Current 4G Networks Limitations Pleading for 5G for Cross-border CAM Services [5G-CARMEN]

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***Abstract*—In this paper, by means of both real field measurements and simulations, we illustrate some key limitations of current networks deployments (up to 4G) with regard to cross-border CCAM service requirements, mostly in terms of received power coverage, service interruption and latency. We first provide a qualitative analysis of on-board data resulting from a preliminary collection campaign, which was carried out on real portions of motorway at both German-Austrian and Italian-Austrian borders. Then, we further exemplify both service coverage shortage and network capacity issues at the latter Italian-Austrian border based on simulations, as a function of road traffic conditions and deployment. Finally, we discuss the previous limitations in light of the gradual performance improvements foreseen with 5G deployments.**

Keywords—Cooperative Connected and Automated Mobility, cross-border services, 5G, Vehicle-to-Network connectivity

I. Introduction

Border crossings pose unique challenges for the future provision of services to vehicles. Within the 5th generation of communication networks (5G), a vehicle is expected to be seamlessly covered with Cooperative Connected and Automated Mobility (CCAM) services, regardless of which country it lies in, which mobile network it is connected to and which network equipment provider has equipped it. Accordingly, several proposals have already been put forward regarding suitable Vehicle-to-Network (V2N) connectivity architectures and strategies in the frame of 5G-related collaborative research projects [1]-[4]. However, given the variable maturity of these proposals (in terms of building blocks development, overall system integration and/or field tests), a strong consensus has not been reached yet, neither on the definitive form to be taken by full-flavored 5G deployments along such corridors, nor on their actual capacity to fulfill all CCAM requirements on real routes (See Table 1).

For this reason, as a complementary contribution to the pure 5G trials currently undertaken in the 5G-CARMEN project [5], we have also considered studying the current situation of a real corridor route from Germany to Italy via Austria, based on the coverage allowed with existing commercial networks and mobile technologies (i.e., 2G to 4G). The main idea was to concretely illustrate some of the major real-life limitations of these networks specifically in cross-border situations, finding out where the transitions between countries take place and which dominating factors are practically at stake. In this paper, we first account for a preliminary cross-border field measurements campaign, while providing a qualitative analysis of resulting received power coverage, interruption and latency observations. Asides, we also report herein system-level simulations of a canonical cooperative manoeuvring case under different traffic conditions, assuming current network deployment and settings. In light of CCAM requirements, the 4G limitations herein shown by means of both measurements and simulations can also give helpful insights and guidelines for the design and dimensioning of such optimized 5G networks.

Use case	Max. e2e latency (ms)	Reliability (%)	Data rate (Mbps)
Advanced Driving	3-100	90 - 99.999	10 - 53
Vehicle Platooning	10-25	90 - 99.99	50 - 65
Extended Sensors	3-100	90 - 99.999	10 - 1000
Remote Driving	5	99.999	25 (UL) / 1 (DL)

Table 1: Typical network requirements for CCAM services [10].

II. Real Field Measurements

A. Field Measurement Settings and Methodology

An evaluation of current mobile networks coverage (mostly in 3G and 4G) was conducted in October 2020 on portions of the motorway at both German-Austrian and Austrian-Italian borders (resp. A12-A93 and A13-A22 junctions). The involved measurement setup was composed of one single vehicle, including an on-board GNSS receiver synchronized with standard commercial mobile phones, thus emulating a geo-referenced car endowed with V2N capabilities. In each tested environment, the experience of crossing the border was repeated many times (in opposite driving directions) to reveal possible asymmetries in terms of network coverage/selection. Ping operations were reported at the average period of 1 sec with SIM cards from Austrian operator Magenta.

B. Qualitative Analysis of Collected Data

1) German-Austrian border

Figure 1 shows a 3D bar representation of the received signal strength (RSS) levels measured (i.e., beyond receiver's sensitivity) from existing cellular sites for both Magenta and Deutsche Telekom (DTAG) networks, while driving along the A12-A93 motorway in the northern direction from Austria to Germany. The distinct bar colours account for different Base Station (BS) sites (i.e., sectors combined) and/or different technologies (e.g., 3G, 4G). It is thus observed that Magenta network can still be received 17 km after crossing the border on the German side. This is due to the co-linear shape of the border. However, interruptions have also been clearly noticed after crossing the border. Typically, an interruption of about 96 sec was reported from Magenta to DTAG networks (i.e., over an equivalent distance of 3.2 km). This long interruption time is caused by the UE scanning the spectrum to find a network it can use, after which the UE needs to register with this new network.

