A Private SDR 5G SA Network: An Evaluation of the Quality of Service (QoS) and Computational Resource Allocation for eMBB Slice

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***Abstract*—This paper assesses the network performance in terms of Quality of Service (QoS) for the enhanced Mobile Broadband (eMBB) slicing of a private Stand-Alone (SA) network and a base station, identified as Next-Generation Node B (gNB), which is operating at 3.75GHz and using a Software Defined Radio (SDR) device. The contributions of this work are the evaluation of the computational resource allocation of a private 5G SA and the comparison of the QoS performance of the private SA network with a controlled laboratory testbed and a simulation tool, which is known as UERANSIM (User Equipment and Radio Access Network). Additionally, open-source monitoring systems were used in order to collect the memory and CPU usage of the network during the experimentation. For the deployment of the SDR 5G SA gNB, the Universal Radio Software Peripheral (USRP) version B210 equipment was utilized. The results also consider the evaluation of QoS metrics, i.e., throughput, jitter, round trip time, and propagation delay, to assess the performance of the private SDR 5G SA network. Additionally, it discusses the potential challenges and solutions for implementing SDR-based 5G mobile network solutions.**

***Index Terms*—5G, eMBB, gNB, SA, SDR**

I. INTRODUCTION

THE Fifth Generation (5G), or New Radio (NR), offers improvements related to network infrastructure, coverage area, better data rate and spectral efficiency, being able to deal with the increasing Quality of Service (QoS) demands. Differently from previous generations, 5G Core (5GC) is virtualized and built around a decentralized architecture using Network Function Virtualization (NFV) and Software Defined Networking (SDN), presenting two ways of deployment: Stand-Alone (SA) and Non-Standalone (NSA) [1]. The former configuration comprises a 5G Radio Access Network (RAN) and a cloud-native 5G Core; the latter uses the existing Long-Term Evolution (LTE) architecture with a 5G RAN. Consequently, most 5G performance goals can only be achieved by SA deployment, which is 5G end-to-end (E2E).

As a virtualized core network, 5G supports Network Slicing (NS), enabling operators to provide the physically combined but logically separate sets of infrastructure to meet the requirements of user applications [2]. These applications are mainly divided into three service categories: Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-Latency Communications (urLLC), and Massive Machine Type Communications (MMTC). Most service category scenarios consider high user-experienced data rates and efficient geographical coverage with mobility support, especially eMBB.

The core network softwarization opens precedents to use Software Defined Radio (SDR) equipment with open-source/close-source platforms to emulate 5G SA and NSA (Open5Gs [3], srsRAN [4], Open Air Interface (OAI) [5] and UERANSIM (User Equipment and Radio Access Network) [6]). Open5GS is an open-source NR/LTE network implementation in which the Core Network (CN) is equipped with gNB/eNB. Likewise, the OAI 5G scope encompasses RAN and the core network. srsRAN is an open-source 5G RAN project, and UERANSIM is a state-of-the-art 5G User Equipment (UE) and RAN simulator developed for testing and studying the 5G SA system. Unlike srsRAN and Open5Gs, UERANSIM only implements the Radio Resource Control (RRC) and Network Assistance Signaling (NAS) layers and does not implement the physical layers. Nevertheless, srsRAN, Open5Gs, and OAI provide the full version of the complete protocol stack in accordance with the 3GPP standards [7].

Both industry and academia have embraced 5G open-source tools to build proof-of-concept (PoC) and commercial wireless testbeds. Recent studies have shown applications using these tools, especially to test scheduling algorithms [8], evaluate remote/autonomous driving and vehicle-to-everything (V2X) scenarios [9], validate cell search mechanisms [10], in addition to transmission measurement [11] and service provision performance [12]. In [11], authors propose a 5G SA system using SDR and measure the transmission performance. In [12], authors evaluated the performance of internet browsing, data calls, and video streaming at different distances in a 5G SA network. Both related works implemented an open-source 5G SA mobile network using a RAN based on OAI and Universal

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Software Radio Peripheral (USRP). Gao et al., in [11], present a how-to installation process to build a customized 5G SA mobile network utilizing OAI open-source project [5]. The authors validated both a successful communication link of the RF communication shared channels and the digital modulation in the uplink direction, which is used by the mobile user. Moreover, the authors claimed that a downlink real-time rate of 219 kbps was obtained. In [12], the authors utilized a 4G RAN and Fraunhofer software for the 5G core network because a full 5G core had limited access. They used this approach to reduce costs since it could be applied in South Africa. The authors deployed a 5G NSA network, and various test cases were conducted, like attachment, internet browsing, video streaming, voice-over IP calls, and soft handover. In [13], the authors evaluated in detail the performance of an open-source 5G SA platform, which is based on [3] and [4], and they compared it with theoretical results. In this context, these studies lack in showing performance metrics and comparing them with high-tech radio test stations as well as an evaluation of computational resource allocation for the eMBB slice.

