5G-MOBIX: The Spain – Portugal Cross – Border Corridor, results of 5G application in shuttle vehicle use cases.

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***Abstract*— 5G deployments are proving to have an impact beyond a simple technological change in mobile networks to become a technology that will affect the economy, industry and society alike in a cross-cutting manner. It is a time of significant change where connectivity will become increasingly seamless and flexible and where challenges such as the deployment of safety-related in-vehicle applications, which rely on low latency and high bandwidth, in cross-border environments (roaming and handover), will become realities. In the case of the automotive sector, it will support the deployment of new autonomous mobility functionalities in the near future. This paper aims to provide as a summary an overview of the 5G network deployment and the conclusions obtained after the analysis of the results of two of the use cases carried out in the Spanish-Portuguese Cross Border Corridor (ES-PT CBC) in the framework of the 5G MOBIX Project. Through the execution of vulnerable road user and remote driving tests, the advantages of 5G technology for CAM applications have been demonstrated.**

Keywords — 5G, Connected and Automated Mobility (CAM), Remote driving, Extended sensors, Shuttle.

I. Introduction

The 5G-MOBIX project focuses on the evaluation of real 5G deployments of network operators in CAM scenarios, with special emphasis on cross-border scenarios and service continuity in inter-operator handovers. The ES-PT CBC is one of the two cross-border corridors of the 5G MOBIX project. It covers the path between the city of Vigo (in the northwest of Spain), and the city of Porto (in the north of Portugal). Along this corridor, two 5G NSA networks have been deployed by different partners with several nodes covering different areas. Inside the ES-PT CBC, different test areas were selected for different use cases with autonomous, connected and legacy vehicles cooperating with the infrastructure leveraging 5G capabilities to test complex maneuvers and services. The field trials, carried out between October 2021 to June 2022, aim to understand the impacts of this 5G technology on CAM functions and to define the necessary requirements for a large-scale deployment and evaluation for CAM.

In this paper, the impact and behavior of the network in one of the real controlled environments, the International Tui-Valença Bridge, is analysed by obtaining results in two test cases performed in the Spanish-Portuguese test corridor, the vulnerable user detection (VRU) manoeuvre and the remote driving (RD) manoeuvre. To carried out the trials the used 5G Network configuration was Home Routed (HR).

II. IT Infrastructure deployment

The deployment by TELEFONICA is shared with commercial network (Spanish nodes work under PLMN 21438), while the NOS deployment is a dedicated infrastructure to the 5G-MOBIX experimentation (Portuguese nodes work under PLMN 26893). Figure 1 shows an overview of the Telefonica and NOS complementary network architectures.

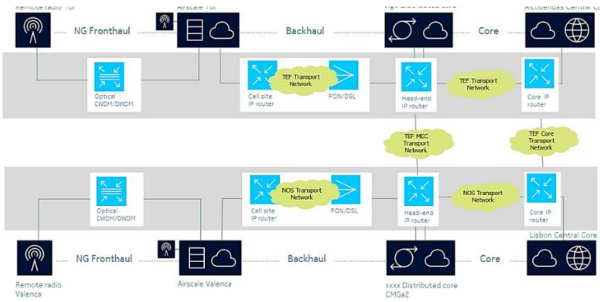

Figure 1 - Telefónica & NOS Network architecture

This is the Release with redirect with S10 interface and home routed traffic implementation. Both core networks are interconnected through two transport networks, one connecting Central Cores and another connecting Distributed Cores. S6 interface is used to validate IMSIs from visiting vehicles and S10 interfaces is used to transfer the context information between the source and destination core.
The distributed core interconnection implemented is supported by a dedicated fibre between the NOS premises and the TELEFONICA premises. This dedicated fibre line provided by TELEFONICA is critical to understand the

efficiency of the handover operation in the project. Not using dedicated fibre between operators implies using Peering mechanisms between Internet operators in different countries, which will mandatorily imply very high latencies (more than 30 additional milliseconds RTT between Spain and Portugal in this border) in the messages interchanged between vehicles and network.

Madrid to Lisbon distance is 628 km, while Madrid to Barcelona is 621 km, so distance is very similar. The average Internet ping Madrid to Lisbon is around 48 ms while the average ping Madrid to Barcelona is 8 ms.

In 5G-MOBIX, a direct fibre connection between Spain and Portugal is used which reduces the latency from Madrid to Lisbon to an average of 17ms, compared to an average of 48ms using the Internet. In this particular case it is possible to observe an improvement in round trip time messages of 30 ms.

