5G-MOBIX: The Greece–Turkey Cross–Border Corridor 5G Deployment and Use Cases Results

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Abstract- **5G becomes a key enabler for Connected and Automated Mobility (CAM), due to its unprecedented performance characteristics. For CAM services extending across national borders, the crossing between two countries is still challenging, as it is extremely hard to guarantee the connectivity service and application session continuity when Handing Over (HO) from one Mobile Network Operator (MNO) to the other. 5G-MOBIX sets out to investigate service assurance aspects and perform large-scale field trials on real Cross-Border Crossing (CBC). This paper presents the Greece-Turkey CBC 5G Deployment, discussing the roaming options in relation to technology capabilities, limitations and optimisations, and then summarises the key results from the extensive trials on four use cases that have been selected to be investigated in the GR-TR CBC**.

Keywords- 5G, Connected and Automated Mobility (CAM), C-V2X, Inter-PLMN handover, platooning, extended sensors.

I. INTRODUCTION

In the context of the European H2020 5G-MOBIX project [1], a 5G Cross-Border Corridor (CBC) has been deployed at the borders between Greece and Turkey in order to perform real-life trials of cross-border operation of CAM [6] services over 5G, focusing on the user stories (US) of (a) truck platooning (b) see-what-I-see (c) truck routing and (d) assisted border crossing, in two use case categories (UCCs) as defined by 3GPP [2], the Extended Sensors and Vehicles Platooning.

The GR-TR CBC, as seen in Figure 1, is located between Kipoi (GR) and Ipsala (TR) as a service area of 9 km that includes hard borders and customs checkpoints. The target of the GR-TR field trials, that were initiated in 2019 and were completed June 2022, has been the evaluation of the 5G network technology and deployment options as commercially available at the time, with emphasis on the impact to service continuity and experienced application latency of the handover from one operator to another (COSMOTE to Turkcell and vice versa) while performing the GR-TR user stories.

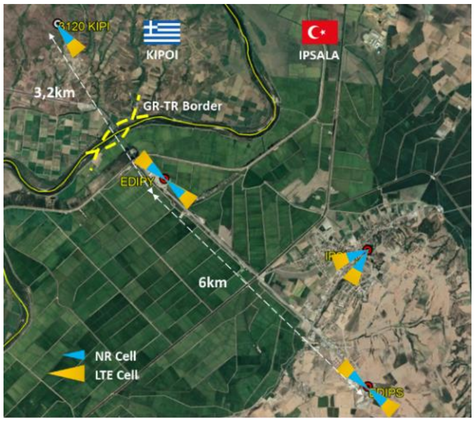

Figure 1: GR-TR Cross-border Corridor Layout

In the following, Section II focuses on the 5G Network Infrastructure of the CBC, introducing the roaming options possible (Home-Routed, Local-Break Out), analysing their technical capabilities and limitations and exposing the significance of the core networks' interconnection to achieve minimum service disruption and optimum performance in terms of latency. Section III then presents an overview of the key results from the 5G-MOBIX trials per each GR-TR user story and finally Section IV summarises the conclusions and proposals for future work.

II. 5G NETWORK INFRASTRUCTURE

5G connectivity at the CBC is offered by COSMOTE in the Greek side and Turkcell in the Turkish side through 5G Non Stand-Alone (NSA) overlay networks, based on 3GPP Rel.15 Radio and Core equipment provided by Ericsson. On the Turkish side, three (3) gNBs with six (6) New Radio (NR) cells (plus LTE anchors) provide the 5G service. The GR side is covered by a single cell site, located 3.2 km away from the nearest Turkcell gNB, as depicted in Figure 1. All cells operate in the 3.5 GHz band, while Active Antenna Systems (AAS) are used on both sides of the border with a NR carrier of 100 MHz bandwidth with a maximum transmission power of 200 W. In Greece, as of December 2020, COSMOTE commercially operates 5G in the awarded frequency bands and in-line with the Greek National Regulation Authority (NRA) guidelines, whereas Turkcell has reserved a test license for the n78 band for the purpose of the 5G-MOBIX trials. A guard band of 50 MHz has been selected for the GR-TR deployment, as depicted in Figure 2, to guarantee minimal to zero interference between the two neighbouring networks irrespective of the TDD pattern used.