This study introduces a unique approach to assessing the QoS performance of an SDR-based 5G SA private network by implementing a method for computational resource evaluation and comparison with a controlled laboratory testbed and a simulation tool known as UERANSIM, which has not been explored in previous works. Additionally, open-source monitoring systems were used to collect the memory and CPU usage of the network during the experimentation. Moreover, the USRP version B210 equipment was utilized to work as a 5G SA gNB. The results also consider evaluating QoS metrics, e.g., throughput, jitter, round trip time, and propagation delay. Section II explains key concepts of the article related to 5G SA, SDR, and QoS metrics. Section III details the methodology used to capture the QoS metrics and computational resources utilized by the private 5G SA setup and describes the specialized wireless communication equipment used. Section IV presents a detailed analysis of the results. Section V discusses potential challenges and solutions for implementing SDR-based 5G mobile network solutions. Finally, Section VI discusses conclusions and future approaches.

II. BACKGROUND AND KEY CONCEPTS

A. 5G Stand-Alone (SA) architecture

The 5G network is deployed in two architectures: SA and NSA, organized in ”options” configurations enumerated from 1 to 5 and 7, as mentioned in [1] and [14]. Despite the ”options” configuration, the main difference between both architectures is how mobile network generation is implemented on the core network. The SA deployment uses the 5G Core, while the NSA uses an Evolved Packet Core (EPC), the LTE core network (4GC). Option 1, option 2, and Option 5 correspond to a 5G SA deployment, and the remaining options belong to NSA deployment. In this work, SA option 2 was deployed in a controlled environment laboratory without external interference signals. For option 2, next-generation node B (gNB) is connected to a full 5GC. Hence, gNB can communicate to the UE without any 4G assistance. With respect to the SA network, the main 5GC NFVs are the Access and Mobility Management Function (AMF), Session Management Function (SMF), User Plane Function (UPF), Policy Control Function (PCF), Authentication Server Function (AUSF), Network Repository Function (NRF), Network Slice Selection Function (NSSF) and Unified Data Management (UDM). The AMF is responsible for managing the mobility and registration process of the mobile subscribers. The SMF manages the establishment of Packet Data Unit (PDU) sessions associated with the QoS profile and QoS flows of the mobile subscribers. Additionally, it is responsible for allocating the IP address. The UPF manages the traffic to guarantee that the data is placed on the appropriate downlink and uplink QoS flows by applying policies rules provided by the PCF through the N4 interface. The PCF node provides policy decisions to the AMF and SMF throughout the registration and PDU establishment request processes. The AUSF is the element responsible for verifying the identity and authentication of users who access a network. The NRF works as a central registration center for all the NFVs. The NSSF can be used by the AMF to support the network slice selection for a particular user. At last, UDM and Unified Data Repository (UDR) are responsible for managing subscribers' data like access and mobility restrictions, data network QoS profiles, and roaming permissions [15]. Fig. 1 summarizes only the main NFV of the 5G SA Option 2 in a reference point representation.

