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Leveraging 5G SA for R&D: Capabilities and Beam-Based Empirical Analysis

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ABSTRACT The deployment of the Fifth Generation (5G) cellular networks has been addressed by the operators during the last years. However, it has been focused on 5G Non-Standalone (NSA) because they have leveraged the current Long Term Evolution (LTE) deployments. NSA mode uses LTE as anchor technology, allowing the operators to keep providing coverage in all the areas they covered with LTE, and to gradually introduce 5G in high-traffic or crowded areas. But NSA operation do not enable all the novelties introduced by 5G in order to achieve better performance. Moreover, novel features (e.g., beamforming) also introduce a lot of parameters whose configuration will become a work item towards network management. At the University of Malaga (UMA) MobileNet research group, a complete 5G Standalone (SA) infrastructure has been deployed for Research & Development (R&D) purposes. It is a private network composed of commercial equipment that allows controlling all the components, modifying all the parameters, and getting metrics from each part of the network. The aim of this work is to describe the infrastructure and potential opportunities regarding the different 5G-enabled Use Cases (UCs). To achieve this, an in-depth study has been accomplished in order to unveil the different options to configure the network, interact with it, and collect its metrics. First, the indoor and outdoor cells’ baseline performance has been measured. Then, research experiments have been performed on the infrastructure, and the results are presented in this paper. The infrastructure capabilities are mainly disclosed, and additional beamforming-based analysis is conducted from the real field measurements. This analysis comprises beam switching, beam-based localization, and Key Performance Indicator (KPI) definition toward network management.

INDEX TERMS 5G, SA, localization, network management, network configuration, beamforming.

I. INTRODUCTION

DURING the last years, the use of cellular networks has experienced a huge increment. Global mobile service revenue has grown around 15% over the last 3 years [1]. Moreover, baseline connectivity, service aggregation and experience-based connectivity are becoming the main driver for this growth in the upcoming years. 5G-New Radio (NR) specification was completed in 2017 and the number of 5G subscriptions started to increase, adding 160 million 5G subscriptions during first quarter of 2024 to exceed a total of 1.7 billion [2], where 5G subscriptions are counted when devices that support NR, as specified in 3GPP Release 15, are connected to a 5G-enabled network. The number of 5G subscriptions is set to reach nearly 5.6 million in 2029 [2].

On the other side, according to GSA, 300 operators have deployed 5G, but only around 14% of them are offering SA [1], [3], [4]. This allowed the Mobile Network Operators (MNOs) to maintain their coverage areas and progressively introduce 5G in areas with higher traffic demands. In some cases, they have been able to offer 5G NSA by developing

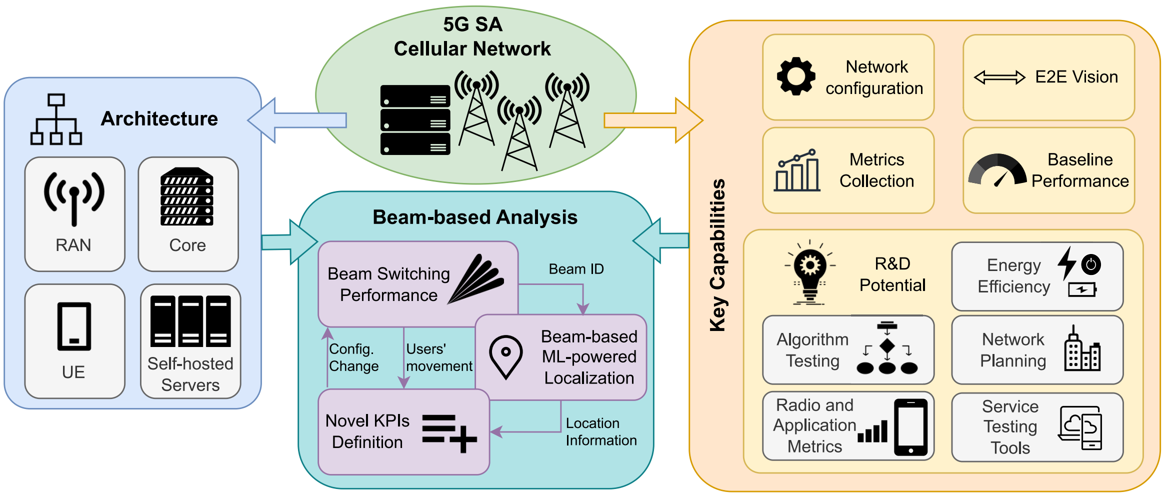

FIGURE 1. Overview of the present work.

a software update [5], becoming NSA networks in a quicker and more cost-effective way to deploy 5G by leveraging existing LTE Evolved Packet Cores (EPCs). Although, 5G have been based on three design principles: flexibility, forward compatibility, and ultra-leanness [6]. This means that MNOs should not find interoperability issues between radio access technologies when deploying it. Similarly, the flexibility in terms of frequency spectrum will enable a wide range of frequencies, from low frequencies for better coverage to high frequencies for enhanced capacity, including the Millimeter Wave spectrum (mmWave). The ultra-lean design deals with the reduction of "always on" transmissions. This latter, the implementation of virtualization technologies, which support multiple virtual networks on shared infrastructure, and the adoption of open-source solutions are expected to reduce infrastructure costs. These aspects outweigh the reluctance of MNOs to deploy 5G SA, primarily due to the economic investment. However, the users attached to 5G NSA are already seeing the 5G icon on their devices, and this may jeopardize the deployment process of SA by the MNOs.

