5G Blueprint: Enabling Cross-Border Automotive with 5G Standalone Seamless Roaming

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***Abstract*—5G and beyond 5G networks will enable a set of novel applications and industry verticals with very different requirements, such as agriculture, transport, or healthcare. For example, to support automotive and teleoperated transport, 5G systems are expected to guarantee URLLC (Ultra Reliable Low Latency Communications) requirements with minimal interruption times. The 5G-Blueprint project aims to provide technical solutions for 5G-enabled uninterrupted (i.e., seamless) communications in cross-border teleoperated automotive use cases. To support these services, we present, to the best of our knowledge, the first practical implementation of seamless 5G Standalone Roaming using off-the-shelf UEs and gNBs. Further, we analyze the factors contributing to the interruption times in the call flows and propose changes to the call flows to reduce them. Preliminary results of our experiments show an interruption time in the range of 100-150 milliseconds, thereby meeting the requirements of teleoperated automotive services.**

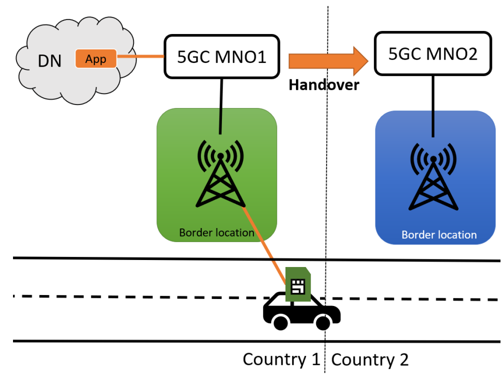


Fig. 1: Seamless SA Roaming: While crossing the border, the UE (subscriber of the green network) is handed over to the blue network.

I. Introduction

Vehicular teleoperation is a step towards autonomous driving and other advanced Cooperative, connected and automated mobility (CCAM) use cases. It is an exciting alternative for road transport and logistics in the context of the current labor shortage affecting multiple industry sectors. However, to enable such mission-critical use cases, 5G connectivity should satisfy stringent latency requirements and remain uninterrupted. This task is more challenging in a cross-border roaming scenario where the vehicle has to be handed over to the network of a different operator in a different country.

In previous trials, cross-border roaming has been enabled in a non-standalone (NSA) setting (i.e., 5G RAN with a 4G core)[1] for cross-border connected vehicles. Furthermore, 5G-Blueprint precursor 5G-MOBIX[2] has implemented a standalone (i.e., two 5G SA cores) roaming solution based on local-breakout (LBO). In this solution, the UE, after crossing the border, (1) disconnects from the current serving PLMN, (2) searches for a new PLMN, and upon finding it, (3) registers and establishes a new session. However, the observed interruption times were in the range of tens of seconds [3], which is not acceptable for teleoperation use cases mentioned above, which can only tolerate an interruption time in the range of hundreds of milliseconds. When looking at the factors that contributed the most to the latency, we can identify two main culprits: (1) the time needed to search for the new network after losing connectivity to the current serving PLMN and (2) the time needed to establish a new session.

To reduce these factors, the 5G-Blueprint[4] project aims to design and demonstrate technical solutions and business and governance models to support 5G-enabled uninterrupted cross-border teleoperated transport. As part of it, this paper presents the first practical implementation of Seamless 5G SA Roaming using off-the-shelf UEs and gNBs. To reduce the time needed to search for a new network upon losing connectivity, 5G SA Seamless Roaming uses the handover procedure between the two PLMNs (Figure 1). Moreover, by leveraging the home-routed roaming, the UEs session in the HPLMN is reused, and the UE can keep its assigned IP, reducing the second factor. The developed solutions were validated in-lab and will be tested during trials on a Dutch and Belgian cross-border corridor with similar settings.

The remainder of this paper is organized as follows: Section II provides a background on the 3GPP standards for seamless roaming and presents the proposed solution. Section III describes the methodology and the obtained results, while Section IV concludes the paper.