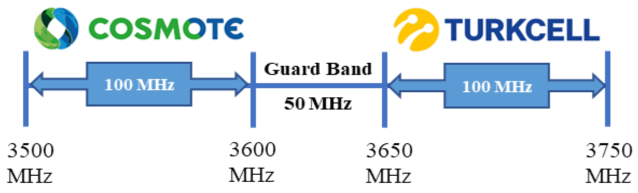

Figure 2: Spectrum Allocation at Greek-Turkish 5G Corridor

3GPP-defined interfaces for roaming and Inter-PLMN handover were established between the two networks, as shown in Figure 3. This includes the S6a-interface, which is used to interconnect the Mobility Management Entity (MME) of the Visited Public Land Mobile Network (PLMN) with the Home Subscriber Server (HSS) located in the Home PLMN, the S8-interface used for user plane data transfer between the Visited Serving Gateway (S-GW) and Home Packet Data Network Gateway (P-GW) entities, and the S10-interface between Visited and Home MME to enable Inter-PLMN handover. [7]

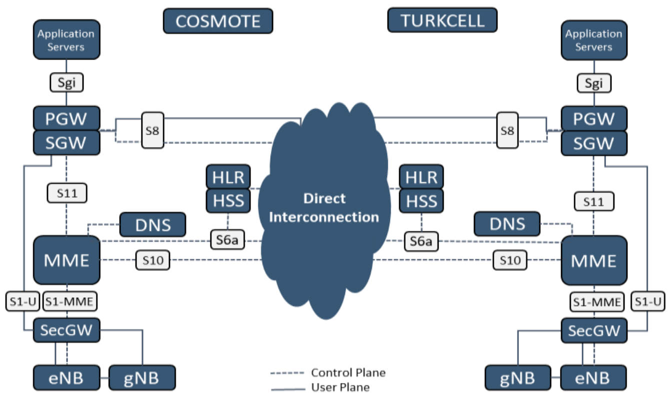

Figure 3: 5G-MOBIX Network Architecture at GR-TR 5G Corridor

Both COSMOTE and Turkcell PLMNs are defined as Equivalent PLMNs within the defined geographical areas of the trial.

A. Inter-PLMN Handover

The assumption is that base stations belonging to different PLMNs and, in this case, even located in different countries would not have an X2-interface established between them. In this case, only the S1-based handover procedure can be used. In case of non-standalone (NSA) 5G, handover is mostly controlled and executed on the 4G eNodeBs (eNBs). The source eNB initiates a handover by sending "Handover Required" message over the S1-interface to its MME. The MME realises that the target eNB is not connected to it but to a different MME and that it has an S10-interface to that MME. It forwards the "Handover Required" message to the target MME through the S10-interface. From there it reaches the target eNB which can decide if it accepts the handover request and if so confirms [3].

As shown in Figure 2, COSMOTE and Turkcell use different frequencies for their test networks. Turkcell eNBs are configured to know and announce the COSMOTE frequencies and the other way around. This way UEs know that they should also perform inter-frequency measurements. Data transmission is interrupted during inter-frequency measurements, so handover events A2[1] and A1[2] are used to decide when to start measuring, according to bad signal quality from the serving cell, and when to stop according to good quality, respectively. Handover event A5[3] is used to trigger the handover. It is configured with two parameters, Threshold1 and Threshold2. Handovers are only considered when the serving cell quality is worse than Threshold1. A handover is only performed if the quality of the target cell is above Threshold2. Reference Signal Received Power (RSRP) was used as indicator for the quality. The tests revealed that different phones and modems conduct handovers at different locations due to different antennas and other external (geographical landscape, antenna position, vehicle traffic condition etc.) factors. In order to safeguard a single and same handover location point, for the sake of the field trials, different thresholds had to be used for different devices. This is possible in a trial setting, but in reality, as there can only be one configuration of these thresholds used by all devices connected to the network, the exact handover location cannot be expected to be common or strictly imposed by the network.