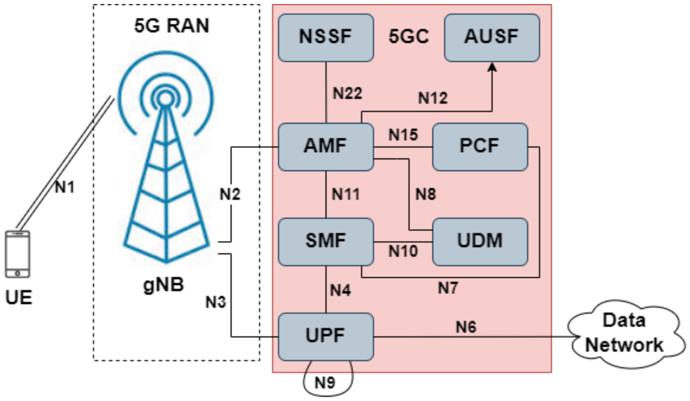

Fig. 1: 5G SA System Overview

B. Software Defined Radio (SDR)

SDR is a technology that allows the implementation of various radio communications systems, including modulation, demodulation, filtering, coding, encryption, and signal processing through software modules, so it recently acquired a special interest among experts in a wide range of applications in the field of digital radio signal processing. In addition, the low price of SDR platforms makes them attractive, and consequently, there is a multitude of SDR solutions on the market. SDR can support multiple standards and protocols alternating between different software modules. Thus, it reduces the need for hardware components and increases system flexibility and adaptability. The main parameters that define the merit figure of an SDR platform are frequency range, Analog-Digital Converter (ADC) resolution, and sampling frequency. Currently, SDR is a crucial technology for the development of 5G as it has the ability to support the integration of multiple access technologies, for instance, Wi-Fi, satellite, and millimeter wave, to provide connectivity and high data rates. In addition, it can allow access to the dynamic spectrum and network slicing to optimize the use of radio resources and network performance [16] [17]. In this work, the B210 SDR version was utilized; more details about its features and specifications are in [18].

C. *QoS metrics*

Quality of Service (QoS) in a communication network aims to provide better services to packets across a network, according to predefined criteria. In traditional networks, various parameters such as bandwidth, delay, jitter and reliability are used to measure the QoS offered by a network.

Delay is defined by the total time it takes for the packet to travel from source to destination. One problem with transmission delay is queuing and processing delay. Jitter is the variation in the arrival time of packets in the packet stream. When packets are sent from the transmitter to the receiver, there is an end-to-end delay variation between them. Jitter can be computed using Eq.1 [19].

$$Jitter = (T_4 - T_3) - (T_2 - T_1) \tag{1}$$

Another concept of QoS metrics is packet loss, which measures the successful delivery of packets from source to destination. Packet loss must be such that the quality of information is not affected [20]. Packet loss is computed as follows [19]

$$Packet\ Loss = \frac{PacketsSent - PacketsReceive}{PacketSent} \times 100 \tag{2}$$

Additionally, as explained in [21], network throughput refers to the actual amount of data and packets sent over the network per unit of time. Round-trip time (RTT) is the duration of time it takes a request to travel from the origin to the destination and back. RTT has several components, including propagation delay, processing delay, queuing delay, and encoding delay. Nevertheless, the processing, queuing, and encoding types of delay have negligible values. For the evaluation of RTT, Eq. 3 was used.

$$RTT(ms) = 2 \cdot Progagation\ Delay \tag{3}$$

III. METHODOLOGY

A. *Device Under Test (DuT)*

The DuT used in the experimentation is a cutting-edge mobile device equipped with a Qualcomm SM8550-AC chipset, a Snapdragon 8 Gen 2 technology (4 nm). It is able to attach to 5G New Radio in an SA configuration. Table I lists the essential components.

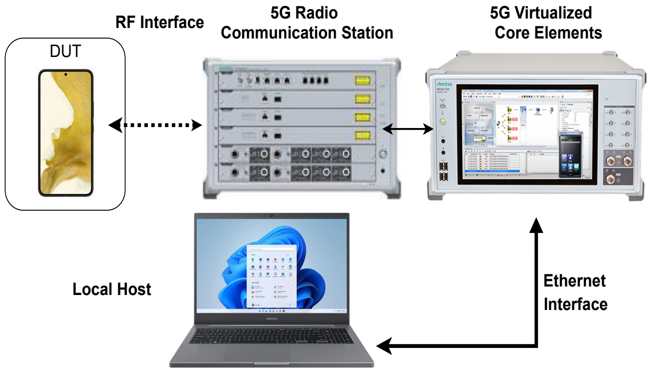

Fig. 2: 5G general controlled environment

B. *Experimental Setup*

There were configured two testbeds. On the one hand, a radio communication station [22] with 5G capabilities was set in a controlled environment laboratory, and the 5G core network was configured using the SmartStudio Manager program [23], which allows the configuration of the virtualized core network elements. The setup configuration is shown in Fig. 2. The controlled environment is located properly inside a laboratory without any interference signals and out-of-band emissions that can affect the performance of the radio station and the deployment scenario. Additionally, the DUT is located inside a shield box to reduce any type of external interference signal.

On the other hand, for the 5G SDR network setup (see Fig. 3), there were used a workstation running on Linux Ubuntu 20.04 and an SDR B210 version [18].The gNB was deployed using srsRAN [4] on the SDR device, which processed RF signals using FPGA, while the core network functions, including AMF and SMF, were handled by the virtualized environment running on the workstation using Open5GS [3].