II. Seamless Roaming

Section II contains the details on the current state in the standardization of the procedures used to implement the seamless 5G SA roaming (Sec. II-A), the description of the used interfaces and the ways the procedures to implement the seamless roaming (Sec. II-B), details on the necessary RAN configurations (Sec. II-C), and the proposed optimizations to the call flow to reduce the downtime (Sec. II-D).

A. *Current state in standardization*

Current 3GPP 5G specifications support two types of roaming implementations in standalone (SA): Local breakout (LBO), where data traffic is directly routed from the UPF of the Visited PLMN to the Data Network, and Home-Routed (HR),

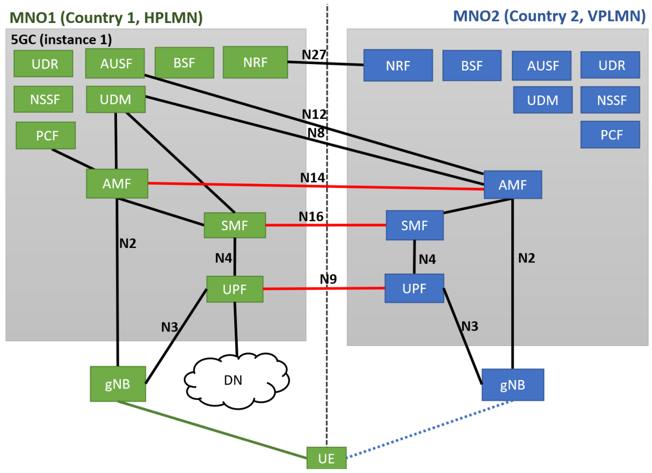


Fig. 2: Architecture for Seamless 5G SA Roaming.

where traffic is sent back to the UPF of the Home PLMN to be classified and routed. However, the roaming call-flows are specified under the assumption that the PDU session is terminated at the home PLMN, and a new one is established at the visited PLMN. This results in long interruption times that are unacceptable for vehicular teleoperation.

Additionally, a procedure is defined for performing a N2 handover between two gNBs within a PLMN via the N14 interface, where the UE context is transferred between two gNBs through the N14 interface connecting their AMFs in two phases: a preparation phase where the context is proactively transferred to the target gNB, and an execution phase where the UE leaves its current gNB and connects to the target gNB. In the latest Release of the 5G specifications (I.e., Release 18), a clarification has been added to the call-flow to specify the exchanged messages between AMFs in an inter-PLMN handover scenario.

Further, another procedure can be found in clause 4.23 from 3GPP T.S. 23.502 [5] for supporting deployment topologies with specific SMF Service Areas to allow I-SMF insertion, change or removal. The procedure can be applied to support scenarios of inter-PLMN handover in Home-Routed roaming between the HPLMN and VPLMN in both directions, and between multiple VPLMNs where the I-SMF is the V-SMF.

B. Procedures and interfaces

To minimize the interruption time, the seamless roaming solution builds on the results and findings of 5G-MOBIX. As shown in Figure 2, the 5G architecture used for 5G SA roaming includes the standardized N14 (Between AMFs), N16 (Between SMFs) and N9 (Between UPFs) interfaces represented with a red line, which were implemented within the project, while reusing the other roaming interfaces from the 5G-MOBIX project.

Figure 3 describes the simplified call-flow of the 5G-Blueprint implementation. It combines the Home-Routed (HR) roaming (interfaces N16 and N9) and the N2 handover over the N14 interface procedures from the 16th Release of the 3GPP specifications[5] with further enhancements to reduce