Nevertheless, most of the enhancements embodied by 5G have been based on radio bandwidth increases [4], but they have not generally been exploited end-to-end yet. To the best of the authors' knowledge, the state of the art has focused on the enhancements introduced by 5G NSA operation, in use cases where throughput is critical (such as 360-video streaming) [7].

Similarly, network simulators are working on their 5G versions, but the first approaches have been based on implementing new propagation models at 5G frequency bands [8]. However, real field experiments usually differs from simulations and theoretical results.

On the other side, 5G promotes the use of Time Division Duplex (TDD) since it is motivated by beamforming techniques. Beamforming consists on steering the transmissions onto several directions in order to achieve better signal quality. But it requires signaling to maintain the connection or change to different beams. Thus, TDD enables the reciprocity assumptions between the Downlink (DL) and Uplink (UL) channels and exploit the channel state information transmitted in both directions. Also, TDD employs dynamic time slots for UL and DL transmissions, which means higher flexibility.

Consequently, new parameters appear because of the novel features, and become crucial from a network management perspective [9]. They will be initially configured with default parameters, but in most cases they could be optimized regarding the specific scenarios and common types of traffic by areas. Most of these parameters have not yet been addressed from the Self-Organizing Networks (SON) perspective. In contrast, operators do not usually support changing parameters on their commercial deployments because any issue could affect many users and give rise to complaints from their clients. Here, private network deployments are key for research purposes and, especially, when a generation change in cellular networks occurs, i.e., from 4G to 5G.

Moreover, some cutting-edge use cases feasibility studies require separated infrastructures as well as specific radio configurations [10]. Thus, the present work enables testing and verification capabilities, as well as the possibility to obtain metrics from all the parts of the network, and analyze how they are related or not in particular situations. In this sense, some services with high requirements, like Extended Reality (XR) or Cloud Gaming (CG), have already been deployed on the infrastructure without depending on any third-party service as a way to avoid uncontrolled bottlenecks at any middle point [7], [11]. This is envisioned by European Telecommunications Standards Institute (ETSI) as Multi-access Edge Computing (MEC) [12] and it will considerably reduce latency for applications as well as network congestion thanks to avoiding uncontrolled aspects of Internet.

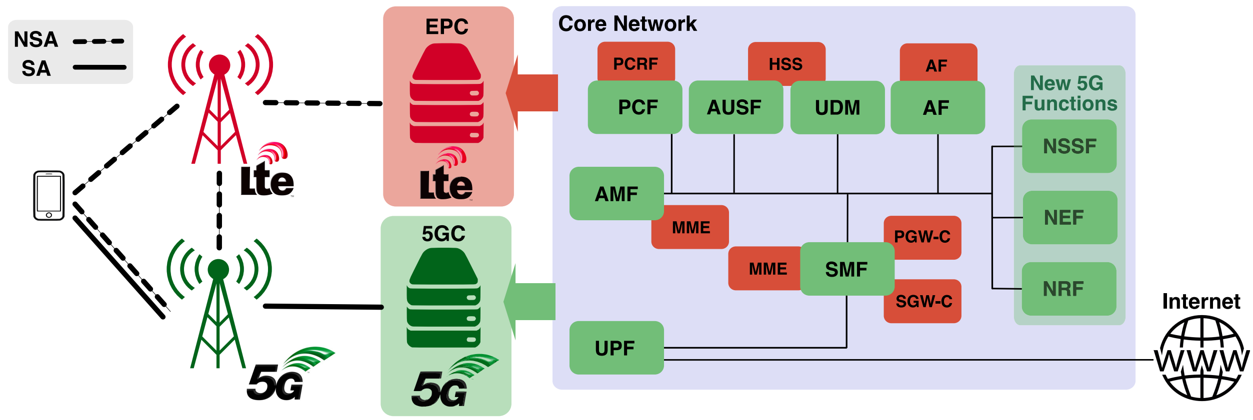

FIGURE 2. Cellular network architecture for 5G SA and NSA, including the mapping between elements of 5GC and EPC.

Furthermore, this deployment coexists with other radio technologies so that it is easy to simultaneously test a service and compare its performance. In [13], they used Ultra-Wide Band (UWB), LTE and 5G radio signals for indoor positioning.

Besides, there is a change in the tendency of 5G Non-Public Networks (5G-NPNs) deployments, where the enterprises seek to isolate their infrastructure from the public network, to hasten the readiness of their specific UCs with demanding requirements within the Industry 4.0 paradigm [14]. In this context, 5G have showed a better performance than Wi-Fi for an increase number of simultaneous users, and multi-connectivity (Wi-Fi and 5G) is also intended to be considered for critical applications [15].

One key contribution of the present work is to unveil the current capabilities of the 5G SA infrastructure deployed at the UMA MobileNet research group, revealing the potential opportunities that it offers for R&D purposes. Figure 1 summarizes the topics covered in this work, including the key aspects of the sections as well as the relationship between them. In this sense, real field experiments have been carried out on the infrastructure, and the results comprise overall performance but also a beam-based evaluation with different approaches, including localization, optimization and failure detection. Thus, it provides a general framework for the R&D activities, that is demonstrated for a real network scenario deployed by UMA MobileNet research group.

In this way, the remainder of this paper is organized as follows: Section II describes the infrastructure itself, and their main components. Section III discloses the technical capabilities regarding configuration, metrics collection, and baseline results for End-to-End (E2E) traffic. In Section IV, a beam-based analysis is carried out using real field measurements with a manifold objective. Finally, some conclusions are retrieved from this work in Section V.