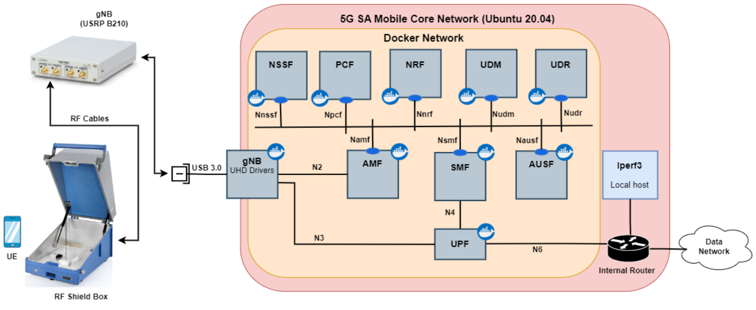

Fig. 3: SDR-based 5G SA network

It is essential to mention that the low-latency OS was not used, which might have reduced the real-time response of the SDR system. Future works should explore alternative kernel configurations or dependencies to enable the use of low-latency OS, which could optimize the system's throughput and reduce SDR system response time. Furthermore, the SDR does not utilize an external pulse signal generator and relies on internal RF converters, likely leading to increased variance in signal quality, affecting jitter and propagation

TABLE I. Features and Characteristics of the Scenarios

Scenario	**3GPP Compliance**	**Open-Source**	**HW Requiremets**	**Frequency Band**	**Duplex Mode**	**Sub-Carrier Spacing (KHz)**	**Bandwidth (MHz)**
Radio Test Station	Release 17	No	Intel Core i7-3770 CPU 3.40 GHz, RAM 16 GB	All	FDD/TDD	15, 30, 60	10, 20, 40, 60, 120
SDR 5G SA	Release 17	Yes	Intel Core i7-7700 Processor 3.2 GHz, 4G RAM, 4 CPU, 20GB HDD	All	FDD/TDD	15, 30	10, 20, 40
UERANSIM	Release 15	Yes	4G RAM, 1 CPU, 20GB HDD	-	-	-	-

DuT	**3GPP Compliance**	**RF Modem**	**HW Requirements**	**Frequency Band**	**Storage**	**Chipset**	**OS**
Feature	Release 17	Snapdragon™ X65 5G	Octa-core 1x3.36GHz Cortex-X3 2x2.8GHz Cortex-A715 2x2.8GHz Cortex-A710 3x2.0GHz Cortex-A510	N77 (3.75 GHz)	8GB RAM	Snapdragon 8 Gen 2 (4 nm), 12 GB	Android 14 ONE UI

delay. For future iterations, it is recommended to incorporate an external clock generator that aligns with the characteristics outlined in SDR B210 to stabilize these parameters, thereby ensuring more consistent performance metrics. This equipment offers higher precision along transmission and reception carrier signals generation, allowing UE to attach much faster and accurately evaluate system performance. Due to the lack of this device, we only use the internal RF converters of the SDR device. As seen in Fig. 3, except for the gNB Virtualized Network Function (VNF), all the VNFs run entirely on the workstation. The gNB VNF runs on both the SDR device and the workstation since this function controls the motherboards (field-programmable gate array, digital signal processor, RF boards, and up/down conversion filters of the SDR device) and sends the I/Q samples using the USB 3.0 interface to the workstation for further processing. At last, the UE was set to 00101, corresponding to a Public Land Mobile Network (PLMN). It is located a 1-meter distance from the base station in a controlled environment without external interference signals from local mobile operators and out-of-band emissions that can affect the performance of the deployment scenario.

According to Brazilian telecommunication regulation [24], the 5G SDR was located at 3.75GHz (N77) in order to deploy a private 5G SA network with a Bandwidth (BW) and Sub-Carrier Spacing (SCS) equal to 40 MHz and 30KHz, respectively. Also, a 256 digital modulation scheme was set. To be able to use the eMBB network slice of the Data Network Name (DNN) [25], the Slice/Service Type (SST) parameter of the Single-Network Slice Selection Assistance Information (S-NSSAI) was set to 1 on the gNB, UPF and SMF NFVs [25]. The power transmission of the SDR SA gNB and test base station were set to -10 dBm and -27 dBm, respectively. Both testbed scenarios are in an appropriately controlled RF shield room to avoid interference and out-of-band emissions to licensed users.

