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5G Connected Vehicle and Roadside Infrastructure for Advanced Driving Maneuvers in a Cross-Border Scenario

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Abstract

The adoption of 5G cellular communications enables advanced V2X use cases, namely ones involving detailed HD-Maps and real-time holistic sharing of vehicle positions and status between autonomous, connected and even legacy vehicles. The 5G-MOBIX project explores the implications of such use cases. This paper presents the Portuguese 5G Connected Vehicle and Roadside Infrastructure that was developed for supporting the 5G-MOBIX project cross-border trials between Spain and Portugal. The paper details the architecture of the 5G Connected Vehicle and Infrastructure, the technology used, how integrations were achieved and how these CCAM solutions enable the use cases of the 5G-MOBIX project cross-border trials between Spain and Portugal.

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1. Introduction

The adoption of 5G cellular communications enables a series of advanced V2X use cases involving vehicle, road infrastructure and cloud communications that were previously unattainable, e.g., the 5G architecture allows for large enough bandwidths to transfer live HD-Maps between connected vehicles and the cloud. These maps offer near real-time road descriptions, with centimeter-level detail. Furthermore, the achievable low latencies of 5G enable real-time position and status exchange between connected and autonomous vehicles. Moreover, traffic radars can retrofit this

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information for legacy vehicles too. The afore-mentioned use cases are precisely the focus of the Portuguese 5G Connected Vehicle and Infrastructure in the 5G-MOBIX project, which this paper will briefly present.

The 5G-MOBIX project is expected to actively contribute to produce sustainable business models for the deployment of 5G for the road transport sector, as well as to standardization and spectrum allocation activities. This European initiative promotes the application of 5G technology to the most demanding applications in Intelligent Transport Systems (ITS) and Connected and Automated Vehicles (CAV) / Cooperative Connect Automated Mobility (CCAM), that cannot be supported by previous generations of communication technologies. This is done in real European roads and highways but not only there. 5G-MOBIX is developing two 5G-enabled cross-country corridors between Spain-Portugal and Greece-Turkey, and six national trials in France, Netherlands, Germany, Finland, China and Korea [1]. The national trials developed, tested, and demonstrated several 5G CCAM solutions, like remote driving and service discovery [2]. A wider set of 5G CCAM applications are being tested at the cross-country corridors, benefitting from the accumulated knowledge from the national trials, and allowing for comparisons and benchmarking. This article reports on the 5G CCAM applications implemented for the Spain-Portugal (ES-PT) corridor trials happening in the spring of 2022, and the technological solutions created by the Portuguese partners to support it. The next section presents the implemented 5G Use Case scenarios. Following that, the Portuguese 5G Connected Infrastructure and the Portuguese 5G Connected Vehicle are presented. Then, preliminary results on connectivity and latency results are summarized. And at the end, some conclusions are drawn.

2. ES-PT Cross-Border Corridor Use Cases

The ES-PT corridor stretches from Vigo to Porto and is comprised of roads and highways in Spain and Portugal [Figure 1 – (a)]. Cross-border activities in this corridor are centred around the northern border of Portugal with Spain, near the cities of Valença and Tui. This cross-country trial includes Advanced Driving, Remote Driving and Vehicle QoS (Quality of Service) support use cases. Adding to the inherent requirements and complexity of each use case, the cross-border trial adds the need for 5G handover between countries. The focus of this article is on the Advanced Driving use cases. These are comprised of 3 distinct driving scenarios: Overtaking, Lane Merge and HD-Maps, where 5G based vehicle communications are the key to road safety, namely when autonomous vehicles are involved.

In the Overtaking scenario, an autonomous vehicle needs to overtake a non-connected vehicle ahead of it. The non-connected / legacy vehicles on the right lane, after and before the autonomous one, do not allow the autonomous vehicle sensors to detect the other vehicles on the left lane. By having the vehicles on the left lane communicating their positions through the 5G network, the autonomous vehicle can perform the overtaking maneuver safely.