Figure 2 shows a similar RSS representation at the same border, while driving from Germany to Austria. The German network was thus still received up to 8.5 km in Austria, whereas an interruption of about 12 sec was reported. It is remarkable that the geographical switching point between the networks is 25.5 km different when travelling south or north on the motorway.

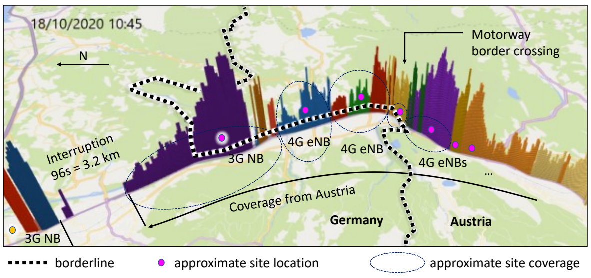

Figure 1: RSS from existing cellular sites (Magenta and DTAG networks), while crossing the border from Austria to Germany.

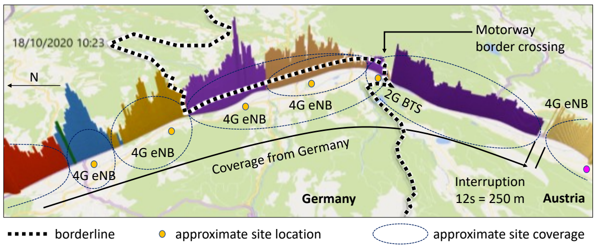

Figure 2: RSS from existing cellular sites (Magenta and DTAG networks), while crossing the border from Germany to Austria.

2) *Austrian-Italian border*

Figure 3 also shows the evolution of RSS levels measured from existing cellular sites for both Magenta and Telecom Italia Mobile (TIM) networks, while driving south along the A13-A22 motorway from Austria to Italy. Interestingly, it can be noted that Magenta's 4G enabled to cover a 800m-long tunnel section on the Italian side right after the border, with a very short/limited gap (in its very last part only). When driving from Austria to Italy, the interruption lasted 25 sec and the Austrian network was received 4 km into Italy. On the other direction, the interruption was 11 sec and the Italian network was still received 3.7 km after the border, using GSM in the last kms though. Some interruptions around the tunnel section and at the border can also be noted. In this case, the interruption from Magenta to TIM networks lasted for about 11 sec only (see Figure 4).

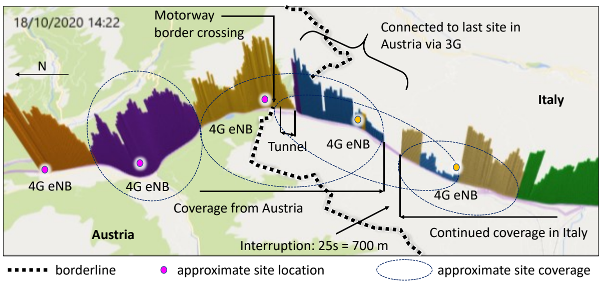

Figure 3 RSS from existing cellular sites (Magenta and TIM networks), while crossing the border from Austria to Italy.

Figure 5 shows the observed latency while crossing the border from Italy to Austria after analysing regular pings (See II.A) to an Italian server (www.unibz.it). We distinguish five corresponding time zones. First, when being fully associated to TIM network, measurements are in the range of 60 and 140 ms. The reason for this order of magnitude lies in the standard home routed procedure for data roaming. All data packets are thus first routed through the TIM network in Italy, forwarded to the home network in Austria and finally forwarded back to the Italian server from Austria. In the second and third zones, the tunnel and the following border area under moderate network coverages can be recognized, experiencing fluctuations and timeouts. The fourth zone under full interruption is pointless. After re-associating with Magenta's network, measurements are more stable again, around 30 ms. Measurements to pinging Austrian and German servers have also been carried out and show a similar behaviour.

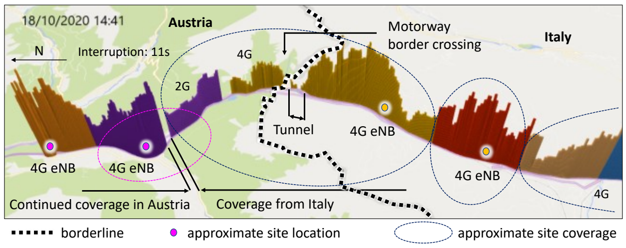

Figure 4: RSS from existing cellular sites (TIM and Magenta networks), while crossing the border from Italy to Austria.