Moreover, the radio test station (see Fig. 2) has considered the evaluation of the MAC layer to meet the upper throughput limit. The main difference between the MAC and IP layer throughput of the Radio Station is that the former deals with the transfer of data frames that contain MAC layer control and data payload; in contrast, the latter encapsulates data payloads along IP header information, i.e., IP address, Time-to-Live. On the other hand, for the theoretical approach, Eq.4 was utilized, which shows the approximate maximum data rate for Downlink [26]:

$$\begin{aligned} \text{data rate (Mbps)} &= 10^{-6} \cdot \sum_{j=1}^{J} \Bigg(V_{Layers}^{(j)} \cdot Q_M^{(j)} \cdot f^{(j)} \\ &= \qquad \cdot R_{max} \cdot \frac{N_{PRB}^{BW(j),\mu} 12}{T_s^{\mu}} \\ &= \qquad \cdot \big(1 - OH^{(j)}\big) \Bigg) \end{aligned} \tag{4}$$

where in [26]: J is the number of aggregated component carriers in a band or band combination. For the j-th component carrier, $V_{Layers}^{(j)}$ is the maximum number of supported layers, $Q_M^{(j)}$ is the maximum supported modulation order, $f^{(j)}$ is the scaling factor, $Rmax$ is the code rate for the Low-Density Parity-Check Code (LDPC), μ is the numerology , T_s^{μ} is the average OFDM symbol duration in a subframe for numerology assuming a normal cyclic prefix, $N_{PRB}^{BW(j),\mu}$ is the maximum resource block allocation in bandwidth $BW(j)$ and $OH^{(j)}$ is the overhead, which is 0.14 for the current scenario.

C. UERANSIM

UERANSIM (User Equipment and Radio Access Network Simulator) [6]) is an open-source simulator for 5G networks. It simulates the behavior of UE and RAN, providing a tool for testing and development purposes. UERANSIM primarily focuses on simulating the higher layers of the 5G NR stack, including protocol layers i.e., Radio Resource Control (RRC), Non-Access Stratum (NAS), Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), and Medium Access Control (MAC), but it does not simulate the physical RF (Radio Frequency) link or the detailed physical layer signal processing. Instead, UERANSIM abstracts the physical layer, it does not account for real-world interference or signal degradation. Therefore, while it provides an upper bound for performance, the results from the SDR setup reflect more realistic conditions, including RF noises and hardware variability. On the other hand, this simulator simulates the UE behavior, including registration, session management, and mobility procedures [6]. Additionally, RAN procedures e.g., cell selection, handover, and RRC connection management.

In such a context, UERANSIM can represent an ideal RF channel without interference or propagation path loss. Additionally, it can be useful for comparing throughput under ideal conditions. By abstracting the physical layer and assuming an ideal RF channel, UERANSIM provides a baseline for understanding the maximum achievable throughput (considering Eq. 4) without external factors like interference or path loss affecting the results. By simulating an ideal RF channel, UERANSIM can establish a baseline for the best possible throughput performance. This baseline can be used as a reference to compare with real-world measurements, highlighting the impact of real-world conditions on throughput. The simulation configurations consider the UE's authentication, permanent subscription key, the eMBB slice (SST set to 1), and DNN. For the gNB was also set the S-NSSAI corresponding to the eMBB slice. The 5G core network uses the same than described in Subsection III-B and Fig. 3.

IV. RESULTS AND DISCUSSIONS

The figures below present the evaluation of a 5G private SA network performance for the eMBB network slicing scenario. Iperf [27] tool using TCP protocol and PING utility network tools were used to evaluate the network performance in the Downlink direction. As explained in [25], QoS metrics were computed between the UE and the UPF NFV. Additionally, the controlled environment setup [23], [22] provides a detailed report about the performance of the mobile system for the MAC and IP layers. Then, once the UE was properly attached and authenticated to the 5G SA private network, each QoS metrics were evaluated for 5 minutes and in the end, a post-processing analysis was carried out.

Fig. 4 shows a comparison of the throughput for the Downlink direction only among a controlled environment setup (both MAC and IP layer), the UERANSIM simulation tool, the proposed SDR-based solution of this work, and the theoretical approach. The theoretical approach is depicted in light green and showed a value of 158.79 Mbps for approximately 80% of the symbols slots allocated for the user channel in TDD mode. In pink, the UERANSIM simulation obtained a throughput value of around 159 Mbps. For this scenario, the mean, minimum, and maximum throughput values were 158.64 Mbps, 158 Mbps, and 159 Mbps, respectively. It is essential to mention that the UERANSIM scenario represents an ideal flat RF channel without interference or fading. For the controlled environment setup (radio station), the throughput is depicted in red and green colors for the MAC and IP layers, respectively. As expected, the throughput evaluation at the MAC layer obtained a higher throughput value (i.e., 145.47 Mbps) than the IP layer (i.e., 144.52 Mbps). There is a minimum difference between these two values. In blue color, the private 5G SA network is evaluated, and the mean, minimum, and maximum values were 139.13 Mbps, 45.4 Mbps, and 144 Mbps. It is important to recall that the fluctuation of the network throughput along the evaluation time is because the virtualized function of the 5G core and gNB were running on a generic Ubuntu, which decreased the testbed's performance, as discussed in Subsection III-B. Additionally, the SDR device does not use an external signal generator that improves the performance of RF converters. Even though the result of the proposed private 5G SA network is only around 6 Mbps below the MAC and IP mean throughput values, which represented a significant achievement.