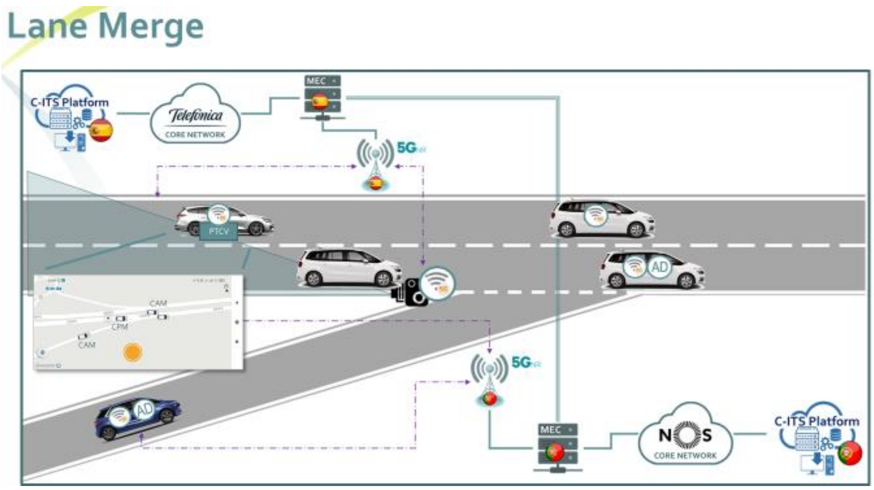


Figure 1 - (a) ES-PT cross-border corridor [3]; (b) Schematic of the Lane Merge scenario.

In the Lane Merge scenario, an autonomous vehicle (blue vehicle in Figure 1 – (b)) needs to merge onto the main road where non-connected / legacy and connected vehicles are coming from. The geometry of the lane entry doesn't allow the autonomous vehicle sensors to detect the upcoming vehicles. A 5G connected radar covering the main road sends the live positions of upcoming vehicles to the network and thus the autonomous vehicle, subscribing these positions, is able to merge the lane autonomously in safety.

In the HD-Maps scenario, an autonomous vehicle approaches an uncharted obstruction zone. For this reason and to ensure the vehicle safety, it switches to manual driving mode but uses its sensors to collect information about the obstructed area and sends it to the cloud, where an updated HD-Map is then built using artificial intelligence techniques. With the updated map delivered to other autonomous vehicles on time, they can remain autonomous while driving through temporary obstacles such as roadworks, minimizing human intervention. Connected Vehicles (CV) can also use the HD-Map to warn the driver about the situation and present him the obstruction in detail, helping the driver plan a safe diversion maneuver.

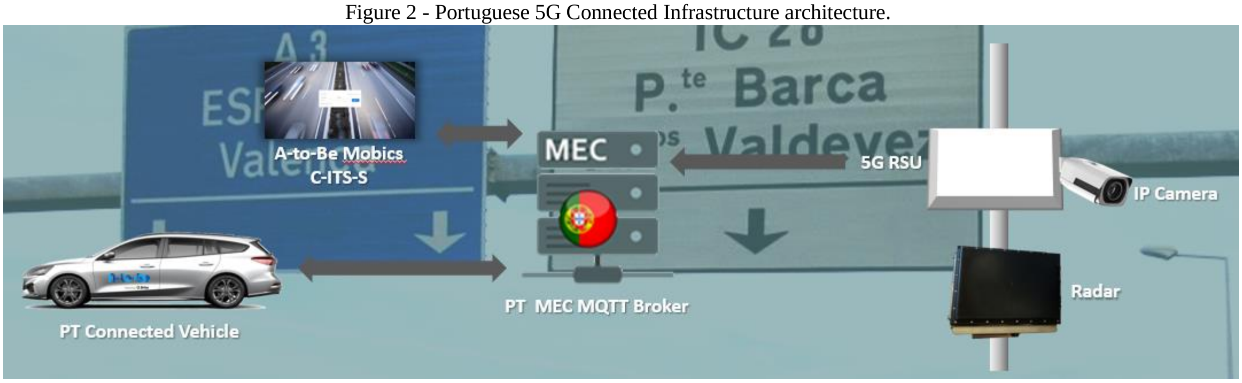
3. Portuguese 5G Connected Infrastructure

3.1. Architecture and the C-ITS Centre

The Portuguese side of the ES-PT 5G-MOBIX Cross Border Corridor (CBC) provides a fully working 5G V2X architecture, going from a cloud Cooperative-ITS (C-ITS) Centre to a 5G connected vehicle, and including a 5G Roadside Unit (RSU), a Radar and a Message Queuing Telemetry Transport (MQTT) broker, hosted at a 5G Multi-access Edge Computing (MEC) node. The MQTT broker at the MEC acts as the central part of this architecture, with each of the other components communicating through it, as illustrated in Figure 2.

