# 5GCroCo: Key 5G technologies and trial results for seamless cross-border CAM services (Invited Paper)

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***Abstract*—The 5GCroCo project conducted large-scale trials of 5G technologies for Connected and Automated Mobility (CAM) in two road corridors along the border areas in France-Germany and Luxembourg-Germany. In this context, this paper provides a succinct description of a subset of the key 5G technologies that have been trialed and highlights representative experimental results that have been obtained for three CAM use cases with a clear focus of achieving seamless service continuity along cross-border and showing the benefits of 5G in comparison to 4G. The trial results provide an experimental validation of the technical feasibility of the technical solutions used in the project.**

***Keywords—5G, CAM, service continuity, cross-border, test and trials***

## I. Introduction

The 5GCroCo project conducted large-scale trials of 5G technologies for Connected and Automated Mobility (CAM) in the European 5G cross-border corridors connecting the cities of Metz-Merzig-Luxembourg, traversing two borders, three countries: France, Germany and Luxembourg.

The provision of CAM services across different countries when vehicles traverse various national borders has a promising innovative business potential. However, the seamless provision of connectivity and the uninterrupted delivery of real-time services across borders also pose different technical challenges. The technical situation is complex given the potential multi-country, multi-operator, multi-telco-vendor, multi-car-manufacturer, and cross-generation scenario of any cross-border layout. In that setting, the 5GCroCo project trialled three use cases, that were selected to validate 5G features that can contribute to a successful deployment of CAM services: 1) Tele-operated Driving (ToD), 2) High Definition (HD) map generation and distribution for automated vehicles (HD Mapping), and 3) Anticipated Cooperative Collision Avoidance (ACCA).

To address the complex technical challenges listed in the paragraph above, the project made use of different key 5G technologies, which include (but are not limited to) 5G New Radio (NR), service continuity, Mobile Edge Cloud / Computing (MEC), and end-to-end and predictive QoS (incl. Network Slicing). These technologies were validated in field trial campaigns carried out at the cross-border corridor areas.

The remainder of this paper is organized as follows. Sections II and III provide a succinct description of the 5GCroCo use cases and developed key technologies, respectively. The focus of Section IV is on the network deployment in the two considered border areas. Section V describes trial results for selected pairs: (use case, key technology). Section VI concludes the paper.

## II. 5GCroCo Use Cases

5GCroCo use cases were selected so that their main needs and requirements could be used to validate 5G features that can contribute to a successful deployment of CAM services and are briefly introduced here. These use cases and their corresponding user stories are described thoroughly in [1], [2].

### *A. ToD*

Current automated driving vehicle prototypes prove the feasibility of truly driverless cars. ToD can be leveraged as an enabling technology to smooth this transition, as edge cases remain, which necessitates falling back on human operators. For ToD, an interface over the mobile 5G network is created that allows a human to remotely control a vehicle. Through such an interface, sensor and vehicle data, e.g., video feeds and velocity are transmitted from the vehicle to the vehicle control centre. There, the data are displayed to the human tele-operator who generates control commands, e.g., desired steering wheel angle or velocity. These are then transmitted back to the vehicle for execution. In 5GCroCo, ToD was trialled with two vehicles. Both vehicles had integrated longitudinal and lateral control, which, based on input from vehicle sensors, can automatically steer the vehicle on defined lanes, hand over / take back control to / from a tele-operator.

### *B. HD Mapping*

One of the cornerstones of autonomous driving is an accurate, actual, and seamless high definition map. The basic functionality is to determine the vehicle's position, but also information about traffic rules like speed limitations, or more dynamic conditions like road closures or construction areas. High-definition (HD) map users expect a continuous availability of the map content, even in cross-border scenarios. Autonomous cars, however, require the map to be constantly up-to-date, and thus when reality changes, the map needs to be updated. Regular map updates by the map provider, typically done a few times a year by driving mapping vans along the roads, are not at all sufficient. To ensure a high reliability of autonomous cars, the map needs to be updated constantly, by as many contributing cars as possible. Broadly speaking, the cars collect information about their surroundings using their on-board sensors, and then use their 5G connectivity to send this information to some backend. Here, the received data is compared to the existing map, and if differences are found, the map can be updated. The data might even come from sources other than cars, e.g., road side cameras. The HD map can also be used as the base upon which more dynamic information can be stored, for example, accidents. All these procedures have to work seamlessly across borders. For example, map updates from cars on one side of a border have to be distributed also to cars on the other side, served by a different operator with the backend running on a public server or a MEC architecture.