II. ARCHITECTURE

In this section, architecture is described, including the details on the different elements. The infrastructure operates in 5G SA mode. Figure 2 depicts the main differences between 5G SA and NSA architectures, which resides in the need of the LTE Radio Access Network (RAN) and Core (EPC). In the figure, the right part illustrates the components of the core networks, mapping the elements from EPC to the new components in the 5G Core (5GC).

Figure 3 depicts the 5G SA network architecture, based on Nokia equipment that is deployed at UMA premises.

A. RAN

Firstly, the RAN is divided into two parts, indoor and outdoor deployments. They both work at band n78, but at different sub-bands, and use TDD. On the one hand, indoor Base Transceiver Stations (BTSs) are divided into six pico Remote Radio Heads (pRRHs), acting as two logical cells. This means that pRRHs operating synchronously as a single cell will be transparent not only for the users but also for the network itself, since there are no individual counters or KPIs per pRRH and no handover are required from one pRRH to another. However, it is possible to turn them on or off individually for energy saving purposes or coverage measurements if required. They are configured with 50 MHz Bandwidth (BW) and maximum output power of 20 dBm. They are placed inside the Superior Technical School of Telecommunication Engineering (ETSIT) building at UMA campus, covering two different floors and modules of the building.

On the other hand, three outdoor cells are deployed in the front part of the building, where there is a parking slot along with a smart natural park that belongs to UMA. They work as individual cells, and support beamforming up to 8 beams, where a set of different beam set configurations is available. Also, they are configured with 100 MHz BW and maximum output power of 31.9 dBm. The RAN parameters of the deployment are summarized in Table 1.

In addition, all radio parameters regarding RAN are configurable within the infrastructure's both indoor and outdoor deployments, including the most novel features, as TDD, where it is possible, e.g., to change the UL/DL patterns.

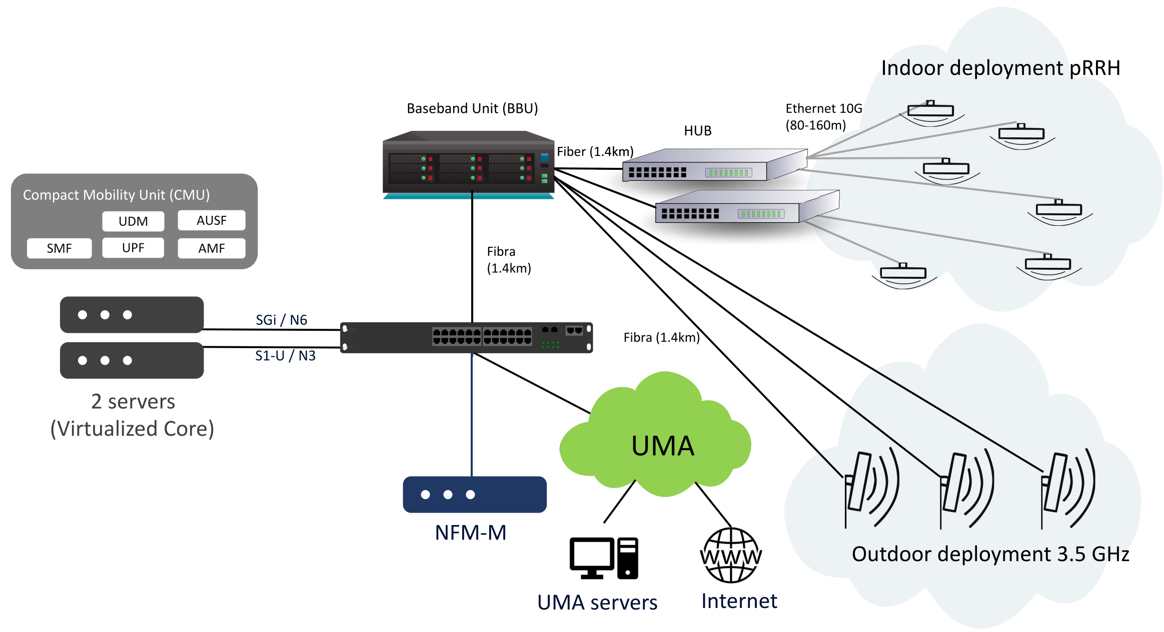

FIGURE 3. 5G SA Network Architecture deployed at UMA.

TABLE 1. RAN parameters of the 5G SA network.

RAN Characteristics	Indoor	Outdoor
Number of Cells (pRRH)	2 (6)	3
Bandwidth	50 MHz	100 MHz
Band	n78	n78
Max. Output Power	20 dBm	23 dBm
Horizontal Coverage	Onmidirectional	± 60º (7 dB)
Beamforming	No	1, 2, 4, 6, 8 beams

Lastly, the physical scenario is illustrated in Fig. 4. Here, the colored areas illustrate the estimated horizontal coverage amplitude of the cells, although the maximum range is not fairly represented. The remaining 3 pRRHs are placed on the 1st floor, specifically in the laboratories 1.1.1, 1.1.2, and 2.1.1, where the middle number corresponds to the floor and the last one to the room. Hence, they can be easily located as well when looking at the Fig. 4.