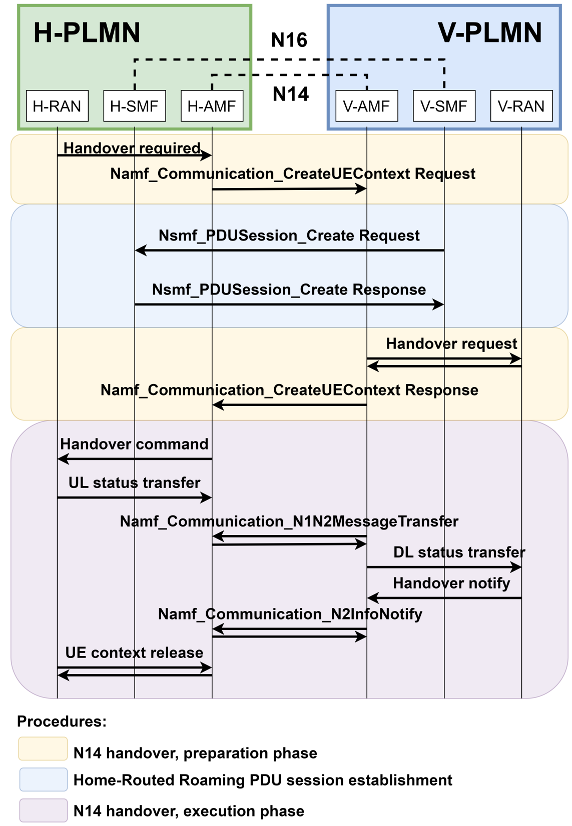


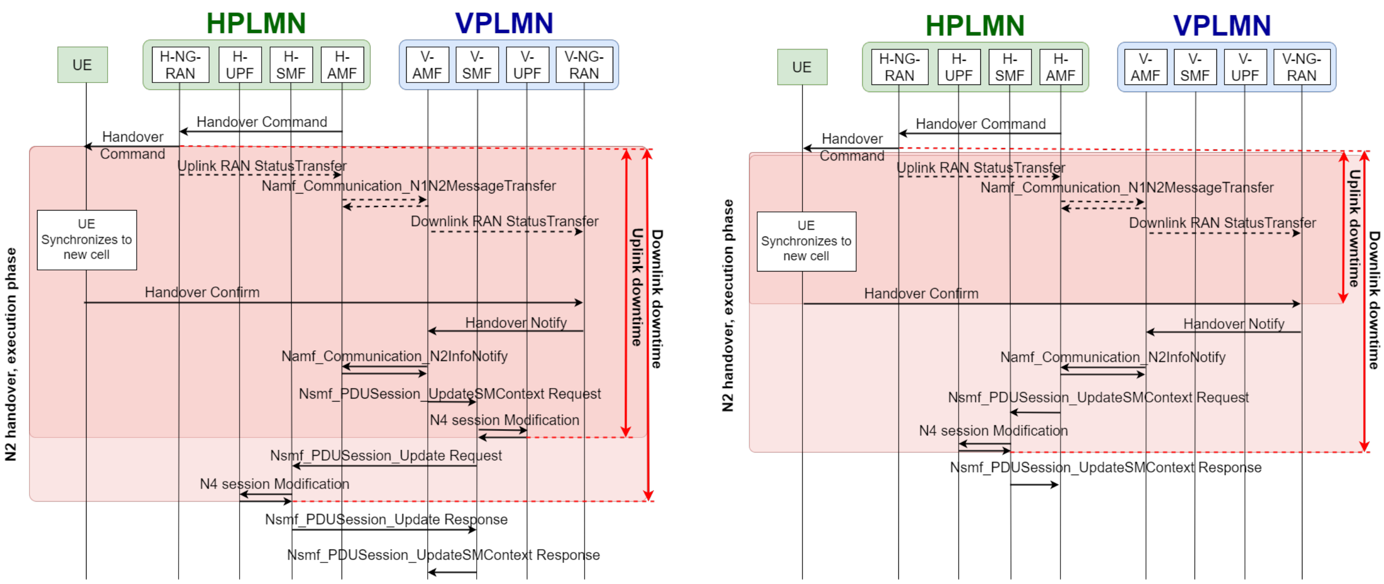
Fig. 3: Simplified call-flow for Seamless 5G Roaming.

downtime compared to the procedure proposed in clause 4.23 from 3GPP T.S. 23.502, as will be discussed in Sec II-D. In this call flow, after the H-RAN determines that a handover for a UE is needed (based on the received UE's measurement reports), it notifies the H-AMF that, subsequently, using the N14 interface, notifies the V-AMF that a handover is needed (yellow square). The V-PLMN provisions all needed NFs (e.g., gNB, UPF), and using N16 establishes a new N9 tunnel to route the UE's traffic back to the H-PLMN after the handover (blue square). Finally, the UE is handed over in the execution phase of the N14 handover (purple square).

