loosely coupled (LC) way, requiring prior positioning using UWB, therefore at least three anchors must be in range. This condition can be eluded in a tightly coupled (TC) system, where the trilateration is implicitly performed by the EKF. However, the LC approach has been chosen to minimize the complexity of the solution.

IV. Implementation

In the Barcelona trial site, apart from the network infrastructure described in Section 2, several UWB anchor devices powered by batteries have been installed at a height of 4 meters. These anchors have been programmed to respond to the localization requests of the UWB tag installed in the vehicles. Fig. 2 shows the vehicles and the infrastructure modules. In this Section we describe the elements that have been implemented in the prototype to enhance vehicle positioning in the ACCA cross-border scenario.

A. Localization prototype

The localization prototype is composed of the following elements: (a) Main computing and communications board based on a Raspberry Pi 4 device, (b) GPS-RTK module, (c) UWB module and (d) INS module.

The GPS-RTK module is composed by the GNSS Multi-band antenna ANN-MB-00 and the application board simpleRTK2B. It is connected through an USB interface to the main board. It is configured to receive corrections from a public NTRIP caster through the cellular network.

The UWB hardware module in both the location infrastructure (anchors) and vehicle (tag) is based on the In-Circuit radino32 DW1000, a fully integrated single chip UWB low-power and low-cost transceiver IC compliant to IEEE 802.15.4-2011.

The integrated IMU is the GY-521, a module based on the MPU-6050 sensor. It combines a 3-axis gyroscope and a 3-axis accelerometer on the same chip. For precise tracking, the gyroscope and accelerometer are full-range scale programmable.

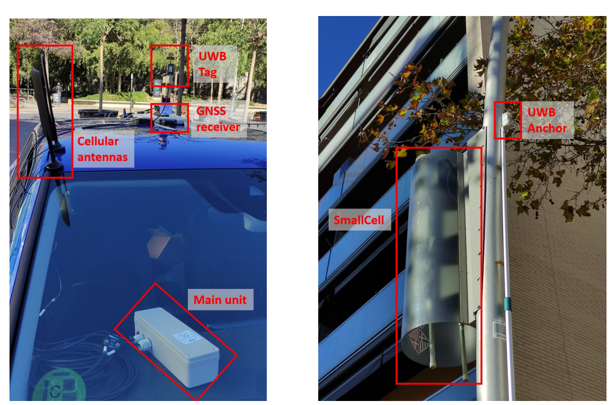

Fig. 2. Equipment installed in the vehicle and communications and positioning infrastructure

The reading of the values from the IMU is done through the Tag.

The system is implemented to obtain and log two kind of independent locations: (1) GPS-RTK measurements and (2) positions calculated by an hybrid UWB/INS algorithm based on KF. A GPSD server has been deployed to share the data in real time with the vehicle OBU through an Ethernet interface.

B. UWB/INS positioning algorithm

Fig. 3 depicts the block diagram of the positioning mechanism. The KF has two inputs: the UWB position and the acceleration measurements. As stated before, the integration is done in a loosely coupled way. The computation of the position is performed with trilateration using the Least Square Error method (LSE).

The LSE positioning block incorporates the detection of possible outliers or positions with higher error. Depending on the error grade, the position is discarded or introduced in the filter with a different noise factor. One of the parameters used to determine whether a position is precise or not is the estimated error of the LSE technique. After this processing, the computed localization is an input to the filter as a measure. INS measures are also pre-processed before being introduced into the filter. The frequency of UWB positions and INS measures is 1 Hz and 10 Hz, respectively. Since their frequencies are different, in the interval between UWB locations, the filter works only with INS measurements, and every second a new UWB position is entered to adjust the filter.

C. On-board unit equipment

The hardware components of the experimental OBU are illustrated in Fig. 4. The OBU is based on a laptop running on Ubuntu 18.04 and connected to an LTE AirPrime EM7565 modem from Sierra Wireless. The LTE connectivity provides the network-based vehicle-to-network (V2N) communication with the ACCA service, and it is connected to the OBU through a USB to mPCI adapter. The Localization prototype provides the real-time and enhanced positioning of the vehicle. At the same time, the OBU leverages the GPS-PPS based Network Time Protocol (NTP) service that runs on the Localization prototype. In this way, the OBU synchronizes its internal clock with the ACCA service. The CAN bus to USB adapter is used to connect with in-vehicle sensors and actuators network. The DC/DC converter facilitates the uninterrupted power supply to all the components of the OBU.