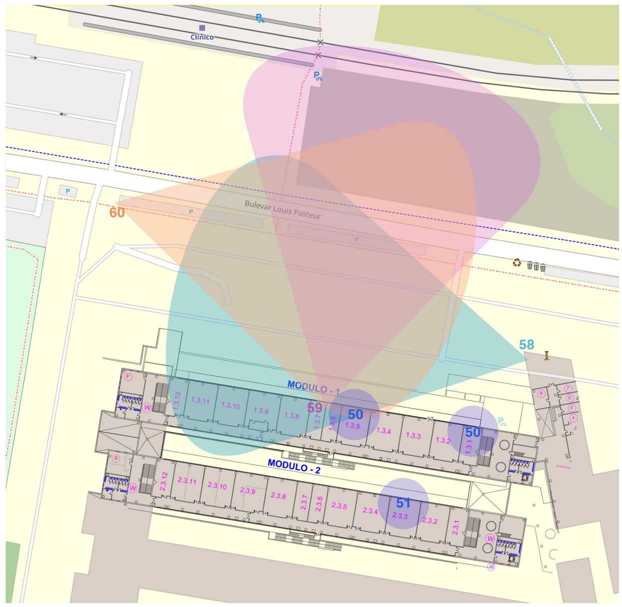

FIGURE 4. Physical scenario for the outdoor and 3rd floor indoor cells. Each number represents the Physical Cell Identity (PCI).

B. CORE

The network core is completely virtualized on 2 redundant servers that have two 25 Gigabit Ethernet (GbE) links between them, and two 25 and 10 GbE links, respectively, to main router. They work together for load balancing purposes as well as individually if there is an issue with one of them. They are running Nokia's proprietary Compact Mobility Unit (CMU), that includes the elements from 5G architecture: Session Management Function (SMF), Unified Data Management (UDM), User Plane Function (UPF), Authentication Server Function (AUSF), Access and Mobility Management Function (AMF). It is a fully commercial core with capability for hosting thousands of users, i.e., resources limitation would not be an issue regarding the core part. In addition, not being fully considered as part of the core, there is a component named Network Functions Manager - Mobile (NFM-M), that enables IP/MPLS management, including statistics and alarms related to traffic between network elements.

C. USER EQUIPMENT

Here, different alternatives to attach to the infrastructure are available. On the one hand, commercial phones attaching to 5G SA are currently restricted. However, it was possible to connect Samsung A52s as well as Motorola Edge 20 models to our infrastructure. On the other hand, external 5G modules that successfully connect are available as well: Simcom SIM8380G and Quectel RM510Q. In this case, they are usually connected to Small Form Factor (SFF) PCs or laptops in order to perform experiments on the network. Additionally, two Huawei Customer Premise Equipment (CPE) Pro 2 devices are in place to be used with XR equipment that do not have built-in 5G but Wi-Fi chipsets, like the Meta Quest 2.

D. SELF-HOSTED SERVERS

Lastly, the infrastructure includes private servers which act as MEC servers for specific applications. Thus, a dedicated 10 GbE wired connection is available between the network core and servers. While Internet connection is usually shared between all users sited in the premises, there is sometimes a requirement to isolate the experiments in order to have controlled conditions. In the same way, Internet access is available to perform test with third-party services or for advanced phases of self-hosted experiments, where it is interesting to be tested under more realistic conditions, with traffic load and unknown server locations.

III. KEY CAPABILITIES

A. NETWORK CONFIGURATION

The present infrastructure was envisioned as a powerful R&D instrument since day one. Therefore, the attention was put on having complete control over all the network points. For the sake of conformity with Section II, the same order is followed in this section.

Regarding the RAN part, cell configuration parameters are accessible. Any configuration could be set up without asking for permission to operators, since we have been granted to use a part of spectrum within the UMA campus area. Configuration plans can also be defined in order to easily activate them as desired. Here, access to all radio counters is available with a periodicity down to 5 minutes. This low value is not feasible for commercial operators given the higher number of cells they have deployed, but it is in our reduced scenario. Here, the historical counters are automatically collected and stored in a local database using a Structured Query Language (SQL) structure, and are available upon request. This is done thanks to a *Docker* container that has been developed in the scope of this work. Consequently, the data can either be visualized directly from the database using open-source tools, e.g., *Grafana*, or exported to a file for further analysis.

B. METRICS COLLECTION

Furthermore, these radio counters are usually the input for computing KPIs. Traditional and Nokia-defined KPIs are available, although there is even more interesting the capability of defining KPIs according to specific research interests, e.g., beamforming, since beam-based communication introduces multiple challenges and procedures in order to keep the connection up in a cellular heterogeneous scenario [16], [17]. The KPIs are not standardized metrics, so manufacturers define a large list of them with the aim of providing useful performance information to operators using their equipment. Although some KPIs have been used for many years by operators and literature, it has not been this way for novel 5G-enabled features. This capability has been utilized in this work (see Section IV) to perform an analysis on the beamforming-related information that is accessible from network side.

Regarding the core network, it is possible to access to core via Command-line Interface (CLI) in order to get real-time information about users currently registered and distinguish whether they are in active or idle state. Also, it is possible to register SIM cards in order to allow them to attach, and provide them with different traffic profile permissions, as well as define different Access Point Names (APNs) within the core. The message exchange tracing between core and RAN can be done, where it is possible to inspect messages, e.g., registration procedure. Here, the core statistics can be obtained directly from the CMU, but also through the NFM-M.

On the User Equipment (UE) side, there are various alternatives to get the information. From lower layers, it is possible to collect Qualcomm logs and extract really detailed information directly from the modem to process it afterwards in an offline phase. This includes additional information coming from the modem as the localization information obtained from Global Positioning System (GPS). Nevertheless, application layer metrics can also be obtained from any application relying on Android Software Development Kit (SDK) to get cellular information, where it is possible to send it to a self-hosted server in real time for management purposes if desired.