In Figure 4, it is explained how the handover mechanism works with the selected parameters. The symbol ***** indicates the selected parametric values. S indicates the RSRP at which the User Equipment (UE) starts inter-frequency measurements. X indicates the RSRP level at which the UE stops measuring. When measuring, according to A1 and A2 Thresholds and A5 Threshold1 is crossed, the UE will try to conduct a handover (area shown in yellow) when it finds a target cell with RSRP above A5 Threshold2. In this example, the handover will occur at the point shown in blue with "HO".

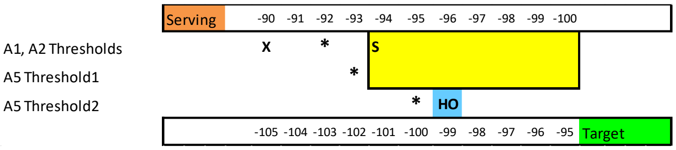

Figure 4: Measurement and Handover Thresholds

B. Home Routed vs. Local Breakout Routed Roaming

Inter-PLMN handover is currently, to the best of our knowledge, not enabled in commercial 4G and 5G networks. When leaving a country, a UE will stay connected to the Home Network until it loses synchronization with the last cell serving it. This can result in a very long period of time where the quality of the radio link is at a very low level and hardly any communication, not even a voice call, is possible. After losing the synchronization, the UE starts searching for a new PLMN in the visited country. It will then establish a new Packet Data Network (PDN) connection and obtain an Internet Protocol (IP) address. Being served by a different network than the home one

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[1] Event A2 is triggered when the serving cell becomes worse than a threshold.
[2] Event A1 is triggered when the serving cell becomes better than a threshold.
[3] Event A5 is triggered when the serving cell becomes worse than threshold-1 while a neighbouring cell becomes better than threshold-2.

is called “roaming”. By default, a UE attached to a Visited PLMN will still use a P-GW in its Home PLMN. This is called **Home Routed Roaming**. The S-GW in the Visited PLMN and the P-GW in the Home one exchange user data over the S8-interface.

Local Breakout (LBO) Routed Roaming can be enabled through configuration in the MME and P-GW. In this case the P-GW selection algorithm in the MME would pick a P-GW in the Visited PLMN when a roaming UE wants to establish a PDN connection. In case of radio handover, including Inter-PLMN handover, the P-GW is never changed. A UE being handed over from its Home PLMN to a visited PLMN will continue using the P-GW of the Home PLMN regardless if Home Routed Roaming or LBO Routed Roaming is configured (see next). The end-to-end latency of user plane data between the client and server can suddenly become very long after such Inter-PLMN handover, as the roaming interconnection of the networks is not optimised for a short path.

Table 1: RTT Comparison between Configurations

Test Results	(HR with Internet Connection)		(HR with Leased line Connection)		(LBO with Leased line Connection)		
	Home NW (GR)	Visited NW (TR)	Home NW (GR)	Visited NW (TR)	Home NW (GR)	Visited NW (TR)	Visited NW (TR)
E2E Avg. RTT (ms)	16,35	97,24	17,38	35,9	17,57	36,05	17,27