Figures 5 to 7 show the violin graphs and box-plot analysis for RTT, propagation delay, and jitter for the Private 5G SDR SA network and the controlled environment for the Radio Test Station (RTS) setup. Fig. 5 presents the results of RTT for the SDR setup in blue color, which shows a left-skewed distribution since the mean and median values are $37.32ms$ and $37.8ms$, respectively. In addition, the minimum and maximum values are $19.2ms$ and $48.6ms$, respectively. Also, to evaluate the dispersion of the data inside the 50% of the dataset, we can compute the Interquatile Range (IQR) by using $IQR = Q3 - Q1$, which value was equal to $IQR_{sdr\_5g} = 10.2ms$. On the other hand, since RTS has a higher and more stable performance and is in a controlled environment, we obtain lower RTT values than the SDR case. In green color, results show a left-skewed distribution as well, with values equal to $13.62ms$ and $14ms$ for the mean and median, respectively. In addition, minimum and maximum values are $4ms$ and $22ms$, respectively. Also, we obtained the dispersion of the data inside the 50%, which is $IQR_{test\_station} = 3ms$. Moreover, the standard deviations (std) were computed, with values of $6.06ms$ and $2.37ms$ for SDR and RTS, respectively. As expected, there is a difference in IQR and std for both scenarios since the SDR testbed is running on a generic Ubuntu OS that can impact the performance of the mobile network; therefore, the values are much more scattered around the mean than for the RTS case that presents a much stable performance. In contrast, the RTS is running on high-tech and homologated equipment. Even though the 5G SDR testbed obtains a mean value of around $37.32ms$, it satisfies the requirement, which is $600ms$ for RTT budget and Non-Guaranteed Bit Rate (N-GBR) [25].