Finally, service metrics, i.e., E2E, are available for different specific applications that rely on 5G for an adequate performance in terms of throughput, latency or other service-specific metrics, like CG [11], [18] or Virtual Reality (VR) [7].

C. E2E VISION

Therefore, there is an added-value on the capability of relating all layer metrics in order to analyze how they jointly perform until different situations, services and configurations. This is called E2E perspective, and provides rich information of the whole system. This way, a service that is experiencing outages or bad performance at application level could reflect that behavior on the network counters or KPIs, so that it will enable network management towards the optimization for that specific service, while keeping in mind that there might be many services and users connected simultaneously to the same infrastructure, and it is usually not affordable to degrade them.

This section introduces results obtained on the described infrastructure in order to provide insights on the 5G SA network performance.

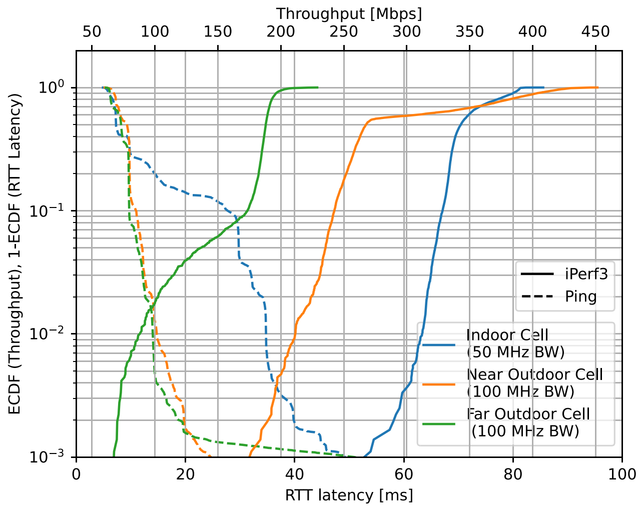

FIGURE 5. ECDF of throughput and latency measurements for UE connected to different cells. Note that CECDF is outlined in the case of latency.

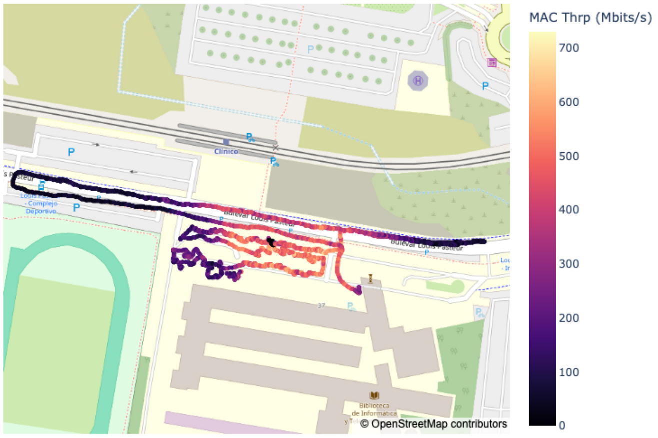

FIGURE 6. Map view of the throughput at MAC layer on the outdoor scenario.

D. BASELINE PERFORMANCE

At TCP/IP Layer, the network performance was measured by triggering simple experiments with the aim of obtaining throughput and latency values. Three experiments were performed in each case towards a private server directly connected to the 5G core: for throughput measurements, each experiment consisted in DL TCP traffic using iPerf3 tool [19] during 1 hour; for latency measurements, each experiment consisted in 1 million ping packets sent to the server with a wait time between sending each packet of 0.01 second.

Figure 5 plots the Empirical Cumulative Distribution Function (ECDF) of the DL throughput, as well as the complementary ECDF of the ping Round-Trip Time (RTT) latency, both measured at UE side using the Simcom SIM8380G module. Only one cell was enabled during each experiment, so the UE was forced to be attached to the target cell, and a single UE was connected to the 5G network for the experiments. The target cells were: an indoor cell with a 50 MHz BW, and two outdoor cells with 100 MHz BW, sited in two different locations with respect to the UE position. Figure 5 reveals a better performance overall in terms of throughput for the indoor cell, despite the fact that it has a reduced BW with respect to outdoor cells. However, it is worth mentioning that the location of the UE was indoor, less than 5 meters to the cell 50, and 30 meters and 125 meters from cells 58 and 60, respectively. Thus, the channel conditions must be much better in the first case. This would stimulate the idea of small cell deployments for indoor scenarios aiming at better performance, although it would require more work to delve into the real costs and expected benefits.

Furthermore, ping tests were performed under the same conditions. Latency results are also presented in Figure 5. The selected frequency of 100 ping packets per second was chosen in order to ensure that the UE stays in active mode, and does not go to idle mode at Radio Resource Control (RRC) layer. In this case, the indoor cell with reduced BW showed the highest latency results, while the outdoor cells showed lower latency values (See Fig. 5). However, minimum achieved latency is similar in the three cases.

In addition, a spatial overview of the throughput performance is depicted in Fig. 6. Here, only the cell 59 (See Fig. 4) is enabled, so it can be clearly noticeable the difference in terms of throughput between the center and the edge of the cell. The measured throughput is achieved using the iPerf3 tool [19] for DL traffic from a self-hosted server.