Table 1 compares round trip times (RTT) between Home Routed Roaming with the networks interconnected over public Internet (IPX Backbone), over leased line (direct interconnection between Alexandroupoli and Ipsala), and with LBO Routed Roaming. The table shows that a direct interconnection can reduce the average RTT from almost 100 ms down to 36 ms. When enabling LBO Routed Roaming the average RTT is around 17 ms and the same in Home and Visited PLMN. Nonetheless, in order to reach LBO Routed Roaming after Inter-PLMN handover, the PDN connection needs to be disconnected and reconnected, and this is a service interruption with potentially negative impact on use cases that needs to be accounted for. 5G NSA, using an Evolved Packet Core, can achieve this in two ways. It is either triggered by the UE (similar to Session and Service Continuity (SSC) mode 1 in 5G SA) or by the network (similar to SSC mode 2 in 5G SA), coming from the MME. 5G SA also adds SSC mode 3 where first a connection to the new gateway is established and then the old one is released to prevent service interruption. For the GR-TR CBC trials SSC mode 1 was used as the only technically available alternative, meaning that devices had to be disconnected and reconnected manually to get to LBO Routed Roaming after an Inter-PLMN handover.

C. Inter-PLMN Handover Mobility Interruption Time

During 4G and 5G handover, communication is interrupted for a short time when the UE lets go of the source cell and is not yet synchronized to the target cell. In case of 5G NSA this refers to the 4G anchor cells, but another interruption can occur when adding the 5G cell as secondary cell in the target network. In our trials the 4G interruption duration was measured as time difference between the *RRCConnectionReconfiguration* message sent by source eNB and the *RRCConnectionReconfigurationComplete* message received on the target eNB. Once the 4G handover is done, a reconfiguration needs to be done to switch the path from 4G to the secondary 5G cell. This includes multiple steps including leg addition, where the 5G cell is added as secondary cell, path switching, where data on the radio interface is being sent over 5G and Core path optimisation through bearer modification. The latter is used to shorten the path which is initially going from the S-GW to the 4G eNB and from there, over the Xn-interface, to the 5G gNB. After the bearer modification, data is transmitted directly between 5G gNB and S-GW without the 4G eNB in between. This procedure can include some small interruptions. Our means to measure the process did not allow to precisely distinguish times where data was flowing or not. Nevertheless, the reconfiguration time was calculated from messages that could be recorded with timestamps. It was calculated as time difference between sending the *SgnbReleaseRequestAcknowledge* message by the target gNB to the target eNB and receiving the *E-RABModificationConfirm* message by the target eNB from the target MME. This is the point in time where data transmission is fully switched from the 4G eNB to the 5G gNB with 5G gNB directly communicating with the S-GW without the 4G eNB in between.

Figure 5 shows the 4G mobility interruption duration and the 5G reconfiguration durations in the trials. It was measured with core networks interconnected through direct leased line and the public Internet. All trials were performed with Home Routed Roaming. The results show that is makes no significant difference which lines are used to interconnect the PLMNs. The reason is that the S10-interface is only used to prepare and initiate the handover. Delays on that interface only change the point where the handover happens, but not the interruption duration. Even with 100 ms delay the handover point would only move by 3.3 m at 120 km/h. Handover interruptions times, as a result of detaching from the source 4G eNB and synchronizing and attaching to the target one takes 58 ms and 54 ms for leased and public Internet lines, respectively. The difference is within statistical uncertainty, as shown by the confidence intervals. It can therefore be concluded that the interruption time is identical for leased and public Internet lines. They can be considered about the same according to the 95% confidence intervals. The 5G reconfiguration requires around 195 ms independent of network interconnection type, as this reconfiguration is only performed in target (visited) network.

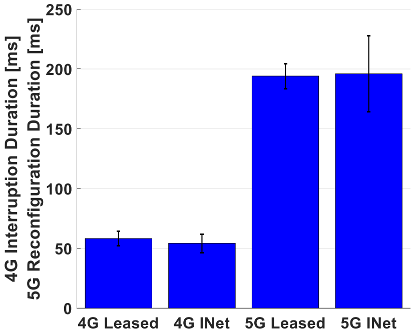

Figure 5: 4G Handover Interruption Duration and 5G Reconfiguration Duration

III. 5G-MOBIX USER STORIES' RESULTS

In the GR-TR CBC, four different User Stories (US) are implemented, belonging to two UCCs as defined by 3GPP [4]. Having finalised the 5G-MOBIX trials, key results of the use stories are presented in the sections below, while details can be found in the project's D5.2 report on technical evaluation [4].