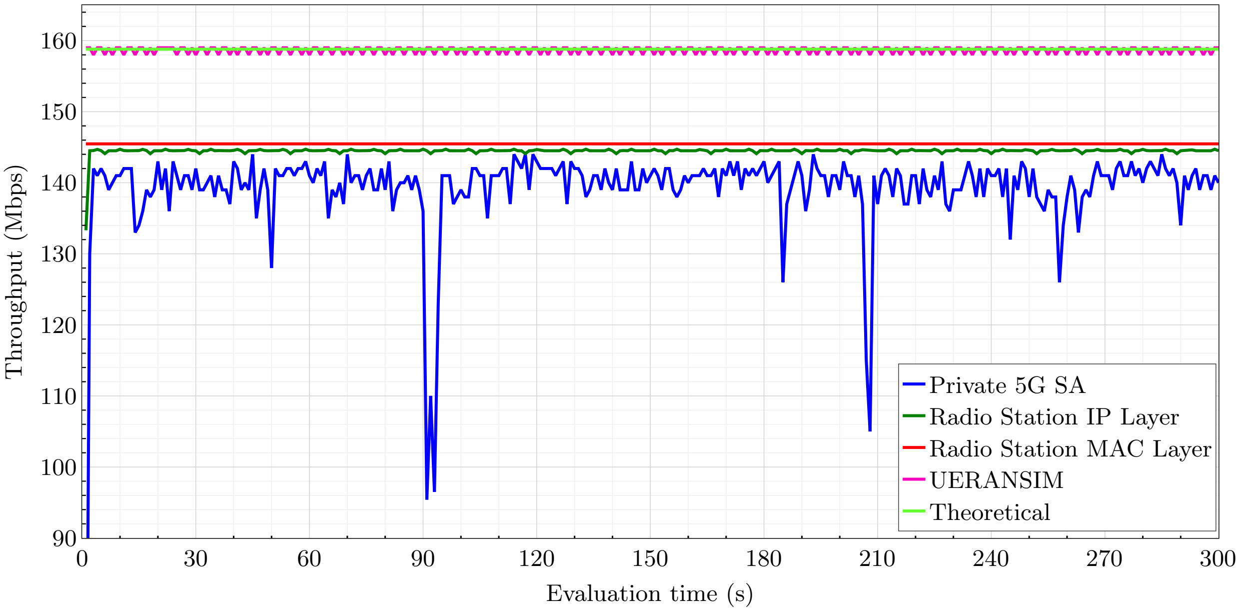

Fig. 4: Comparison of Throughput

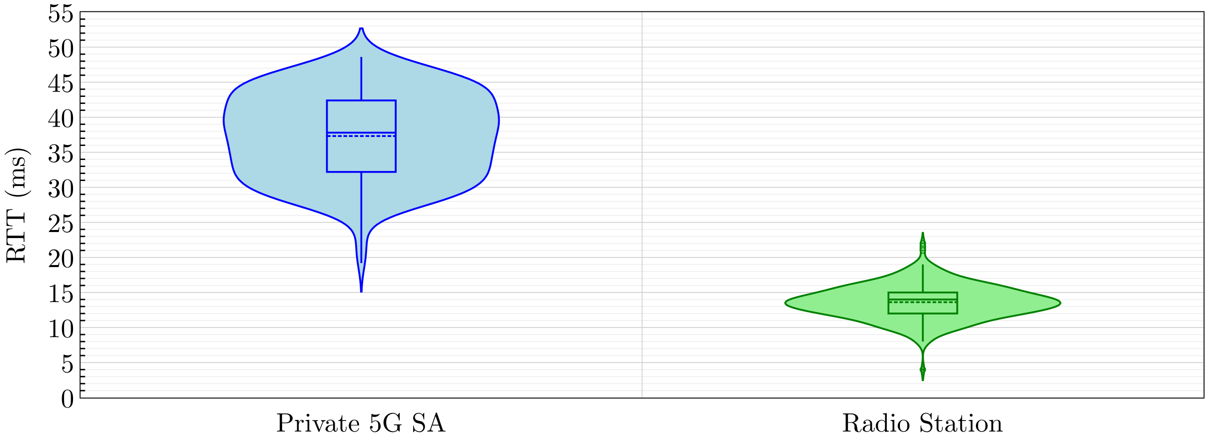

Fig. 5: Comparison of RTT

Therefore, by using an SDR Private 5G SA network, we obtained a high QoS performance system that provides a higher downlink bit rate to the UE using a portable gNB.

Fig. 6 presents the results of the propagation delay. A left-skewed distribution is presented for the SDR setup since the mean is marginally lower than the median, whose values are $18.65ms$ and $18.9ms$, respectively. For the propagation delay, the minimum and maximum values are $9.6ms$ and $24.3ms$, respectively. The IQR was $IQR_{sdr\_5g} = 5.1ms$; the higher the IQR value is, the less stable the service is, but there weren't any interruptions of the service. As expected, on the other hand, lower values for the RTS were obtained than for the SDR case. In green color, the results show a left-skewed distribution as well, with values of $6.80ms$ and $7ms$ for the mean and median, respectively. In addition, the minimum and maximum values are $2ms$ and $11ms$, respectively. For the RTS, the $IQR_{test\_station} = 1.5ms$ shows a much more stable performance of the network in comparison with the SDR scenario. Moreover, for both scenarios, the std was computed with values of $3ms$ and $1.18ms$ for SDR and RTS, respectively. As expected, the RTS case presents a much more stable performance of the 5G scenario; nevertheless, even though the 5G SDR testbed is less stable, it satisfies the requirement, which is $300ms$ for delay budget and Non-Guaranteed Bit Rate (N-GBR) [25]. Therefore, the proposed testbed of this work offers a high