E. R&D POTENTIAL

The described infrastructure is envisioned as a powerful tool for R&D purposes. Here, the possibilities are open to different types of experiments, from radio configuration to application layer performance. The configurability of the infrastructure allows for testing cutting-edge network automation algorithms, as well as beamforming selection techniques, or mobility management strategies, either based on handover or beam switching. It is also affordable to evaluate energy efficiency techniques, like automatic cell sleep implementations, while measuring other KPIs and comparing the energy consumption of the cell during both normal and sleep modes. The cell power is a configurable parameter as well, so it is affordable to analyze network planning tools and algorithms, and compare the results theoretical results with the real field measurements. Although, the infrastructure is not compliant with Open RAN (O-RAN), some of the concepts that are envisioned to be implemented as rApps or xApps, may be preliminarily tested with non-automatic actions on the network. Moreover, as mentioned before, two complete service testing tools have been developed for the CG and XR UCs [7], [11], respectively. They are fully integrated to be automatically run under the desired network conditions, and configured to obtain service-specific metrics in real time. Finally, there are software tools from different vendors [20], [21], which are able to collect detailed radio and service quality metrics in order to verify, optimize and troubleshoot the network.

IV. BEAM-BASED ANALYSIS

This section focuses on the beamforming feature introduced in 5G [16]. While the main motivation to use beamforming technology is to reach further distances and better signal quality overall, there are some drawbacks that need to be addressed, e.g., the beam switching [22], [23]. In addition, beamforming also enables some opportunities regarding localization or users' movement, that will be described in this section. The following experiments were conducted using the described infrastructure (See Section II), and a Simcom SIM8380G module connected to a Lenovo L390 laptop running Ubuntu 22.04 acting as UE.

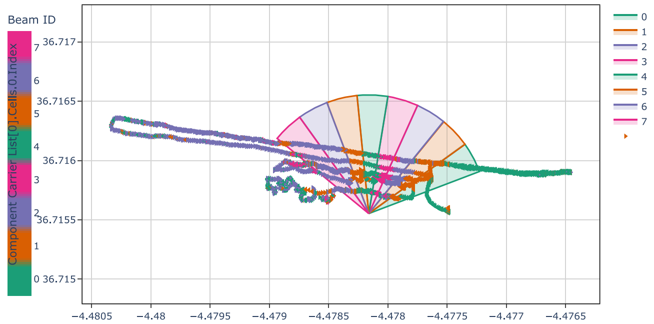

FIGURE 7. Beam set configuration of BTS (colored sectors) and UE's reported beam ID per location (color dots).

A. BEAM SWITCHING PERFORMANCE

The described infrastructure allows for location-based experiments within the UMA campus. A beam-based analysis was realized with the aim of analyzing the beam switching performance, and contrasting the serving beam IDs actually measured with the expected ones given the spatial distribution of the beam set as well as the UE location. Beamforming configuration can also be changed for a better comparison. However, the reproducibility of the results gets complex due to the real field experiment factors, e.g., UE speed, exact physical route, and other uncontrolled radio conditions. Figure 7 illustrates the expected coverage footprints for each beam under an 8-beams configuration in the BTS, represented as colored sectors, together with the actual serving beam IDs at each position, represented as dots. While the expected results coincided with the actual results in the east area, the west area showed up an unexpected behavior: beam ID 7 was never reported. In this case, it was due to a firmware issue in the version that was installed in the cells, but it could also be related to a blocked beam due to a physical obstacle. In the presence of obstacles, the plot represented in Fig. 7 will not be that clear in terms of expected and serving beam IDs, and the beam switching performance will be affected.

A single UE was used for the experiments, and the location was registered with the integrated GPS of the radio module. Then, the statistics are computed from the raw data, and ping-pong occurrences, beam failures, and beam' Time of Stay (ToS), are analyzed, together with radio metric values before and after beam switchings. As described in Section III, the infrastructure enables the network side data collection, which means that all the counters and KPIs are available for the joint analysis.

B. BEAM-BASED ML-POWERED LOCALIZATION

In 5G, localization is envisioned as key for network management tasks [24], as it provides useful information about attached users, i.e., common trajectories for handover/beam switching optimization, crowded areas where the network may get overloaded, or the last user location before a coverage hole occurrence. Therefore, there are several works in the literature addressing the localization topic in 5G networks: using Machine Learning (ML) for Time-of-Arrival (ToA) estimation [25]; using unknown Orthogonal Frequency Division Multiplexing (OFDM) signals [26]; and based on multipath tracking for indoor positioning [27]. While there are efforts to standardize the localization information exchange between the network and the users, it is still not a reality in commercial deployments to the best of authors' knowledge. One of the main drawbacks is the privacy aspect, since knowing the user location at every moment is not well accepted by the users and regulation organisms.

In this respect, 5G networks introduce the beamforming features, as described above, in order to provide better coverage. However, the use of beamforming can be useful for localization purposes. The radio quality metrics has traditionally been utilized to determine how far the user is from the cell. With the information from two additional neighboring cells, the user location can be estimated using trilateration techniques. Here, the accuracy obtained is not enough, and it requires the visibility of three cells concurrently. Although, beamforming uses different beams horizontally distributed (vertical distribution is also possible) with different beam IDs. Given that the beam set distribution is known by the cell, the beam IDs provide the azimuth angle of the user with respect to the cell. In this case, the radio quality metrics determine the distance to the cell, so the user location can be estimated with a higher accuracy than traditional techniques. The proposed localization technique can be understood as a polar coordinate system, where the serving cell is used as reference point, and the distance and azimuth angle are retrieved from the radio metrics (Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ)) and beam ID, respectively. This is powered by ML techniques, and alternative algorithms may be used to outperform the obtained results in this work. Although this technique can not be compared to Global Navigation Satellite System (GNSS) accuracy, it is a good alternative to get localization from network side at no cost in terms of overload, since radio quality metrics and beam IDs are transmitted anyway.