A. 5G Platooning

The 5G Platooning user story was tested in two different locations with two Ford F-MAX trucks. The Application system diagram can be seen in Figure 6. An MQTT mechanism was used for Uu-based (instead of PC5) message exchange, since the message rate was less than 8kbytes and MQTT is lightweight, reliable protocol. For that purpose, an MQTT broker was installed in Turkcell core and IMEC OBUs hosted MQTT clients. Platooning messages were generated by autonomous trucks and sent to OBUs. All autonomous vehicle algorithms and system design were developed by Ford Otosan, while MQTT Broker was developed by Turkcell.

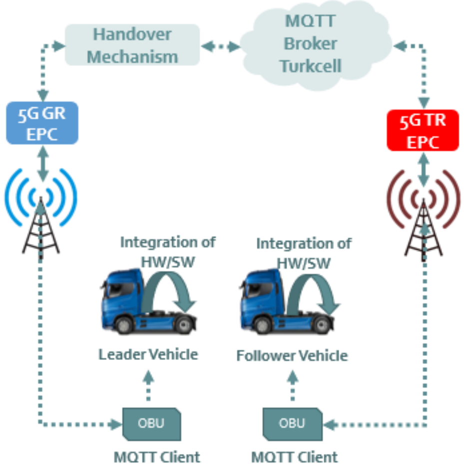

Figure 6: 5G Platooning Application System Diagram

First test location is just before the entrance of Ipsala – Turkish Border Gate, road E84 and it is approximately 4.5 km long. In this area, Platooning was performed with all manoeuvres and physical distance maintained by autonomous trucks. As second location, bridge on buffer zone between GR – TR was used. This area is strictly controlled by security forces of both countries, and it is impossible to maintain the gap between two trucks with autonomous mode, due to speed limits (maximum allowed speed is 30km/h). Additionally, road width is too narrow, and huge truck queues exist in this area. Due to these restrictions, in this area two trucks exchanged related 5G Platooning messages, but trucks did not operate autonomously.

Application was tested with 5G NSA HR network configuration. To collect and analyse results, DEKRA TACS4 Tool [5] was used. To see 5G network performance, TCP round trip time was measured (between a truck and the MQTT server), since MQTT message exchange is TCP-based. As it can be seen in **Error! Reference source not found.**7, round trip times are less than 100 ms in average for *all routes.*

According to measurement results, we saw that reliability of the 5G connection between OBUs and Cloud is 100%. This result could be different if exchanged message rate would be higher than 8 kbytes. Additionally, handover interruption time was measured less than 200 ms, as it can be seen in Figure 7.

Figure 7: 5G Platooning TCP RTT Measurements

Platooning application has been mainly demonstrated with ad-hoc networks (DSRC or C-V2X PC5) so far, but our results show that 5G can be also another communication interface for platooning applications with its reliable, secure and low latency features.

B. See-What-I-See

The See-What-I-See video streaming application was demonstrated in the cross-border trials of the GR-TR CBC TS. The application targets the exchange of seamless video streams between moving vehicles e.g., within a truck platoon so as to increase following safety driver awareness and reduce anxiety. The evaluation of results has focused on the analysis of latencies, the user experienced data throughput and the associated reliability in both home routed scenarios (public connection and direct interconnection), using the DEKRA tool [5]. The measurements took place between the two (video) edge servers, residing at each PLMN, and the client devices (Jetson and Raspberry Pi – RBPI). The use case requires E2E latencies lower than 300 ms for assuring seamless video streaming. In the following figures, the uplink (UL) and downlink (DL) latency are separately given; their sum confirms that the required latency threshold is satisfied at both scenarios. Comparing the results, the direct interconnection is the prevalent choice for better and stricter latency and stability requirements, however it comes with certain operational costs that need to be balanced, from a business point of view.