The 5G RSU equipped with a traffic radar produces CPMs (Collective Perception Messages) [4] that can be used by the connected and automated vehicles to know the location of other vehicles, including non-connected ones. This information needs to arrive in real-time, to promote the most correct decisions of autonomous vehicles and human drivers. Connected and autonomous vehicles are also continuously sending Cooperative Awareness Messages (CAMs) [5] in order to provide their current location and other status data. These CAMs are used to display the location and status of CAVs, complementing the information from CPMs.

Figure 2 - Portuguese 5G Connected Infrastructure architecture.



3.2. MEC Broker and GeoServer

This subsection describes the MQTT brokers and GeoServers in the ES-PT CBC MECs. To exchange messages between connected network devices, such as vehicles, roadside infrastructure, or ITS Centres, MQTT brokers are installed in each side of the ES-PT border. There is one broker in the ES MEC node and another one in the PT MEC, as shown in Figure 3 – (a).

The messages published on the brokers are organized by topics according to each message type: CAM, DENM, CPM or MCM (Manoeuvre Cooperation Message) [10]. Besides the MQTT broker itself, there is also a GeoServer application running in each MEC node, which is responsible for handling the messages published by all connected elements. The strategy used to distribute only the relevant information to each subscriber is to split the map into geographical tiles or quadtrees. As a result, the broker topics names are defined as follows: **<general_topic_header>/<message_type>/<tile>/<StationID>**.

The tiling structure allows the calculation of the relevant geographic tiles for a specific location. The maximum level of zoom used in the project is 18, corresponding approximately to a 150-meter square tile side. The quadtree to publish in will be computed by the connected device (vehicles, RSUs, etc.) based on the position of the cooperative alert/message that is needed to notify.

These messages are published in the in-queue topics of the broker, for instance:

its_center/inqueue/cam/0/3/1/3/3/2/2/1/3/3/2/3/2/3/3/3/3/3/986

After the messages are published to the broker, they will be received and processed by the GeoServer application that subscribes to all in-queue topics. Then, the GeoServer calculates the adjacent tiles, and republishes the message in all of them, making it available for the connected vehicles that are in that tile surroundings (Figure 3 – (b)). However, in this case, the messages will be published in the out-queue topics. For their part, vehicles and Vulnerable Road Users (VRUs) will dynamically subscribe to the topic corresponding to the tile they are currently in. This way they receive the C-ITS messages from that tile and its adjacent ones. This option was selected instead of relying on vehicles' subscriptions to the tiles they judge of interest, because the GeoServer has a more general overview of the traffic system and thus, can better manage the publishing tiles to fulfil specific message dissemination purposes.