For a proper comparison, localization estimation errors have been computed with respect to GPS location, which is considered the ground truth since it is outdoors, for different beam set configurations, and the results are shown in Fig. 8.

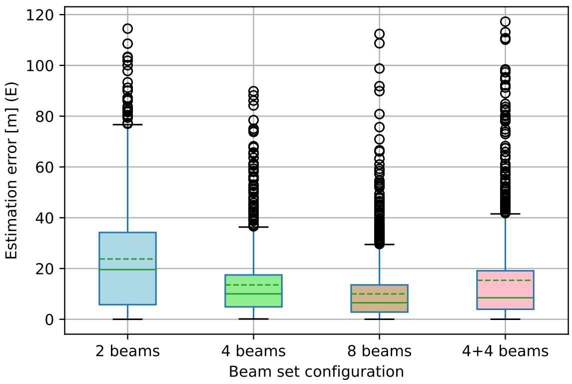

FIGURE 8. **Boxplots of localization estimation errors for different beam set configurations. The boxplot shows the median, the first and third quartiles, and the whiskers represent the 1.5 interquartile range. Green dashed line represents the mean value. Outliers are represented with black dots.**

The estimation error represented in Fig. 8 is obtained by:

$$\mathrm{E} = \sqrt{\phi^2 + \lambda^2}, \tag{1}$$

where ϕ and λ represents the estimation error in latitude and longitude axes, respectively, with respect to GPS, both previously converted to meters before the ML-based estimation, and estimated individually.

Although it may seem that the localization estimation error is high, it is important to remark that the location information is obtained at zero overhead cost, i.e., no additional signaling or measurements are required. Additionally, this technique can be extrapolated to indoor scenarios, where there are no better alternatives for localization other than UWB-based or other proprietary solutions requiring additional hardware deployment on site, to the best of authors' knowledge. Thus, the proposed technique provides location information to the user as long as a beamforming-enabled cellular network covers it, leveraging the control information exchanged for the cellular connection itself.

The scenario used in this work is 170m long and 50m wide, and the number of measurements was reduced. Based on the obtained results, a better model could be achieved using a larger scenario, and especially when considering the neighboring cell beams' measurements, which are also available on the UE side. In further scenarios, the distance to the cell could be estimated with higher accuracy since the difference in the received metrics (e.g., RSRP) is more significant, and the serving beam IDs are more distinct as the users are farther from the cell, i.e., fewer beam switchings will be triggered.

On the one hand, the knowledge of the localization information enables applications for the users, where the beam-based location can reduce applications' launching time, e.g., when it needs to search satellites. On the other hand, this information can be used on the network side for analytics to pave the way for new services for 5G verticals [28].

In addition, the proposed method becomes more interesting when considering mmWave deployments, where the attenuation is higher, the sensibility to obstacle increases, and the beam switching is more critical. Here, the localization information can be used to optimize the beam switching procedure, and reduce the number of ping-pong beam switchings [29]. Moreover, the maximum number of beams used at the BTS is 64 in 5G mmWave, which means that the azimuth angle resolution is higher, and the serving beam IDs gives more precise information about the angular range, then the localization estimation error could be reduced. Similarly, higher power attenuation provides higher accuracy in the distance estimation of the cell since the correlation between the radio metrics and the distance to the cell increases due to this fact. At mmWave, the use of beamforming is key for the operation, and the movement of the users may cause outages due to obstacle blocking, thus the localization plays a crucial role in the network management.

C. NOVEL KPIS DEFINITION

The infrastructure allows defining new KPIs based on the available counters. The definition of KPIs has been key for traditional network management, since the combination of counters provided a richer overview of the network performance. Here, the advent of beamforming introduces new counters, related to serving/neighboring beams and beam switchings. They enable additional knowledge at network side that become useful from a network management perspective. In this work, multiple KPIs have been defined, and their values during the measurement campaigns have been analyzed.

First, a *UE Cross Movement (UEXM)* KPI is defined as the aggregated number of beam switchings considering the number occurrences from beams pointing to the left/west side from the gNB to beams pointing to the right/east side, and then comparing the sum with the opposite case, i.e., beam switchings from right to left. Then, the expression for *UEXM* is given by Eq. (2):

$$\mathrm{UEXM} = \sum_{\substack{0\le x<N \\ 0\le y<N \\ x>y}} \mathrm{BSo}_{x,y} - \sum_{\substack{0\le x<N \\ 0\le y<N \\ x<y}} \mathrm{BSo}_{x,y}, \tag{2}$$

where $\mathrm{BSo}_{x,y}$ is the number of beam switching occurrences from beam x to beam y, and N is the number of beams used in the beam set configuration.

Thus, this KPI provides information about *UEs' perpendicular movement with reference to gNB*. The network then knows how is the movement of the users, and it can be used for beam switching/handover optimization, since different patterns may appear in each cell regarding the hour of the day, the day of the week, or the season of the year.