### C. ACCA

Towards the realization of autonomous vehicles, car manufacturers are adopting and developing sensors that allow vehicles to sense their environment and control the vehicles. Driving automation systems rely on a variety of sensors like cameras, radar, lidar, etc. Despite the increasing number of in-vehicle sensors, the environmental perception of the vehicle remains limited. In certain situations, typical stand-alone sensing systems will not be able to detect and localize dangerous events on the road with sufficient level of anticipation. In such situations, too late detection of a dangerous event will trigger a hard braking or a dangerous manoeuvre or potentially lead to a collision. The ACCA use case relates to the possibility to anticipate certain potentially critical events in order to reduce the probability of collisions in situations when typical sensors will have no visibility or a short detection range (e.g., a few 100 m). The aim of the ACCA use case is to induce smoother and more homogeneous vehicle reactions by facilitating the anticipated detection and localization of temporarily static events such as traffic jams, high deceleration, emergency braking or unexpected manoeuvres of vehicles in front, etc.

## III. 5GCroCo Key 5G Technologies

The 5GCroCo project considered input from different standardization bodies to scope its solution architecture for CAM in cross-border environments. The 3GPP 5G New Radio specifications were considered the main set of input documents. Some key aspects are widely considered being a part of 5G, but are not within the scope of 3GPP specifications. For these, other standardization bodies, as well as best practices from open-source communities, were considered instead.

The baseline for this project was, therefore, the state of the art of technologies implemented and integrated today in 5G networks that are currently being deployed. It includes Physical and Virtual Network Functions (PNFs and VNFs) and SDN to interconnect them. For the baseline, 3GPP 5G New Radio Access Network (RAN) with a 4G LTE EPC was considered. This is referred to as non-standalone (NSA) 5G New Radio. This deployment is being rolled out in most parts of the world today, including Europe. Experience from previous network generation rollouts shows that this deployment could remain in place for several years. Some, but by far not all, 5G Core features are also available with 4G EPC since the LTE specifications are also being evolved. According to this baseline, all use cases described in the previous section benefited from the increased capacity, reduced latency and improved reliability offered by design by 5G. Section V.C below contains results from many trials where 5G and 4G performance are compared (see [3] for additional details).

On top of this baseline, components were added, and/or their configuration was optimized to serve the challenges of cross-border CAM. As pointed out above, the three use cases used in 5GCroCo allowed to systematically discover the different facets of those challenges to design a network capable of supporting a wide range of advanced use cases.

QoS prediction was identified as one key solution. Its baseline is the 3GPP QoS framework currently mostly used for voice calls. For this rather simple application, the current way of describing QoS requirements by delay budgets, packet loss rates and throughputs is enough. More advanced use cases have more complex requirements. A first version of Generic Network Slice Templates (GSTs) was defined by Global System for Mobile Communications Association (GSMA) [4] and we considered these templates a solution to describe service requirements across MNOs and country borders. Their generic principle is equally applicable to 4G and 5G core networks, but the respective document [4] explicitly references the 5G Core specifications [5]. Furthermore, the standalone 5G New Radio with its defined Slice/Service Type (SST) for Vehicle-to-Everything (V2X) will allow better integration with the vehicle and backend, especially for identifying the right slice.