The graphs below present the video streaming latency when the trucks are on the move and make a complete route from GR to TR area using COSMOTE SIMs on the OBUs and roaming from the COSMOTE network to Turkcell. With black circles, we indicate the time of perceived handover of the first truck when it crosses the handover point for first time. In the aggregate, the overall E2E latency between UEs on the trucks can be computed at about 70 ms in average for each one scenario.

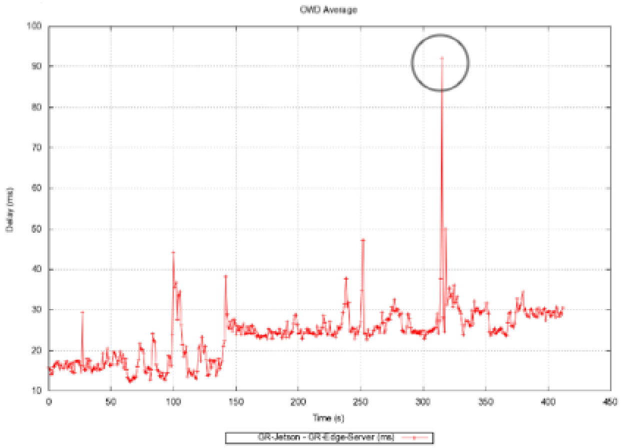

*Figure 8: **UL** latency in direct interconnection scenario*

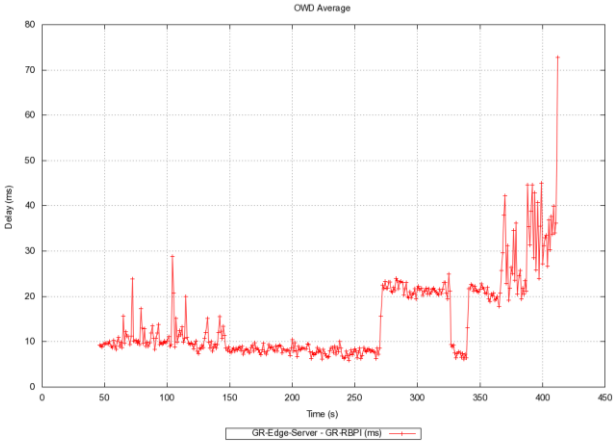

*Figure 9: **DL** latency in direct interconnection scenario*

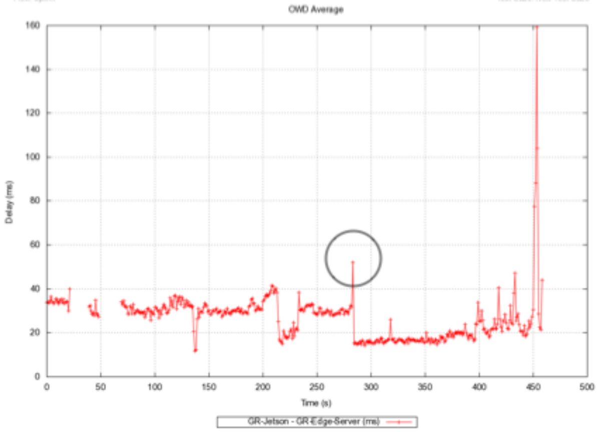

*Figure 10: **UL** latency in public internet scenario*

Considering the necessary reliability, the packet loss has also been evaluated during the application test runs. The packet loss was derived by the measurement tool giving with increased accuracy how many packets were dropped per test run. In both scenarios, the reliability values of UDP datagrams are so close to 100% (99,99%).