Moreover, *Specific Beam Switching Ratio (SBSR)* is devised as a ratio that reveals whether a specific beam switching is occurring much more frequently than others. This KPI, unlike UEXM, would be categorized as a performance indicator. It is calculated as *the ratio between the sum of a specific beam switching, i.e., from beam x to*

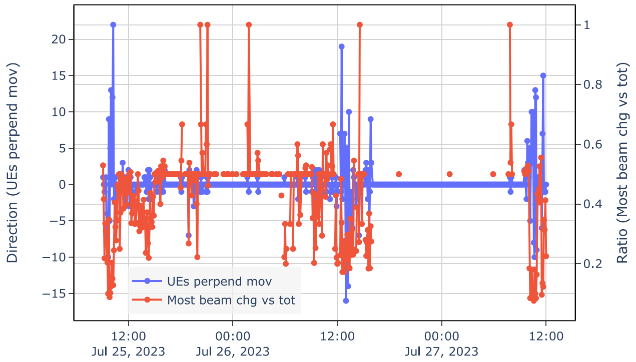

FIGURE 9. Evolution over time of defined KPIs for two consecutive days.

beam y, with respect to the total number of beam switchings. Although this KPI can be computed for each beam switching pair (x, y) individually, the most-repeated beam switching pair is considered the most relevant to extract insights about the current network performance. The expression for *SBSR* is provided by Eq. (3):

$$MRBS = \frac{\max_{\substack{0 \le x < N \\ 0 \le y < N \\ x \neq y}} \left(\mathrm{BSo}_{x,y}\right)}{\sum_{\substack{0 \le x < N \\ 0 \le y < N \\ x \neq y}} \mathrm{BSo}_{x,y}}, \quad (3)$$

where $\mathrm{BSo}_{x,y}$ is the number of beam switching occurrences from beam x to beam y, and N is the number of beams used in the beam set configuration.

MRBS close to 1 may imply undesired conditions (repeated beam switchings between specific beams). Even values lower, around 0.5, may be undesirable when the number of total beam switchings is high. This KPI must be taken into account in a weighted manner, depending on the total number of beam switchings, being more relevant as the number of total beam switchings takes higher values. If the total number of beam switching is 1, i.e., an extremely low value, *SBSR* must be ignored, since its value will also be 1, as it is the unique beam switching occurred.

Figure 9 sketches the evolution of the aforementioned KPIs for two consecutive days, where three of the measurements campaign were realized. They correspond to the results presented in Sections IV-B and IV-A, so there was movement of users within the scenario. These defined KPIs are independent to the beam set configuration in use, they will be available as long as beamforming is enabled with at least 2 beams. The measurement campaigns consisted in continuous movement from one side to the other, and then back, for the sake of being served by all the beams within the beam set configuration. Therefore, the *UEXM* KPI represented in Fig. 9 is not high and neither maintained over time. This indicates that there is no tendency of users moving towards one particular direction. While the users are stationary, *UEXM* gets down to zero, as it is shown in the figure for the times between campaigns.

Besides, the *SBSR* KPI scarcely reaches 0.5 or more, which indicates that there are no switching that is being triggered much more frequently than others. This may happen, e.g., when a beam is blocked due to a physical obstacle, and the UEs are switched to the same another beam. A more in-depth analysis of the beam-related counters will allow detecting failures in the RAN network, e.g., ping-pong beam switchings, when the most-repeated *SBSR* and the second most-repeated *SBSR* are reporting significant values over a fair amount of time.

These counters enable new network capabilities based on the additional information they provide. Here, the information regarding the beam switchings and serving beams over time may be used to detect clusters of static users, a high mobility area, or a beam that is never used. Therefore, the network management may predict problems as congestion, lack of capacity at a specific area, or potential coverage holes, in a more precise way than traditional KPIs.

V. CONCLUSION

This work evinces the potential of the 5G technology by means of a commercial equipment infrastructure deployed at the UMA campus, privately managed by MobileNet research group. Its main goal is to provide a real field environment for research purposes, where the network is fully controlled. The network details are described in detail and the R&D possibilities are not limited to the ones addressed in this work. Moreover, the baseline performance of the network is provided for the different available cells.

Finally, a beam-based analysis is accomplished, where the beam switching performance is studied from an optimization approach. The beam switching procedures envisage a similar behavior to handover procedures, and some parameters may be adjusted to achieve better results. Then, an ML-powered localization technique is introduced, where there are no costs in terms of overload and energy usage. While the accuracy is not comparable to GNSS, it is a potential method for the cases where GNSS is not available, either from the network side or at indoor scenarios from UE side. Besides, novel KPIs are defined, leveraging the information obtained from the beamforming-related counters. These KPIs provide useful insights for network management, as well as from a failure detection perspective.

Moreover, the datasets used in different sections are available in [30], including the user and network side metrics as well as user localization information. In conclusion, a wide range of research opportunities may be implemented on real field with the described infrastructure, being the presented results just a small sample of the potential of the infrastructure.

The present work opens the possibility of further research on the addressed topics. Firstly, the beam switching performance is envisioned as a potential topic for optimization in the O-RAN paradigm, where the actions on the radio parameters can be near-Real-Time (RT) or non-RT thanks to the RAN Intelligent Controller (RIC). Also, the performed analysis can be extrapolated to mmWave, where the number of switchings is expected to be higher, and its management is more critical since it can lead to connection drops. Then, the beam-based ML-powered localization can be enhanced either by using different beam sets or metrics as input or by improving the ML part, as well as extended to mmWave. The exploitation of this localization source is also open to future research, where multiple additional applications can be fostered. Lastly, the KPIs definition proposed in this work is envisioned to be extended with other metrics. Thus, the main goal is to jointly analyze them with other traditional KPIs in order to provide a richer overview of the network performance. In addition, a multi-cell analysis is also intended to be performed, where the defined KPIs will provide a two-dimensional direction of movement for the users. From a multi-cell perspective, handover-related KPIs can be considered, providing a richer overview of the users' movement regarding network performance analysis.

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