Besides information on instantaneous QoS, looking ahead in time and allowing selection of alternative QoS has been studied in 3GPP (QoS Sustainability Analytics [6]). The required new interfaces and/or changes to existing ones, so far, were only specified for the 5G Core. For the 5GCroCo project trials and intermediate deployments and tests, similar but proprietary interfaces were used. Appropriate inputs for different prediction algorithms were evaluated in the context of the conducted trials and an example result can be found in Section V.A below.

For a special subtopic of prediction allowing to deliver large data volumes at reasonable monetary price, the Background Data Transfer (BDT) functionality was identified as a candidate to support a selected user story of the High-definition (HD) Mapping use case. QoS prediction is needed for BDT to identify the best times and/or places to download HD map updates.

3GPP specifications only allow QoS management within the RAN and core domain. End-to-end performance guarantees are difficult or even impossible to fulfil with one end of the communication in the public Internet. MEC enables operators to deploy backend applications within their domain. This often requires a so-called Local Breakout through additional gateways. The capabilities of the 4G EPC to dynamically select and especially switch the gateway to reach the closest or otherwise best suitable MEC host are very limited. The 5G Core adds Session and Service Continuity mode 3 for an uninterrupted gateway reselection. EPC and 5G Core are currently not capable to provide this in a cross-MNO environment as experienced across country borders. Within 5GCroCo, solutions were studied to address these aspects. An example trial result using MEC-hosted applications across borders within the Anticipated Cooperative Collision Avoidance (ACCA) use case is briefly described in Section V.D.

Handover from one MNO to another one across country borders is technically feasible but rarely enabled and the required links for the interfaces across MNOs are usually not present. The project demonstrated the benefit of such interfaces for enabling and improving handover between different MNOs, as succinctly described in Section V.A.

Today, roaming is usually realized with Home Routed Roaming using the packet gateway in the home network. Particularly in context of MEC, it is preferable to use gateways in the visited network. As of today, no solution allowing service continuity across country borders (cross-MNO handover) and using a gateway in the visited network is specified. 5GCroco evaluated if and how the capabilities of the 5G Core for more dynamic and seamless gateway selection can be applied across MNOs in [7].

## IV. Network Deployment

In the architecture of the 5GCroCo solution for the three networks in France, Germany, and Luxembourg deployed in the two corridor border areas (France-Germany, F-D; Luxembourg-Germany, D-L), the Home and Visited networks support cross-MNO handover. The two corresponding network pairs (F-D, D-L) were connected through the S10, S8 and S6a interfaces, which establish the necessary exchange of information so that a user can be handed over between the networks in two different countries (as would happen in a border crossing), in the very same fashion as in a regular handover between two MMEs in the same network (e.g., when traveling within a single country).

The following two sub-sections focus on providing a description of the 5G architecture deployed at the 5GCroCo corridor areas and the related handovers taking into account the presence of MEC .

### *A. Corridor France – Germany (F-D)*

The French 5G NSA radio cells deployed in Forbach (France) were connected to a core network hosted by Ericsson in Aachen (Germany), which is about 200 km away (air distance). The user data was locally broken out in a data center of Orange in Forbach. The local breakout and MEC were thus only about 5 to 10 km away from the radio cells (depending on each radio cell location). The German NSA cell deployed in Saarbrücken was connected to a core network also hosted by Ericsson in Aachen. Due to mandatory usage of existing backhaul lines of Deutsche Telekom, the backhaul link went via Munich to Aachen, obtaining thus a total distance of about 860 km (air distance). The German network had also a MEC server, but it was located in Aachen and, thus, not locally on site. As it was co-located with the core network, and thus about 860 km away, the term "MEC" is questionable and brings us back to the definition of the "Edge", but, considering the situation with the French MEC described above, it allowed the project members to experience the difference between a local MEC server and a MEC server further away. For the corridor F-D, a direct connection between the two MEC servers was present, which was not realized in the corridor D-L as detailed next.