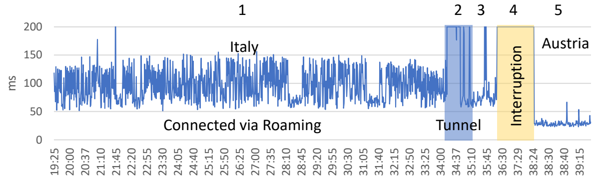

Figure 5 Latency as a function of time, while crossing the border from Italy to Austria (different measurement than Figure 4).

C. *Discussion on Measurements*

The very long interruption times are not discussed further, as they are deficiencies of the current generation networks without inter-PLMN handover for data services. The measurements clearly show that the current networks have long ranges into neighbouring countries and handovers to the neighbouring network take place as late as possible. In all measured cases, the first available site of the new operator after the border has been ignored, which shifts the handover point very far inland. For future 5G CCAM services, this leads to very sub-optimal situations in some areas. For example, all transit traffic coming from Austria is still 17 km connected to the Austrian network within Germany. However, local German traffic in the same direction is connected to the German network. Localized critical services like Cooperative Lane Merging (CLM) are thus complicated between such vehicles. These reasons argue for the introduction of geographically defined handover points at border crossings used in 5G to be able to offer optimal low-latency services in all motorway sections. Hereafter, based on complementary simulations, we assess other current networks limitations, in terms of capacity and reliability, which could not be captured by previous measurements.

III. SIMULATIONS

A. *Success of V2N-based CLM Negotiations*

The considered CLM use case is illustrated in Figure 6 [6], [7], where one first vehicle (initiator) intends to insert onto a side lane comprising other vehicles. We assume V2N connectivity with respect to 4G BSs, which are connected to a centralized computation-storage resource running the manoeuvre management application (e.g., Multi-access Edge Computing (MEC)). In a typical centralized messages exchange sequence [6], [7], broadcast status messages from the vehicles are collected by BSs and forwarded to the MEC. The initiator sends an event-driven request-to-merge message, which is forwarded to the MEC. In return, to the best of all collected status messages, the application sends via the BSs some recommendation message(s) to the side vehicle(s), as well as a safe-to-merge (or merge denial) message to the initiator. The period between the initiator's request and the manoeuvre execution is referred to as the negotiation phase. We assume 125-bytes request-to-merge, notification and safe-to-merge/denial messages. Communications to vehicles are based on Decentralized Environmental notification Messages (DENMs), whereas Status update messages of 200 bytes are based on Cooperative Awareness Messages (CAMs).

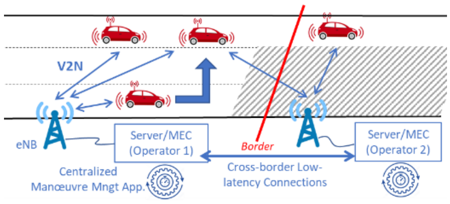

Figure 6: Generic deployment and system architecture for centralized CLM.

In a first system-level simulation flow [7], time-stamped Simulation of Urban MObility (SUMO) traces are generated offline. Deterministic power path loss maps are calculated via a proprietary simulator based on real BS sites/bands and a 3D digital model of the terrain in the Unity real-time development platform [9]. Finally, both path loss maps and mobility traces are injected in ns-3 network simulations. The test environment consists of a 4.5 km-long portion of the A22 highway at the Italian-Austrian border (See Section II.B.2). In this area, real measurements revealed an upper (resp. lower) limit on the average traffic density of 83 (resp. 28) vehicles per km, which has been used to configure our SUMO parameters. We assume default LTE specifications recommended in 3GPP 37.885 [8] for V2N evaluations and consider the closest BS operated by TIM at 800/1800 MHz in Italy and the closest two-sector BS operated by Magenta at 800 MHz in Austria.

For illustration purposes, Figure 7 shows the power path loss [9] with respect to the closest serving BS on the Italian side, along with 7 (resp. 30) simulated CLM locations (i.e., vehicles' centroids in red) under low (resp. high) traffic densities, assuming a unilateral flow of vehicles from Italy to Austria. Figure 8 shows the corresponding negotiation success rates averaged over all the CLM events as a function of so-called extra-latency. The latter stands for the a priori duration between the CLM request and the reception of the CLM notification, thus impacting the perceived location information. The performance gap between low and high traffic densities reflects the spatial distribution of CLM events.