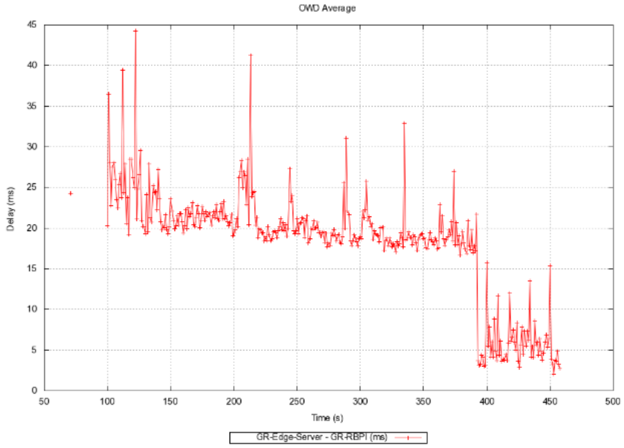

*Figure 11: **DL** latency in public internet scenario*

C. Autonomous Truck Routing

The Autonomous Truck Routing (ATR) user story, developed by TUBITAK BILGEM, enables autonomous driving of a truck by using road-side sensors and on-board GNSS inside the TR customs area from the cloud via Turkcell 5G. According to the scenario, when a truck arrives at the customs and requires an X-ray scan, the driver gets off the truck at the entrance and truck drives itself to the X-ray building. In this way, the process time decreases as the driver can handle the required paperwork. Also, since the driver gets off the truck before the X-ray scan, the process is more secure.

Autonomous driving is achieved by mounting Road-side Units (RSUs) to the area. RSUs are equipped with Velodyne VLP-32C Light Detection and Ranging (LiDAR) sensors and 5G antennas. They send the raw LiDAR packages to the TUBITAK Cloud via 5G. Additionally, the Ford Otosan truck sends status information to the cloud that includes, truck's speed and GNSS information with cm precision. The cloud application uses these data and fuses them into a static map to get a local dynamic map. Using the updated map, the cloud application plans the path and velocity for the truck. The planned path is sent to the truck as 25-metre-long safe waypoints together with the planned velocity. These safe waypoints are converted to the wheel and pedal input on the truck to enable autonomous driving. The message flow of the application is depicted in Figure 12.

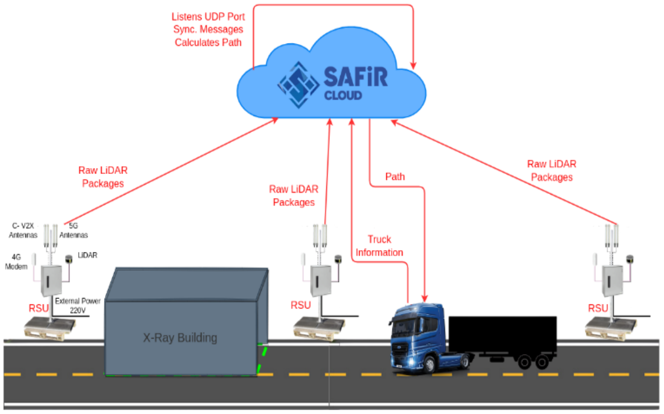

Figure 12: Autonomous truck routing application message flow

The Autonomous Truck Routing demo was performed at Ipsala TR customs. Measurements taken for indirect and leased line connections are depicted in Figure 13 and Figure 14 respectively. The measurements were taken using the DEKRA TACS4 Tool [5]. Depending on the density of the trucks in the customs area and the movement of the test vehicle during the test, outliers were observed in the delay values and these outliers were disabled while calculating the average values. Average Cloud-to-OBU E2E latency measured 37.5 ms for indirect connection and 36.4 ms for leased line connection. These latency values are sufficient and at the targeted level for autonomous driving to be realised. In terms of network reliability, when the packet loss values are examined, it is seen that it is less than 1% in both connection types.