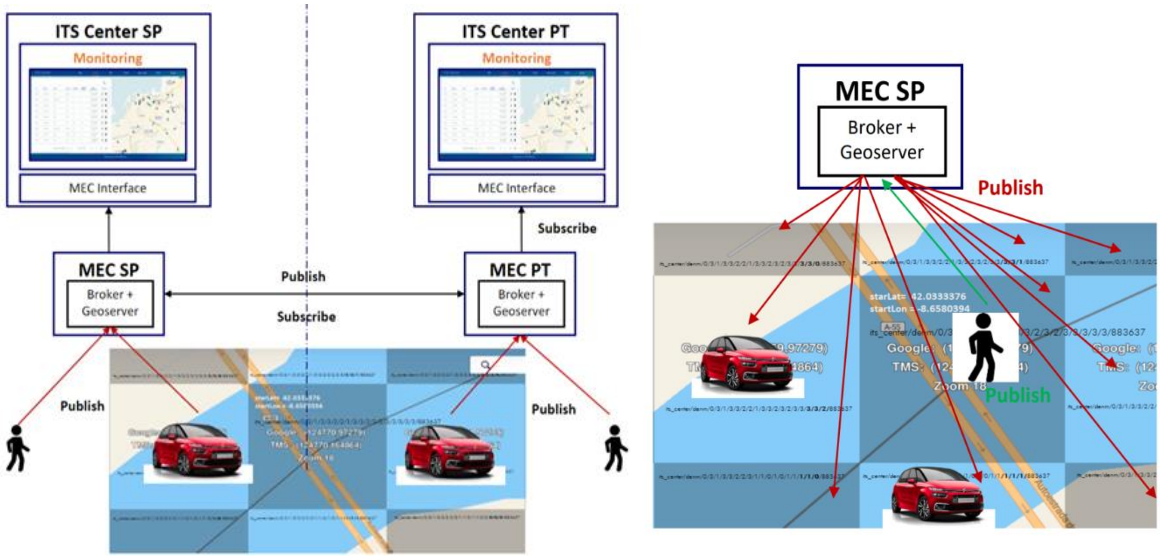
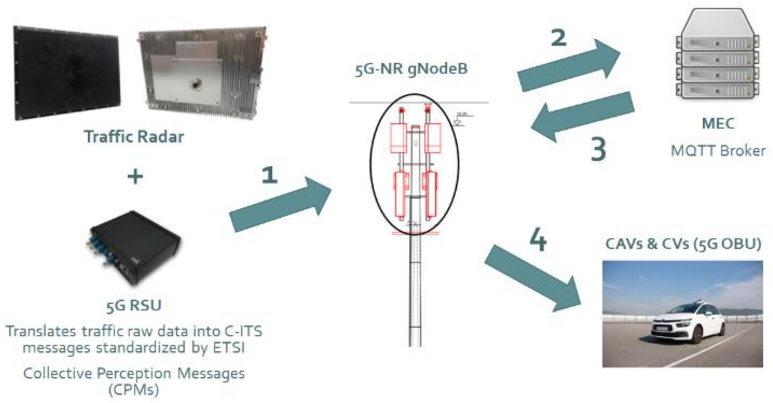


Figure 3 - (a) MEC Brokers and GeoServers in ES-PT CBC; (b) GeoServer republishing strategy.

There is also exchange of messages between MEC nodes, to provide service continuity in the cross-border areas, so that vehicles and VRUs connected to one of the MQTT brokers can also receive information published in the broker of the other country. This interconnection is attained through the GeoServer application that subscribes to specific topics called "inter_mecs" in the other's country MQTT broker and republishes those received messages in outqueue topics of the co-located broker. This is a simple but efficient solution for inter-MEC connection.

3.3. 5G Roadside Unit

The role of the 5G RSU is to translate the raw detection data from the traffic radar into CPMs, and forward them to the MEC broker, where all information can be accessed by the vehicles and the ITS Centre. Figure 4 – (a) presents the complete data flow between the traffic radar and the CAVs & CVs.



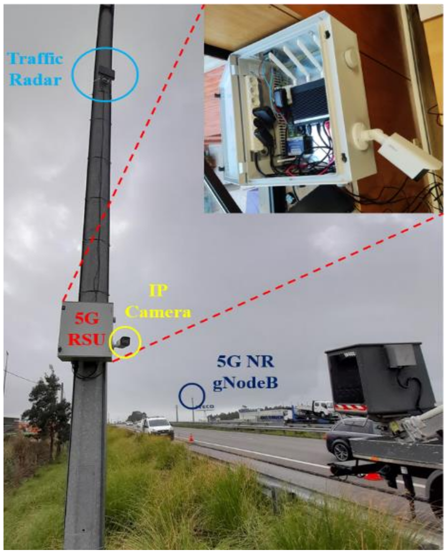


Figure 4 - (a) Message flow from the 5G RSU to the CAVs.; (b) Roadside infrastructure equipment installed on A28 highway near Porto.

The data flow is as follows:

1. The 5G RSU receives the traffic raw data from the radar and uses it to compose CPMs that are sent via the 5G modem to the 5G - New Radio (NR) base station (gNodeB).
2. These messages travel from the gNodeB to the MQTT broker located in the PT MEC, being published in a specific topic dedicated to CPMs.
3. A Geoserver service located in the MEC broker publishes the incoming messages in the outqueue topic (following a geographical tiling scheme), forwarding the messages to the adjacent areas of the sender's location and other interconnected brokers (in this case the Spanish one). This way, the CPMs also become available to the vehicles connected to the ES MEC broker.
4. The connected automated vehicles subscribe to the MQTT topic of interest, based on their geographical position, receiving the CPMs via 5G Uu interface, and process all information for data fusion with the vehicles' sensors.