C. RAN configuration

To support a handover between the gNBs of different PLMNs, each gNB should be configured with the PLMN ID of the other network as an Equivalent PLMN to enable UE context transfer between the gNBs. Alternatively, for a more automated configuration of the gNBs, the Mobility Restrictions List (MRL) in the subscription data of the UE could be used to specify that (a set of) gNBs of the V-PLMN are allowed for the UE, which allows the H-PLMN to select a gNB from the VPLMN as targets for handover.

Further, each gNB taking part in the seamless handover must have the gNB(s) from the other MNO(s) configured as a neighbor cell(s). To configure the neighbor cells, the MNOs need to exchange information, such as SSB frequency, physical cell ID, etc.. This way, the current serving gNB will instruct the connected UE's to perform measurements on frequencies used by other MNO's gNBs in the area.



(a) Original procedure as described in T.S. 23.502, clause 4.23.

(b) Optimized procedure as described in Sec II-D.

Fig. 4: N2 handover execution phase without (a) and with (b) the optimizations proposed in Sec. II-D. The downtime of the optimized procedure is reduced by already adding forwarding rules in the preparation phase, and reusing the interface between the H-AMF and H-SMF to change the downlink FAR parameters.

Finally, if both of these configurations are present on the gNB, the cells from the other MNOs will be considered valid handover targets for the connected UEs.

D. Proposed optimizations

To further reduce downtime, we modified the original call flow (T.S. 23.503, clause 4.23) by transferring additional information on the UE context between PLMNs in the handover preparation phase, which allows removing two inter-PLMN messages between SMFs in the execution phase and reduces downtime. Namely, by transferring the SM context ID in the preparation phase, the N4 session modification procedure in the UPF of the HPLMN can be triggered by a pre-existing earlier message between the AMFs, and does not require a message exchange between SMFs (which, as inter-PLMN messages, introduce a more significant latency penalty compared to intra-PLMN messages). Removing those messages allows us to perform the N4 session modification and restore connectivity sooner, ultimately reducing downtime.

Moreover, in the preparation phase, the uplink rules in the V-UPF are already provisioned to forward data, causing the uplink to work from the moment the UE is synchronized to the new cell in the VPLMN. Figures 4a and 4b illustrate the difference in downtime for both the uplink and downlink, without and with the proposed optimizations, respectively.

Figure 4a shows the execution phase for the N2 handover procedure as described in the 3GPP standards in T.S. 23.502, clause 4.23. After the UE synchronizes to the new cell, and sends the Handover confirm message to the VPLMN, the V-AMF informs the V-SMF and H-AMF of this. V-SMF subsequently changes the associated Forwarding Action Rule (FAR) in the V-UPF for the uplink data to Forward. Next,

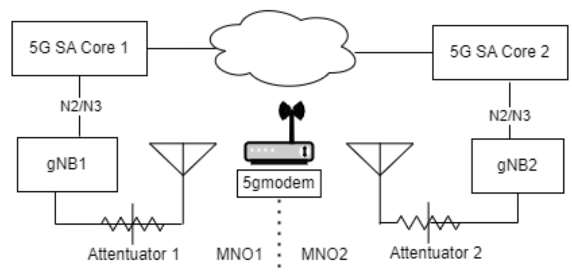


Fig. 5: Lab setup

the V-SMF informs the H-SMF and instructs it to change the downlink FAR to forward data to the N9 interface instead of the N3 interface. After this message, both uplink and downlink are re-established.

Figure 4b shows the optimized procedure as described in Section II-D. After the UE synchronizes to the new cell, and sends the Handover confirm message to the VPLMN, the uplink data is already processed properly (as the uplink FAR was set to Forward in the preparation phase). Next, similar to the original procedure, the V-AMF informs the H-AMF that the handover was successful. Then, different from the standardized procedure, the H-AMF immediately informs the H-SMF which then directly changes the downlink FAR to forward data to the N9 instead of the N3 interface.