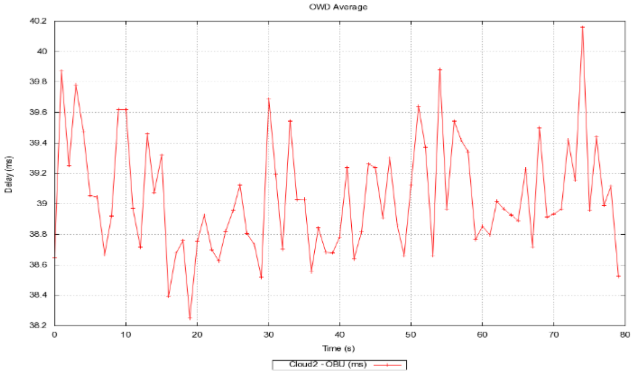

Figure 13: ATR indirect connection Cloud-to-OBU latency

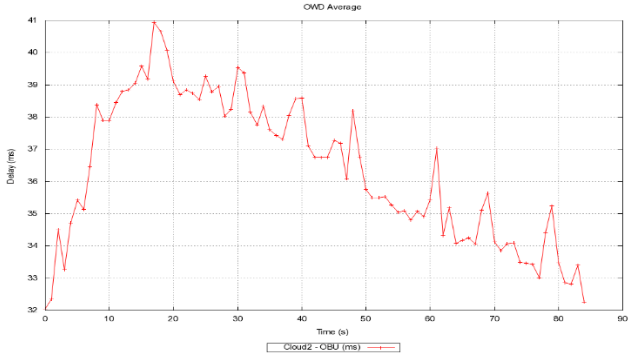

Figure 14: ATR leased line connection Cloud-to-OBU latency

D. Assisted Border Crossing

The assisted zero-touch border-crossing story utilizes the detailed data provided by the CAM enabled truck's sensors (Lidar, radar, GPS, etc.) as well as the data from surrounding heterogeneous information sources such as traffic cameras, road side sensors, smart phones, wearables and more, increased intelligence can be created based on a cooperative awareness of the borders' environment. Service continuity during the inter-PLMN HO is of utmost importance in such cases, and the existence of intelligent functionality deployed at the edge close to the border greatly facilitates continuous service by identifying imminent HO's and helping the network operators prepare for it based on the available information.

IV. CONCLUSION AND FUTURE WORK

In the GR-TR CBC we thoroughly investigated Home Routing Roaming, and took a step further showing how Local Breakout Routed Roaming in conjunction with Edge Computing allows latencies in Visited networks to be identical with those in the Home network. We have furthermore showed that seamless 5G Inter-PLMN handover in possible across country borders. Experienced interruption times of 50 ms should not have noticeable impact on Connected Automated Mobility services

Within these trials the transition from Home Routed Roaming to Local Breakout Routed Roaming was done manually by disconnecting and connecting the end-devices after Inter-PLMN handover. For the future, we would like to demonstrate an automated transition to Local Breakout Routed Roaming. We would furthermore like to demonstrate it in conjunction with SSC mode 3, enabling uninterrupted transition from Home Routed to Local Breakout Routed Roaming.

Although being close to reality, the trial environment did not replicate a true roaming deployment as used in current commercial deployments. Roaming Exchange Hubs and Diameter Exchange Agents, as deployed today to assure secure interconnection among multiple MNOs, can introduce control plane latencies in the range of up to 200 ms. We therefore suggest further performance evaluation campaigns taking into account such deployments with all elements that could introduce further delay.

From the user stories perspective, and the See-What-I-See video streaming application, numerous tests about its key functionalities with regard to user experience data, the involved latency, and service reliability were successfully completed highlighting the application's perspectives for further development. In the future, it is expected that the application will also prove and present its functional flexibility for reliable video streaming in LBO and IP change network configurations. For Autonomous Truck Routing and assisted border crossing user stories, the network configuration successfully satisfied the autonomous driving of vehicle over a cloud in terms of both latency and reliability. The application functionality can be improved for future work, but it is left open since this is a 5G focused project.

ACKNOWLEDGEMENT

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