4. The Portuguese 5G Connected Vehicle

4.1. Architecture

The Portuguese 5G Connected Vehicle (PT 5G CV) includes a 5G On Board Unit (OBU) and a Mobile App, that serves as the Human Machine Interface (HMI) used by the drivers. This regular passenger vehicle is not equipped with any automated driving functionalities, being solely retrofitted with a 5G OBU, a dashboard smartphone, a GNSS receiver and a Time Server (Figure 5). The vehicle's OBU integrates a 5G Quectel module for V2N/N2V communications. The smartphone is used to display information to the vehicle's driver and other passengers. The GNSS Trimble is placed on the car's roof allowing accurate geo-localization of the vehicle, and there is also a local Time Server for clock synchronization of the 5G OBU. This OBU subscribes to the topics of interest in the MEC MQTT broker, namely the ones regarding CAMs, DENMs and CPMs, as well as the HD-Maps JSON updates. The

5G OBU also publishes CAM messages with vehicle's parameters in the appropriate broker topic. All these messages are forwarded to the V2X App, being displayed in the smartphone's HMI for driver awareness.

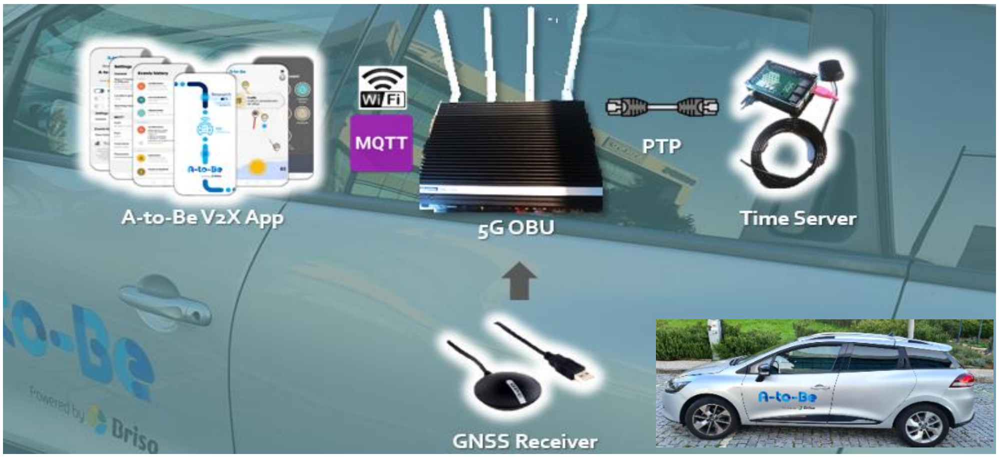


Figure 5 - Portuguese 5G Connected Vehicle architecture.

4.2. 5G OBU and V2X App

The 5G OBU implementation is very similar to the previously described 5G RSU implementation, but besides publishing awareness messages to the MEC broker, it also consumes information from it. The 5G OBU is connected to a local Time Server machine with the sole purpose of providing a precise source for clock synchronization, using the Pulse Per Second signal available in an independent GNSS receiver. This accurate time synchronization is very important for the logging and the evaluation measurements of key performance indicators (KPI), such as communications latency in a 5G setup. The Precision Time Protocol (PTP) is used to synchronize the 5G OBU to the Time Server. A Wi-Fi dongle is used to create a hotspot that enables the wireless connection with smartphone devices. This allows the communications between the OBU and the V2X App, including both the exchange of C-ITS messages as well as the HD-Maps information updates.