Figure 9 also shows particularized negotiation success rates per CLM index (i.e., per CLM location). The dominating impact of location is then even more noticeable, with 4 (resp. 17) failed CLMs out of 7 (resp. 30) under low (resp. high) road traffic density. This is typically the case for CLMs occurring in the tunnel, thus corroborating the interruption observed on Figure 4, and/or at the cell edge, with no possibility to perform fast handover/network reselection (i.e., in lack of inter-MNO cross-border coordination beyond conventional roaming). Besides, the acceptance ratio of other CLMs occurring under V2N coverage is excellent according to the connectivity criterion. Other simulations (not shown here for paper length limitations) assuming systematic 10 Hz transmissions by 250 other vehicles in the same area show that heavy network loads experienced under high traffic could make CLM acceptance rates decrease down to 12% (rather than 43% previously).

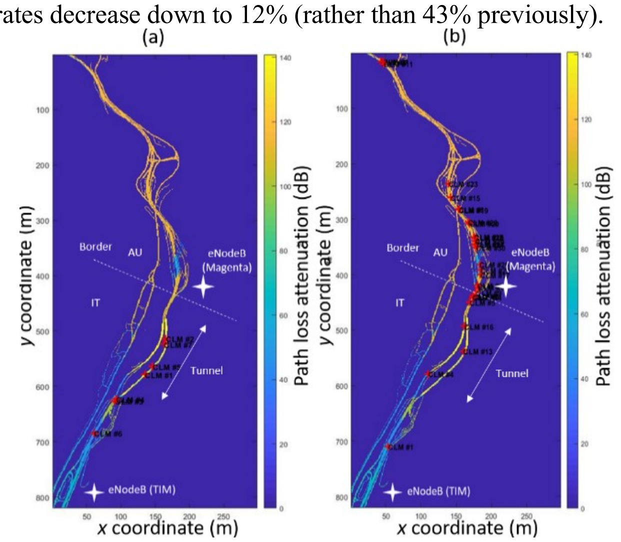

Figure 7: Power path loss wrt. one 4G BS operated by TIM at the Italian-Austrian border, along with simulated CLM events under low (a) and high (b) road traffic density.

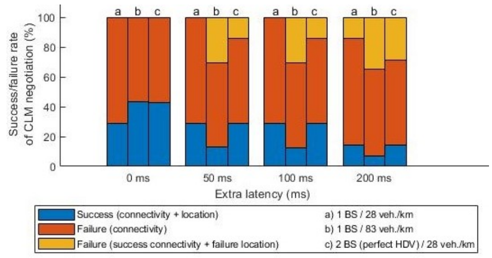

Figure 8: Average success rate of centralized CLM negotiations wrt. one 4G BS -a & b- (vs. seamless cross-border handover -c-), as a function of traffic density and overall negotiations duration.

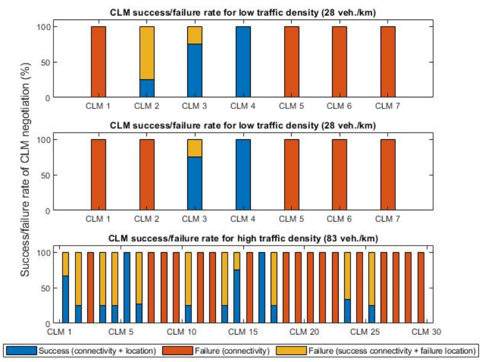

Figure 9: Success rate of centralized CLM negotiations per CLM event wrt. one 4G BS -top & bottom- (vs. seamless cross-border handover -middle-), as a function of traffic density.

For benchmark purposes, we have considered an idealized situation where cross-border handover would be transparently performed with respect to the first BS station on the Austrian side, as shown on Figure 8 (c) and Figure 9 -middle- for low traffic. As expected, the northern CLM event (#2) occurring right at the tunnel exit under decent coverage from at least one sector of the closest Austrian BS (See Figure 7 (a)) has now restored 100% of CLM acceptance in terms of connectivity.

B. V2N Capacity

As a complementary approach, for validation purposes, we also carry out preliminary evaluations of the capacity improvement in the same Italian-Austrian border scenario when deploying 5G base stations. This is realized by emulating a cellular radio network planning in a realistic version of the border scenario, initially matching the actual deployment of base stations (Dec. 2020). We perform this procedure aided by the same proprietary pathloss prediction tool as before (See Sec. III.A.2 [9]), as well as a capacity simulator developed in Unity. This simulator implements in a detailed model the geographical aspects of our border scenario. It also uses the Unity Asset Urban Traffic System 2020 (UTS Pro) for the on-the-fly generation of vehicle users with the same traffic densities as in Section III.A.2.