III. Test Setup

A. Lab setup

Our lab setup consists of two Intel NUCs, each running a 5G SA core, two off-the-shelf gNBs (e.g., Ericsson, Huawei),

	Preparation phase duration	Average UL downtime	Average DL downtime
Unoptimized procedure	22 ms	97 ms	98 ms
Optimized procedure	29 ms	92 ms	95 ms
Unoptimized procedure (20ms delay)	105 ms	137 ms	159 ms
Optimized procedure (20ms delay)	108 ms	93 ms	115 ms

TABLE I: Procedure optimization results

and a 5G modem (e.g., Quectel, V-TRON) acting as a UE. Two attenuators are used to attenuate the signals from the gNBs. This way, we are able to mimic cross-border scenarios (e.g., a car moving away from the coverage area of MNO1 to the coverage area of MNO2). The two NUC machines were time-synchronized using `chrony` to be able to compare timestamps across the cores. Lastly, `tc-netem` was used to introduce delay in the control plane connections between the NUC machines, enabling us to study how our solution can scale as inter-core latency (and thus the latency for all the inter-PLMN messages) increases. The procedure is tested with no delay and with 20ms delay between the cores.

B. Results

We compared our implementation to the results achieved in the 5G-MOBIX project. To do so, we generated UDP traffic from the UE (using iperf) and measured the time needed for the UE to switch the UE data traffic between the MNOs. All experiments were run 10 times. Our results show that, due to the N14 handover and the reuse of the already established session in the HPLMN, the average downtime can be significantly reduced from 14s (which was the minimum achieved in 5G-MOBIX) to 92ms for the uplink and 95.25ms for the downlink.

Additionally, to evaluate the proposed optimization to existing 3GPP procedures, experiments have been conducted by measuring the downtime for the proposed solution and comparing it with the downtime obtained from the implementation of the procedure in clause 4.23 from 3GPP T.S. 23.502 in the same setting. The results can be found in Table I. They show a decrease in downtime that scales with inter-core latency. When the latency between the cores is less than a millisecond, the optimized procedure is marginally faster than the original procedure: 92 and 95 milliseconds up-link downtime respectively. We can observe a similar pattern for the down-link downtime: 95 and 98 milliseconds respectively. As we introduce delay between the networks, this difference becomes larger. Indeed, after introducing a 20 millisecond delay (both ways) between the two cores, we see that both the up-link and down-link differences have grown to more than 40 milliseconds.

IV. Conclusion and Future Work

To enable cross-border teleoperated services, the 5G-Blueprint project proposes a solution that combines the Home-routed roaming and N14-handover, which preserves the vehicle's session and context and minimizes service interruption time to the range of hundreds of milliseconds. Moreover, the proposed solution introduces optimizations that minimize the downtime compared to the standardized procedure in 3GPP and is validated in lab.

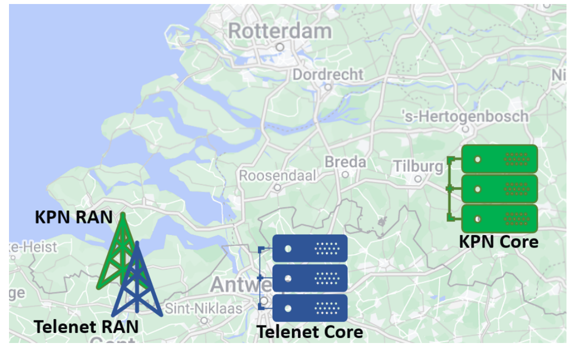


Fig. 6: Setup for the trials.

As future work, the roaming implementation is to be further evaluated in the field at the border between the Netherlands (San van Gent) and Belgium (Zelzate) as shown in Figure 6. The trial tests consist of a vehicle driving across the border a number of times to collect measurements for: RTT (Round Trip Time), Signal Strength, and throughput (for both uplink and downlink). To do that, the same 5G SA cores and configuration of the gNBs from the lab are used. Our preliminary field results show no significant deviation from the lab results.

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