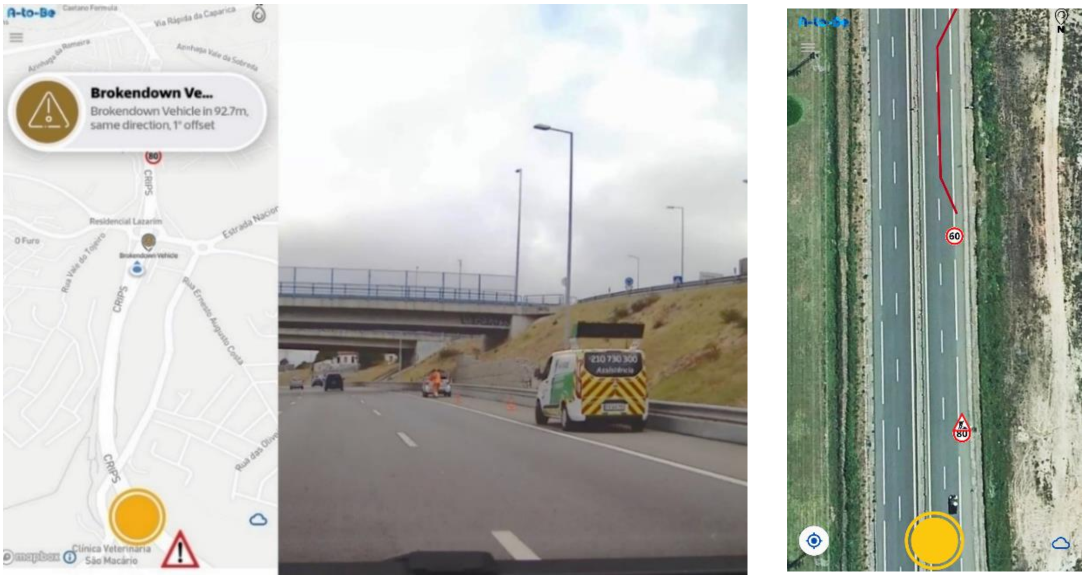


Figure 6 - (a) Broken down vehicle warning in the V2X App; (b) App displaying an HD-Map update for an obstacle on trials at the A55 (Spain).

The V2X App is Android-based and provides drivers with a live map, where it represents DENM and IVIM situations, HD-Map updates, as well as other vehicles presence (through CAMs and CPMs). The V2X App is able to alert drivers approaching relevant situations (Figure 6 – (a)). All the information is exchanged with the 5G OBU using a local MQTT broker hosted in the OBU itself, with XER (XML) encoding of the C-ITS messages and JSON for the HD-Map updates. These JSON include detailed information about temporary road signs, their location, and the 3D geometry of road obstructions. This information is presented in A-to-Be's V2X App in 2D, with the road signs and obstruction lines represented, helping the drivers know when and where to expect obstacles (Figure 6 - (b)).

5. Preliminary Results on 5G Connectivity and Latency Values

Initial tests were performed at the new Valença-Tui bridge border site to analyze the 5G connectivity in vehicles' OBUs and on RSU devices. The uplink and downlink latencies were measured at the application layer, which also included delays from the communications and message handling services running in the platforms. These preliminary tests allowed the verification of valid 5G network connectivity status, existing MEC broker connection for message exchange and correct publication/subscription to the MQTT topics. Figure 7 shows the obtained latencies values during a 2-minute test, when the PT connected vehicle's OBU was registered in the 5G Portuguese network in the border, publishing CAMs to the MEC broker and subscribing them back, to measure the observed end-to-end and intermediate delay values. Figure 8 exhibits two histograms for the uplink and downlink values of another test with CPM packets transmission between the RSU and the MEC MQTT broker. These results show satisfactory latency values, however there are some observed peak delays, specifically in the 5G OBU test, that need to be further analyzed and improved, to support all the safety-critical use cases.