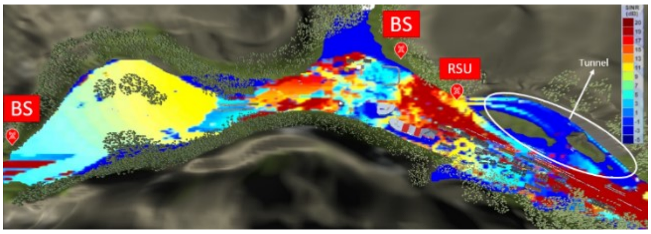

Figure 10: SNR results from the current deployment at the Italian-Austrian border.

Figure 10 shows the Signal-to-Noise Ratio (SNR) results of the current deployment assuming an upgrade of the two already existing cellular sites to 5G at 3.8 GHz (besides non-upgraded RSU). As shown, while the coverage is average, it is rather poor in the tunnel area (marked with a white ellipse). To solve this issue, we design a potential cellular deployment aiming at supporting a set of hypothetical 1st stage, 2nd stage, and 3rd stage deployment phase Vehicle-to-Anything (V2X) communication services, demanding 3, 6 and 30 Mb/s respectively. This is carried out by a heuristic, although machine-assisted, human engineering process that iteratively selects the number and best candidate locations of potential new cellular sites, while checking that the capacity constraints are fulfilled. Figure 11 shows the resulting coverage enhancement when 4 more cellular sites are added (green), with two 120º sectors each, for a total of six sites. The SNR improvement in the tunnel is hence particularly remarkable.

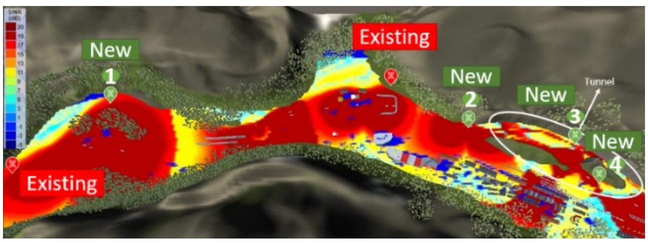

Figure 11: SNR results for a potential cellular deployment supporting hypothetical 1st to 3rd stage deployment phase services.

Deployment phase	Data rate requirement	Minimum received power	Probability of outage
1st stage	3 Mb/s	-85 dBm	0%
2nd stage	6 Mb/s	-82 dBm	1%
3rd stage	30 Mb/s	-67 dBm	4%

Table 2: Capacity results for each deployment phase

Finally, Table 2 summarizes the capacity results for the potential cellular deployment proposed with respect to each of its phases, and the obtained outage probabilities it is not fulfilling data rate targets. As shown, with almost 4% of outage, in this scenario, the 30 Mb/s requirement is difficult to fulfil in tunnels without deploying additional cellular sites.

IV. Conclusion

In this paper, based on both field measurements and simulations, we have concretely illustrated current limitations of existing cellular networks (i.e., up to 4G) for V2N-based CCAM service provision in a challenging cross-border context. As expected, the data collected on the field show that these 4G capabilities (i.e., based on current deployments and settings) would not meet the demanding CCAM requirements in terms of service continuity (with interruptions of several 100 s of meters in the best case) and latency figures (up to 200 ms) incompatible with foreseen high levels of automation (typically, level 4), thus clearly calling for the adoption of 5G. Simulations also show that in typical CLM applications under realistic cross-border traffic densities (especially under high network load), a large proportion of the CLM negotiations would fail due to unfavourable V2N connectivity with current 4G settings, suggesting densified deployments to restore full network capacity and/or tighter inter-MNO for truly seamless handover in 5G. Another finding from the specific geographic conditions of the corridor is that parallel borders and tunnels can lead to the unwanted effects that close vehicles in CLM are connected to different operators. Vehicles not crossing the border and transit vehicles should not have different behaviours on the same motorway section. In 5G, such large overlapping areas, where handovers are expected to take place, would require a tighter coordination between MNOs.

Other on-going works [5] concern a new 5G non-standalone measurements campaign in the same cross-border motorway environment for benchmark purposes (scheduled by Spring 2021) and new simulation-based techno-economic studies (incl. network and MEC deployment considerations), while assessing recently revised key performance indicators.

Acknowledgment

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