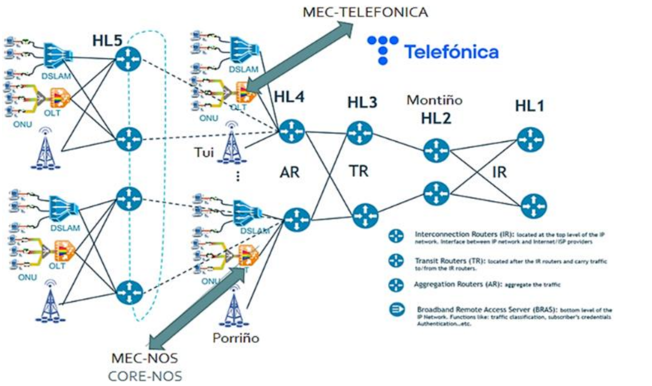

Figure 2 - Distributed Cores and MECs Interconnection

In Figure 2, shows how the distributed cores and the MECs have been interconnected using a dedicated fibre line between the two operators. Packets between the SGW and PGW of both operators are transported by this fibre line, saving precious time for efficient V2X message interchanges between both operators.

In Internet peering interconnections the packets are sent to HL1 routers that are very centralized in Telecommunications operators and this implies more kilometres of fibre lines and more routers hops that takes more time.

A. *Radio handover while crossing the border*

To control the handover process it has been decided to use 3GPP A1, A2 and A5 events. Events A1, A2 and A5 are based on RSRP (power measurements of connected radios or neighbour radios) messages. The criteria for triggering and subsequently cancelling each event are evaluated after layer-3 filtering has been applied. The criteria for each event must be satisfied during at least the time to trigger. A1 and A2 activates the UE measurements, while A5 is used to configure the minimum RSRP on the actual radio network and the minimum RSRP on the neighbour radio network to start the radio handover event to the Network Cores.

TS 36.331 [(ETSI, 2016)] describes the message sent from the gNB to the UE (Measurement information elements) to advice it to measure a certain cell (in this case from a different PLMN) and report the measurement when certain conditions, that can also be configured, are fulfilled. The most Inter-Freq (IF) measurement thresholds used in NSA deployments could make use of the following standardized thresholds:

- A2 threshold (RSRP, RSRQ) – activates IF A3/A5 measurements
- A1 (RSRP, RSRQ) - deactivates IF A2/A3/A5 measurements
- A5 (RSRP) - IF Coverage measurements.

B. *Corridor radio deployment*

The radio nodes in the Spanish side were reconfigured several times during the project duration. The Telefonica network is in current commercial operation, so 4G and 5G nodes are used by real users. This implies that Telefonica is regularly upgrading the radio nodes firmware, and it is also deploying new radio features as they become available to support new 5G features and some radio optimizations.

Figure 3 depicts the coverage of the radio cells of both Telefónica and NOS networks in the ES-PT CBC, with the indicative RSRP threshold levels to trigger the handover procedure. For instance, in the case of a vehicle leaving the area covered by NOS PCI #105 and entering Telefónica PCI #168, the handover will only be triggered when the RSRP value of NOS network signal in the 5G modem drops below –75 dBm and the one from Telefónica raises above 822 dBm.

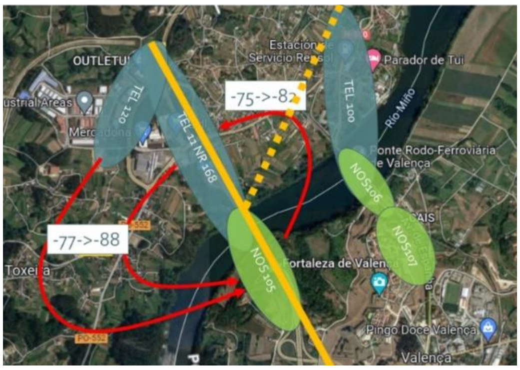

Figure 3 - 5G network handover configurations in ES-PT CBC

Radio cells (A5, A1 and A2) parameters were configured in order to fix the area of handovers for the different use cases. Similar configurations were performed for the Portuguese network, however in this case there was more flexibility since the 5G radio network was only serving 5G-MOBIX project trials, not being shared with commercial users. In Table 1, one can see the parameters used to configure the handover mechanism with some example values for a specific trial run. These parameters are adjusted for each use story in order to obtain the handover event in the desired location for the target CAM manoeuvres. The configuration includes for instance the RSRP threshold values and the time to trigger the handover procedure.

Location	Cell	PCI	Threshold2InterFreq	Threshold2A	threshold3InterFreq	threshold3aInterFreq
NEW_BRIDGE	31	104	-105	-102	-105	-90
NEW_BRIDGE	32	105	-105	-102	-105	-90
OLD_BRIDGE	33	106	-92	-90	-94	-100
OLD_BRIDGE	34	107	-92	-90	-94	-100

Table 1 - Example of ES-PT CBC Radio Cell Parameters

The cores are configured with home routed traffic to support a handover in the user plane without user plane interruption. This is only possible with home routed configuration, where vehicles' modems do not change the IP.