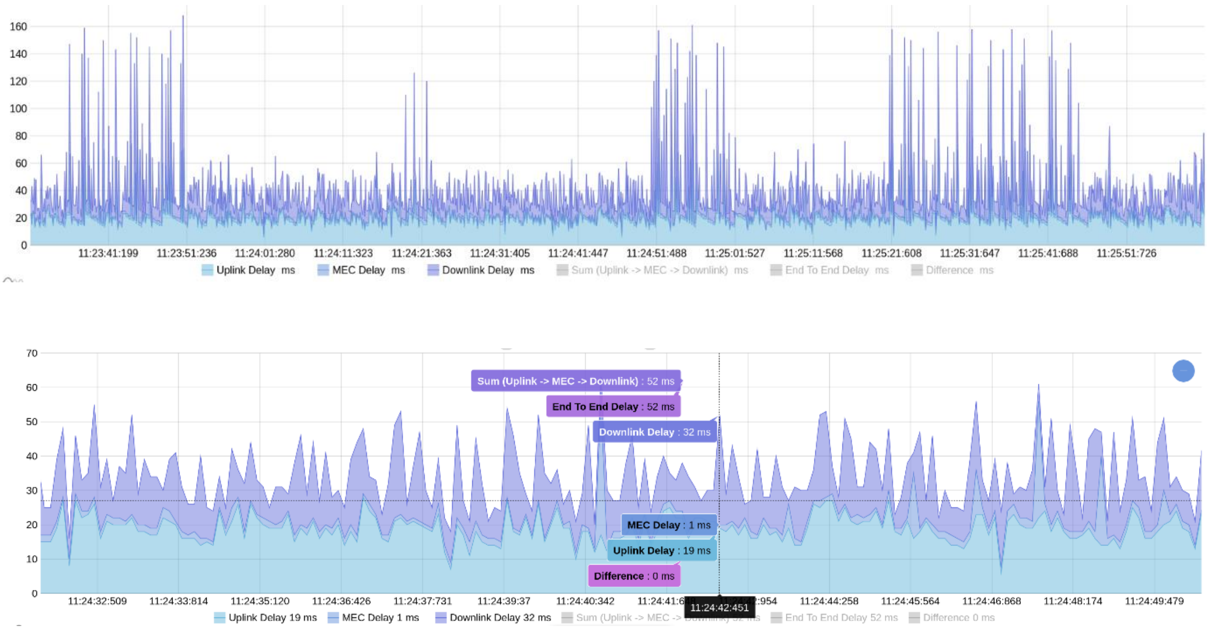


Figure 7 - Preliminary 5G latency test with the PT Connected Vehicle OBU: (top) test overview; (bottom) 25 s window detail. Note that delays are displayed cumulatively.

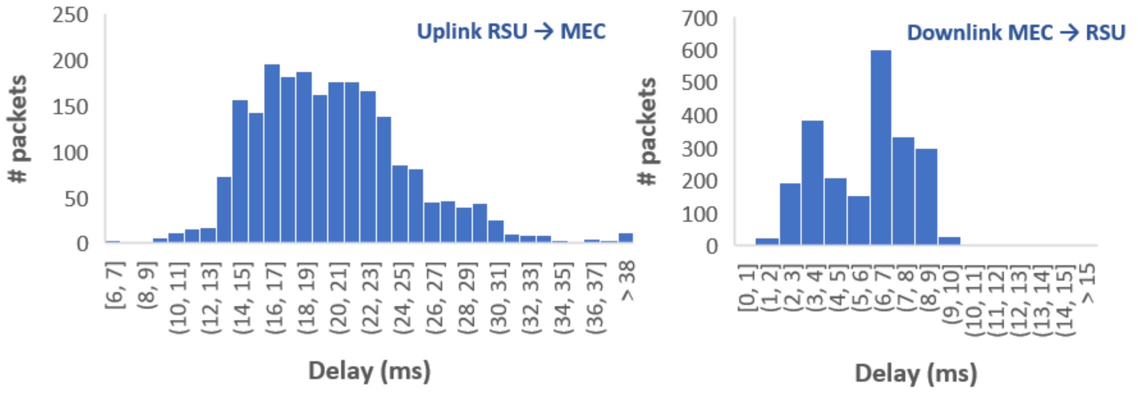


Figure 8 - Histograms of the uplink and downlink values of the PT 5G RSU.

6. Conclusions

Creating the Portuguese 5G CCAM infrastructure and Connect Vehicle, involved adapting existing solutions like the C-ITS OBU and the central C-ITS station, but also integrating and creating new tools, like the HD-Maps component or the 5G RSU and Radar integration. This 5G CCAM architecture is enabling the ongoing 5G-MOBIX ES-PT CBC trials. It is now possible to evaluate the usage of this trial 5G network for demanding CCAM applications, with a series of technical and functional KPIs allowing a much deeper understanding of the behavior of 5G, and of the technical solutions used in the Valença-Tui and A28 trial locations. Comparison and benchmarking will also be possible by testing solutions from other 5G-MOBIX trial sites at the ES-PT CBC and comparing results. In the future we plan to initiate further trials of our 5G CCAM architecture in urban areas and accompany the ongoing adoption of 5G in Europe.

Acknowledgements

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