### *B. Corridor Germany – Luxembourg (D-L)*

The Luxembourgish 5G NSA radio cells deployed in Schengen (Luxembourg) were connected to a core network hosted by Post in Luxembourg City which is about 20 km away (air distance). The user data was locally broken out there as well. The local breakout and MEC were thus only about 20 km away from the radio cells. The German NSA cell deployed in Perl (Germany) was connected to a core network hosted by Ericsson in Aachen. For the same reason as above, the backhaul link went to Aachen via Munich. The local breakout and MEC server were placed there as well. This is about a total of 910 km (air distance). In the D-L case, the two MEC servers did not feature a direct connection.

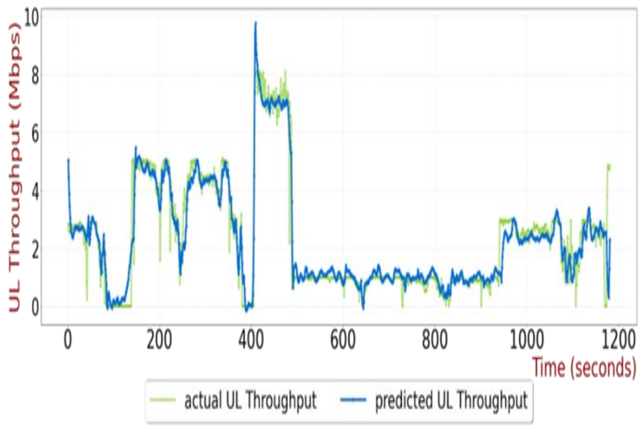


Fig. 1. Dynamic QoS prediction method (5-Seconds prediction horizon): Actual vs predicted ToD UL throughput

## V. Trial Results

### *A. Use case agnostic results*

The trials carried out in the two corridor areas proved that seamless service continuity on 5G networks can be guaranteed across borders. The service continuity solution implemented in 5GCroCo is achieved through a cross-border (and cross-MNO) handover as described in Section IV, which results in an almost imperceptible service interruption time of around 120 ms. This low interruption time is to be compared to the service interruption times that are achieved with other solutions, like Release with Redirect (RwR), which comes in two flavors depending on whether or not an S10 interface is available between the two national mobile networks. When an S10 interface is available, RwR achieves interruption times around 730 ms, which go up several seconds if the S10 interface is not available. In the latter case, the connection breaks and needs to be reestablished, which took more than 6 seconds with the devices used in the conducted trials.

### *B. ToD – Predictive QoS*

During the ToD trials, the performance of QoS prediction techniques presented in [7] was evaluated. The analysis focused on the prediction of the UL throughput of the ToD flow, which is an important metric for high-quality video streaming. The evaluation contributed to investigating the feasibility of the real-time QoS prediction at the service flow level to derive useful observations. Different types of configurations were used, according to the selected input data, in order to predict the ToD UL throughput by using the static and dynamic QoS prediction methods. The input data consisted of application and network related information such as current location information of the vehicle (latitude, longitude, velocity), future location information of the vehicle (latitude, longitude), uplink throughput, uplink BLER, uplink SNR, uplink MCS, and RSRP. The exploited dynamic QoS prediction model was an LSTM (Long Short-Term Memory)-based Autoencoder neural network. The Autoencoder consisted of one Bidirectional LSTM encoder and one LSTM decoder. The results shown in Fig. 1 visually indicates that the combination of the ToD service application and network-related information can provide high prediction accuracy for a 5 s time horizon. More detailed results can be found in [3].

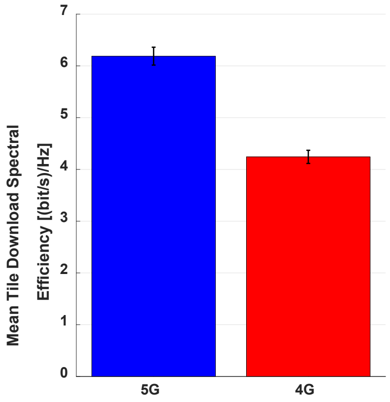


Fig. 3. Mean Tile Download Spectral Efficiency for Static Vehicle in Luxembourg for Tile Size 130 MByte; 4G vs. 5G.