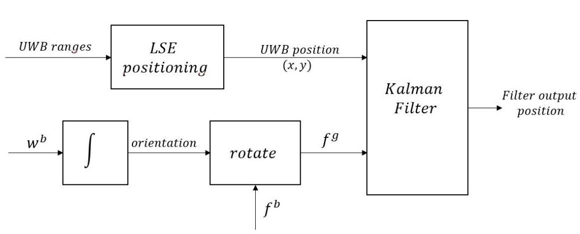

Fig. 3. Design of the UWB positioning KF. $\mathbf{w}^b$ are the angular velocities in body reference frame and $\mathbf{f}^b, \mathbf{f}^g$ are the acceleration forces in body and global reference frames, respectively

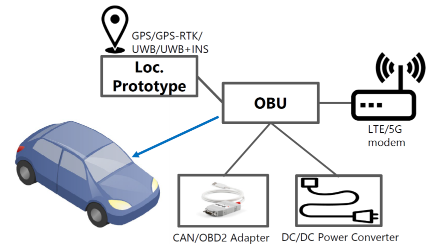

Fig. 4. Basic hardware components of the OBU.

V. Evaluation

A. Scenario

5GCroco Barcelona trial site tests have been performed in a real urban scenario with an intersection of two streets. In order to track the vehicle within the road, anchors have been installed along the whole path attached to city lampposts, ensuring that the UWB tag always detects at least three of them. Fig. 5 illustrates the path of interest (red line) followed by the car and the disposition of the anchors (yellow diamonds). A total of seven anchors have been deployed in this scenario, covering approximately 150 m. The aim is to study the impact of geometry, of the amount of active anchors and of the anchors' distance, on the precision needed for lane positioning.

To evaluate the different positioning solutions, a set of experiments have been carried out. First, the positioning accuracy of GPS-RTK and UWB stand-alone is analyzed. Multiple tests have been performed by foot (controlled scenario) following the lane delimitation mark depicted in the street, which has been used as reference. Then, real driving tests have been conducted with the system attached to the vehicle (as shown in Fig. 2) at a maximum speed of 30 km/h. In this case, it was not possible to determine a cm-precise baseline since the real trajectory followed by the car would slightly vary between consecutive tests, but a comparison between the localization of the two techniques is provided. Furthermore, an hybrid UWB/INS solution is compared to the UWB stand-alone one. Also, since the number of anchors would be a key point to reduce the infrastructure cost and improve the scalability of the system, this paper analyzes the impact of reducing them in the overall precision of the system.

B. Validation of the integration within the ACCA service

The OBU can readily be integrated into any vehicle and can be used as a driver-assistance system in collision avoidance use cases such as the ACCA service. It is equipped with a Human Machine Interface (HMI) with several functionalities,

Fig. 5. Pilot scenario and position of UWB anchors

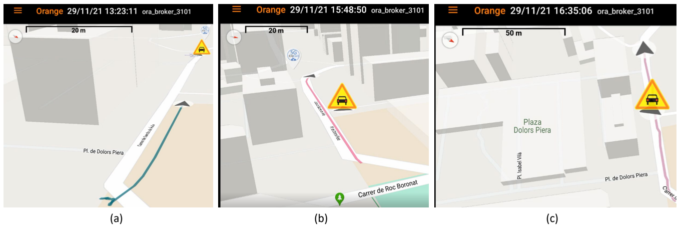

Fig. 6. Screenshots of Orange HMI during the trial using different positioning technologies (moving vehicle): (a) GPS, (b) GPS-RTK and (c) UWB/INS

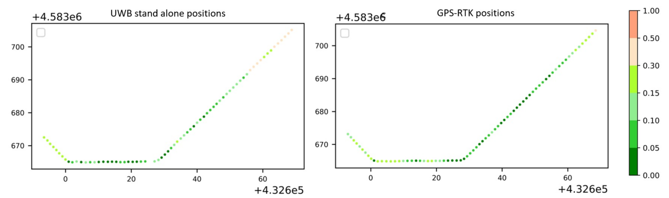

Fig. 7. Comparison of UWB and GPS-RTK. Controlled scenario (by foot). X and Y axes represent the UTM coordinates in meters. The color scale shows the error rate in meters of the position compared with the real trajectory.

including event-driven hazardous reports (DENMs) generation upon detection of roadside events such as stationary vehicle, collision risks, and accidents, as well as periodic safety messages (CAMs) generation based on ETSI ITS standard. The CAMs are transmitted periodically every 500 ms to the ACCA service.