III. AUTOMATED SHUTTLE USE CASES

The use cases at low speed have been tested with the last mile automated shuttle developed by CTAG in the cross-border between Spain and Portugal considering two use cases:

- Cooperative Automated: the autonomous shuttle receives information from vulnerable road users by means of a camera and adapts this speed accordingly
- Remote Driving: the autonomous shuttle drives following a predefined map when an obstacle blocks its route and an operator takes control remotely

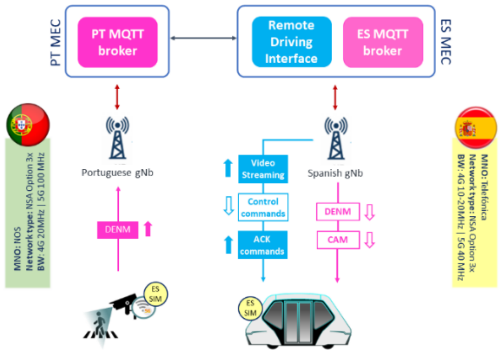

Figure 4: Network architecture of the shuttle use cases

Both use cases require low latency so the servers were deployed directly in the MECs. The cooperative automated is using a copy of the MQTT broker in each MEC for the shuttle to receive the DENM messages at 10 Hz with the pedestrian information. The remote driving is using one single instance of its interface on the Spanish side, with a gateway to the Portuguese one, to send the video from the shuttle to the remote control center and for the shuttle to receive the control commands to be driven remotely. For static purposes, each use case has been executed six consecutive times.

IV. COOPERATIVE AUTOMATED EVALUATION

The analysis is focused on the connectivity indicators of the data flows, meaning the ETSI messages between the shuttle and the pedestrian detector system and the MECs. In cross-border areas, the are many factors affecting the delivery of seamless CAM services because of the roaming and handover processes. In this sense, the design of the interconnection between Telefónica and NOS networks was oriented towards the reduction of this mobility interruption time with cores distributed in the trailing area. This is calculated as the time difference between the RRC connection reconfiguration and the reactivation of the data transfer. On average, this time is 242 ms, being shorter enough to avoid an impact on the data transfer.

Table 2 shows the statistics of the latency values at the network layer to isolate application effects and understand the 5G behaviour under these circumstances. The results are satisfactory being in DL lower than in UL because of the asymmetric configuration of the network. The difference between the mean and the median values is due to the peaks in the latency instants after the handover process.

	mean (ms)	median (ms)	std (ms)	max (ms)	min (ms)
UL latency	18.6	16.8	6.8	42.8	9.7
DL latency	19.3	10.8	25.8	155.6	6.3
E2E latency	44.8	34.9	34.3	493.8	20.7

Table 2 - Latency at the network layer for the DENM messages

Figure 5 shows the E2E latency at the application layer between the shuttle and the pedestrian system with values below the target value most of the time and few outliers because of the handover process. The behaviour among the test runs is quite uniform.

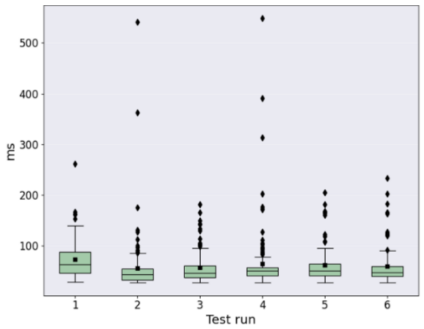

Figure 5: E2E latency at the application layer for the DENM messages

During all the test runs the reliability was 100% since the MQTT is using the TCP protocol to ensure the delivery of messages. This is not a throughput demanding use case being 240 kbps on average.

In order to address the service continuity, the home MQTT is publishing directly the messages in the visited one (and vice versa) managing both brokers the same messages at every moment. Table 3 details the inter MEC latency for the messages travelling from the Spanish MEC to the Portuguese one through the fiber between them separated by 100 km.

	mean (ms)	median (ms)	std (ms)	max (ms)	min (ms)
Inter MEC latency	4.0	4.0	0.1	5.4	3.6

Table 3 - Inter MEC latency at the network layer for the DENM messages

All the indicators fulfil the use case requirements enabling the performance of the use case on the safe side in cross-border conditions.

V. REMOTE DRIVING USE CASE

In this use case, remote driving of a shuttle vehicle using immersive HMDs over a 5G network has been done. Therefore, the evaluation of results has focused, as in the previous case, on the analysis of latencies and interruption times and also reliability.