### *C. HD Mapping – 4G vs. 5G*

In the HD Mapping trials, two advantages of 5G over 4G were observed and quantitatively validated: The lower delay of 5G allowed to quicker reach the peak throughput, which is benefitial for small map tile sizes, in this case 13 MByte. Furthermore, the higher peak througput of 5G vs. 4G allowed higher throughputs per tile, which is especially obvious for large tile sizes 130 MByte and 10 Mbyte for downloads and uploads, respectively. Observe that large tile sizes correspond to many vehicles simultaneously using the network.

Fig. 2 visualizes the throughput advantage of 5G over 4G measured in the trials carried out for the HD Mapping use case. A fair comparison can only be achieved by normalizing for the spectrum bandwidth and TDD pattern. The 5G system operated at 40 MHz bandwidth with 3.75 out of 5 resources in time allocated to the downlink. This resulted in 30 MHz effective bandwidth. For 4G operating in FDD, the bandwidth 10 MHz was used to calculate the spectral efficiency. As it can be visually observed in Fig. 2, the spectral efficiency gain of 5G over 4G in the downlink is 45 %.

### *D. ACCA – Cross-border/-MNO handover with MEC*

The Cross-border / -MNO ACCA trials carried out in the F-D corridor used a home routed handover. In France, the data was locally routed to the MEC server, while in Germany, the data was home routed to the French MEC server. This is the classic handover occurring at the border.

Fig. 3 shows Application Level Latency measurements for a collection of 10 handovers obtained by crossing the border between France and Germany forward and backward, France being the home country, Germany being the visited country. The results were obtained in two different days with continuous driving for a longer period of time on the same route. As can be seen, lower latencies were observed when the vehicle was connected to the French network whereas, higher latencies were observed while the vehicle is connected to the German network, which is, of course, to be expected given the network architecture described in Section IV.A. Notice that the overserved latency in France is about 25 ms and in Germany about 90 ms, with the different spikes between 150 and 350 ms corresponding to the handover situation. We recall here that these values correspond to application level latencies and are compatible with the handover interruption time of about 120 ms described in Section V.A.

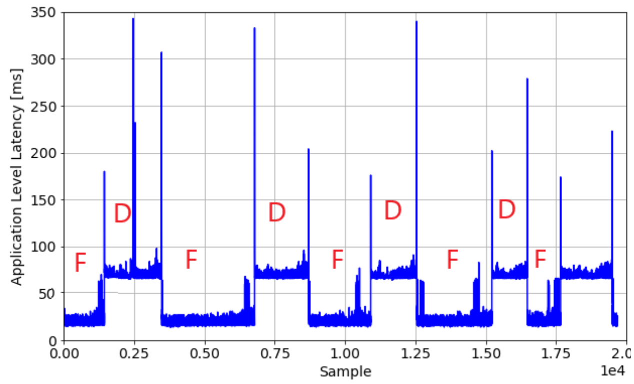


Fig. 2. Application Level Latency measurement with Hand Over enabled from France to Germany and back

## VI. Conclusions

In 5GCroCo, key 5G technologies for CAM services have been analysed and validated across borders. All three 5GCroCo use cases (ToD, HD-Mapping and ACCA) were completely set-up and realized and car-OEMS implemented all the necessary components directly in their vehicles. All test and trials were carried out, including at the cross-border, with dedicated KPIs measured and analyzed.

The service continuity solution implemented in 5GCroCo is achieved through a cross-border (and cross-MNO) inter-PLMN handover, which results in an almost imperceptible service interruption time of around 120 ms, ensuring the continuity of CAM services. Although not presented in this paper, the conducted trials also validated that the 5GCroCo network provided a mean network RTT latency of around 8-9 ms and maximum observed DL/UL throughputs were around 800 Mbps and 150 Mbps, respectively. Trials carried out in the cross-border corridor areas proved that seamless service continuity on 5G networks can be guaranteed across borders and provided an experimental validation of the key 5G technologies, out of which selected examples were presented in this paper.

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