First we validated the integration of the localization prototype within the ACCA subsystem by reproducing User Story 1 of 5GCroCo's ACCA Use Case [1]: a stationary vehicle sends Hazard Reports to the GeoService and a moving vehicle receives a Hazard Notification, being both vehicles connected to different MNOs. The performance of the ACCA system in this scenario was evaluated in a previous trial; the interested reader is referred to [13] for a detailed analysis of the selected KPIs, like application latency or reliability.

In this trial, we focused on validating the inclusion of the precise localization in the CAM message sent to the ACCA subsytem by the moving vehicle. For that purpose, we used the Orange HMI, which is a dedicated V2X Android application developed in-house by Orange that provides real-time remote monitoring of the ACCA system according to CAM and DENM messages. Fig. 6 shows the position and the path of the vehicles involved in the trial during different experiments. The figure evidences differences between the localization accuracy of the different technologies, as will be analyzed in detail in the following sections.

C. Analysis of positioning results

In this section, the results of the different tests will be presented and analyzed. To determine the suitability of the solution for precise localization in urban scenarios, a threshold of 30 cm error is established. [14] describes the derivation of this constraint depending on the vehicle and road width.

1) Positioning precision: Fig. 7 illustrates the positions computed by GPS-RTK and UWB stand-alone in the controlled scenario (road lane delimiter). The color of each point determines the precision of the position in comparison with the real trajectory.

TABLE I. ACCURACY EVALUATION

Error (m)	UWB	GPS-RTK
Max	0.47	0.36
Min	0.00	0.00
Mean	0.14	0.11
Std	0.10	0.07

Table I shows the error study for both techniques. Based on the obtained values, GPS-RTK provides a slightly better and more stable performance. However, it is important to state that even though GPS-RTK is in general more accurate than UWB stand-alone, some exceptions have been observed. In some of the tests, an absolute error of 3.50 m has been detected, though having a good GPS-RTK quality. Moreover, in urban/suburban scenarios low satellite visibility situations or multipath situations might be common, due to the presence of narrow streets, high buildings or tunnels. In these cases, the performance showed by UWB states it as an interesting alternative for precise positioning.

2) Analysis of the UWB/INS fusion: Tests have been performed with the system installed in a vehicle driving at a maximum speed of 30 km/h to analyze the performance of stand-alone UWB, hybrid UWB/INS and GPS-RTK. As the measurements obtained with GPS-RTK in the controlled path have shown to be accurate, they have been used as a baseline for the comparison of UWB stand-alone and hybrid UWB/INS. Fig. 8 shows the graphical representation of the error of each location and Table II contains the analytical values.

On the one hand, comparing the UWB stand-alone results by foot and at driving speed, it can be seen that the obtained error figures are similar. This means that the fact of increasing the speed does not have an impact in the performance of the solution. On the other hand, when a KF is created to fuse the values of acceleration with the UWB positions, the maximum of the errors increases, in comparison to UWB stand-alone. This behavior can be explained from the fact that in the interval during two consecutive UWB samples (1 second), the system relies on the INS values, which with time can lead to a drift. However, attending to the mean and the standard deviation it can be determined that maximum errors happen in specific

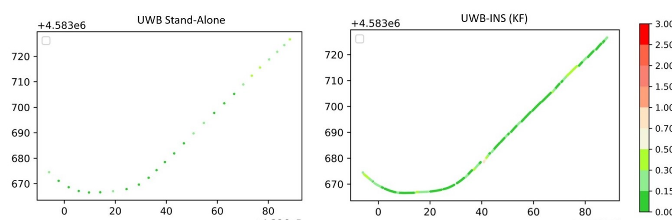

Fig. 8. UWB/INS accuracy at driving speed. X and Y axes represent the UTM coordinates in meters. The color scale shows the error rate in meters of the position compared with the real trajectory.