A. Results in the national area and results in the border

To compare which is the behavior in the border with some reference, several tests were done in an area in which the 5G network was using the same core and MEC than the ones in the border, but with enough distance to the border so that no handover procedures involving roaming were produced. The remote driving was evaluated by measuring the Round-Trip Time from the application point of view which, by definition, takes longer that a RTT measured using for instance a ping test. Reason being for this is the fact that the application layer takes additional time and extra traffic is injected in the network. The use case requires RTT latencies under 100 ms for comfortable remote driving and under 300 ms for safety reasons. There is a relevant study in which these figures are studied in detail for deeper information [4]. In the Figure 6 shows how the values are under 50 ms with very few outliers most of them under 200ms while in the Figure 7, which is the corresponding to the border tests it can be seen that the values are. An exception, in the third test in which some roaming handover procedure with values between 45 and 85 milliseconds.

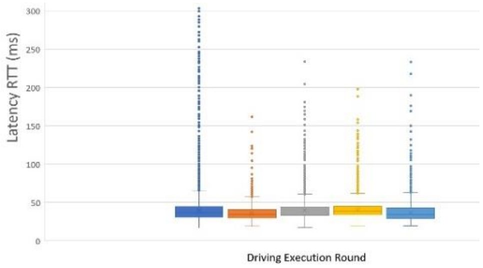

Figure 6 - RTT Latencies during field National Test

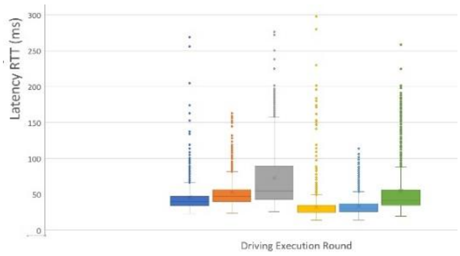

Figure 7 - RTT Latencies during field Roaming Test

In this case, packet loss has also been evaluated the package loss while executing the remote driving application in both scenarios. It has been verified by labelling the control data packages of the protocol and, as every control data message needs to be returned with an associated acknowledge telemetry one, it is possible to analyze how many of them either did not arrive to the vehicle or were not returned to the cockpit. In both scenarios, national and border, the reliability values of UDP commands are close to 100% (99,99%).

B. Handover Impact

Another thing to evaluate the impact, the KPIs which are associated to the use case need to be carefully analyzed. One of them is the frames per second decoded in the HMD used for immersive driving. In the first case (see Figure 8) a national scenario appears in which a slight oscillation around the theoretical constant frame rate is observed, while when it is in the roaming scenario with background traffic there are points in time in which the decoding frame rate goes close to zero (see Figure 9)

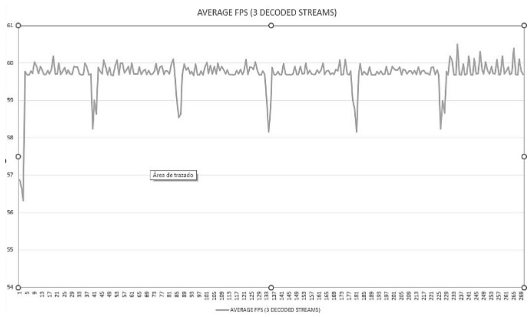

Figure 8 - Decoded frames per second - National

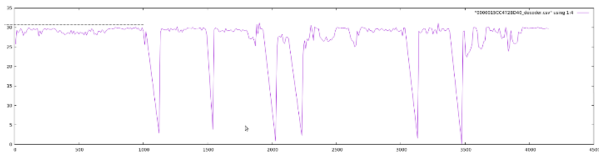
Figure 9 - Decoded frames per second - Border scenario

Again, the RTT might be critical despite the implicit protection of using asynchronous protocols both at transport level (UDP for video and control) and application level (Asynchronous nodeJS paradigm). For that reason, it is needed to find when the successful (or unsuccessful) handover take place (see Figure 10) and then focus the RTT graph in these points to analyze the impact (see Figure 11). In this case we notice a cloud of scattered points moving in the 100-150 ms range during the process of handover.

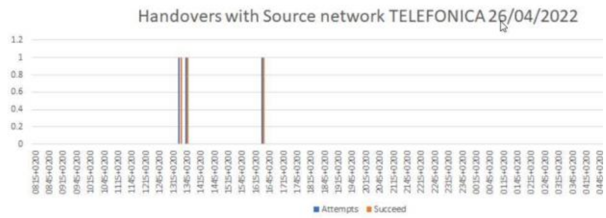

Figure 10 - Handover attempts

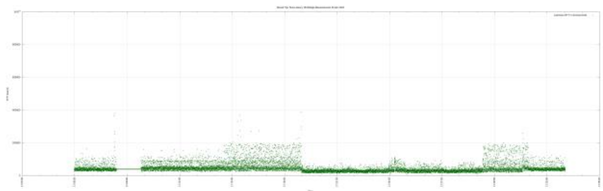
Figure 11 - RTT while doing handovers

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