TABLE II. UWB VS UWB/INS ACCURACY (DRIVING SPEED)

Error (m)	UWB Stand-alone	UWB/INS
Max	0.49	1.18
Min	0.00	0.00
Mean	0.13	0.17
Std	0.11	0.16
Mean nº samples/test	29	297

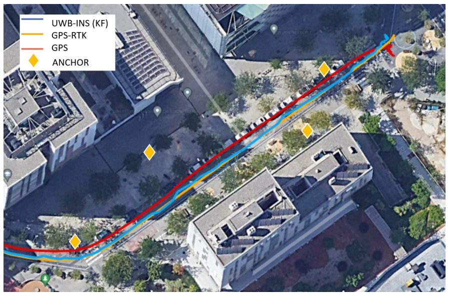

Fig. 9. Scenario with optimized infrastructure

TABLE III. COMPARISON OF UWB/INS AND AUTONOMOUS GPS VERSUS GPS-RTK. OPTIMIZED INFRASTRUCTURE SCENARIO

Error (m)	UWB/INS	GPS
Max	1.18	3.63
Min	0,00	0.93
Mean	0.20	2.46
Std	0.18	0.74

situations. In general, the use of hybrid UWB/INS shows an adequate performance for lane detection applications, with the 83% of the positions within the 30 cm error threshold.

Moreover, Table II also indicates the mean number of samples per experiment with each positioning method. The use of hybrid UWB/INS solutions allows a higher positioning rate (10 Hz), in comparison to the UWB stand-alone solution (in this case, 1 Hz), that can be combined with a higher frequency of CAM messages to enhance the performance of CCAM services such as ACCA. As shown in Fig. 8, hybrid UWB/INS solutions would permit to build a better representation of the path followed by the vehicle.

3) Optimization of the number of anchors: This subsection studies the feasibility to optimize the amount of anchors deployed in the scenario, without compromising the precision of the positioning. For this purpose, different geometries of the anchors have been studied, by deactivating some of the deployed anchors. The best combination is presented in Fig. 9, which results in a minimum set of four anchors.

In these experiments, autonomous GPS reception (without GPS-RTK) was also tested to reflect the positioning performance that might be achieved with conventional GNSS receivers. Fig. 9 shows the position of the four anchors and the resulting tracked path for GPS, GPS-RTK and hybrid UWB/INS. As it can be observed, the trajectory of GPS-RTK and UWB/INS is quite similar and accurate, locating the vehicle in the road, while GPS track surpasses the road limits. The mean error and the standard deviation (Table III) of the hybrid UWB/INS solution have increased slightly compared to the 7-anchors case, While the maximum error is maintained. The accuracy of the system is still below 30 cm for 75% of the cases, which could still be an acceptable trade-off for reducing the infrastructure. The comparison of autonomous GPS versus GPS-RTK leads to differences between 0.93 m and 3.63 m, with an average close to 2.5 meters, what corroborates that the system can hardly be used for ACCA services.

VI. CONCLUSIONS

The results of the 5GCroCo trial performed in Barcelona small-scale test site state the feasibility of using GPS-RTK and UWB-based approaches for accurate positioning in advanced CCAM services such as ACCA. The evaluation shows that both approaches obtain an adequate performance for lane detection applications. The performance achieved with UWB technology is comparable to GPS-RTK results, especially when combining with INS in the hybrid approach; thus, the solution can be considered as an alternative or complement for vehicular positioning in areas where GPS-RTK cm-accuracy is not reliable or not possible (e.g. inside of tunnels) or in critical places where driving safety needs to be reinforced.

Finally, looking into a near future, according to [15] by 2025 around 25% of cars will come equipped with UWB access technology and 1/3 of smartphones will incorporate UWB radio. This would facilitate the implementation of UWB-aided vehicular positioning/location applications among vehicles, making it possible to relax infrastructure requirements. Furthermore, UWB-enabled devices would allow to easily incorporate pedestrians and Vulnerable Road Users (VRUs) as actors/consumers of enhanced vehicular services/applications.

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