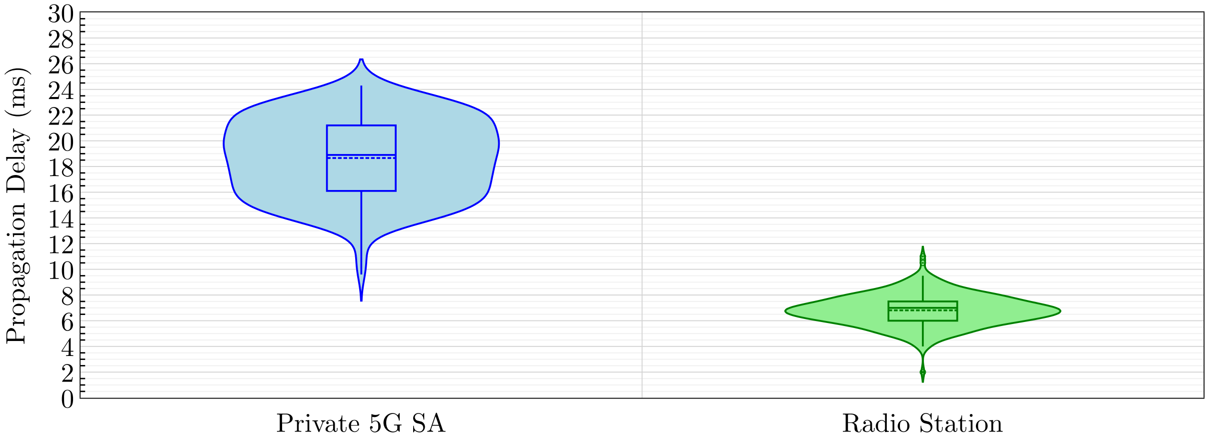

Fig. 6: Comparison of Propagation Delay

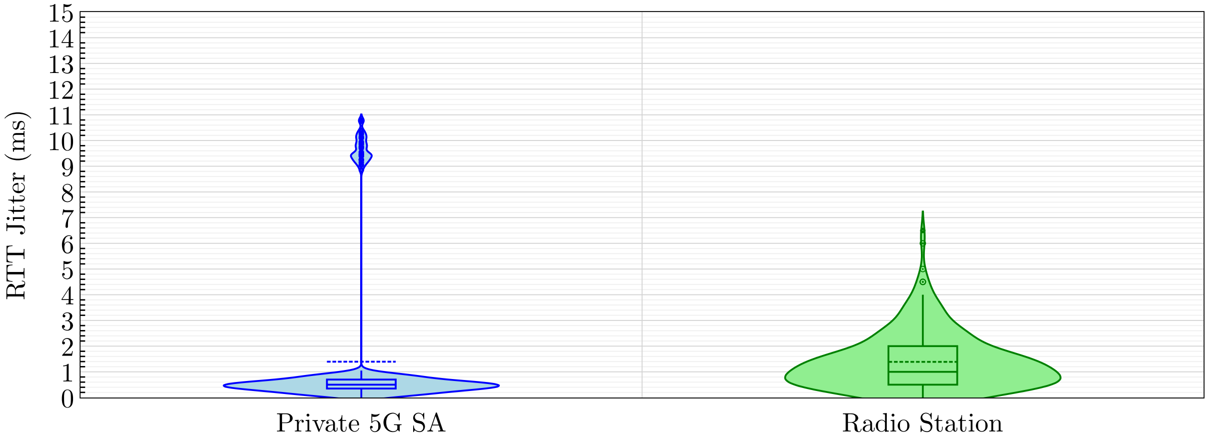

Fig. 7: Comparison of Jitter

QoS performance using a low-cost gNB.

Fig. 7 presents the results of the RTT jitter. SDR case presents a multi-modal statistical distribution since, as explained before, this scenario is running on a generic Ubuntu OS, and a low-cost device is used, which influences the performance of the 5G mobile network. Nevertheless, the RTT jitter presents an std equal to 2.77 as well as lower mean and median values, which are $1.39ms$ and 0.5. As shown in Fig. 7, the highest value is $10.8ms$. In contrast, the RTS presents a stable performance, as discussed in the previous sections, with std, mean, and median values equal to $1.09ms$, 1.39, and 1, respectively. Even though the 5G SDR testbed is less stable, it offers to mobile users a private 5G SA mobile network using a low-cost gNB with higher network throughput.

Fig. 8 presents the results during the experimentation of the average memory usage for the 5G core containers, mainly for the AMF, UPF, SMF, and gNB 5G core elements, which are the essential NFVs involved in the user plane performance. There were assessed three scenarios: when only 5G core VNFs were running on the workstation, when the 5G SDR gNB was running and attached to the 5G network, and when the complete setup was running throughout the QoS performance evaluation for the eMBB slice. As we can observe, for the AMF, UPF, and SMF VNFs, the average memory usage is neglected for the aforementioned scenarios since the highest value is approximately 42 MB of memory usage (for the SMF case). For the gNB, on the other hand, the average memory usage is higher in comparison with the core NFVs. When there is no UE connected to the 5G SDR private network, there is an increment of the average memory usage, which is 4.97 GB. Furthermore, when the UE is attached, and the network throughput is evaluated over the radio communication channel, there is an incremental of 26.23% of memory usage (6.27 GB), which impacts the performance of the setup but with neglected

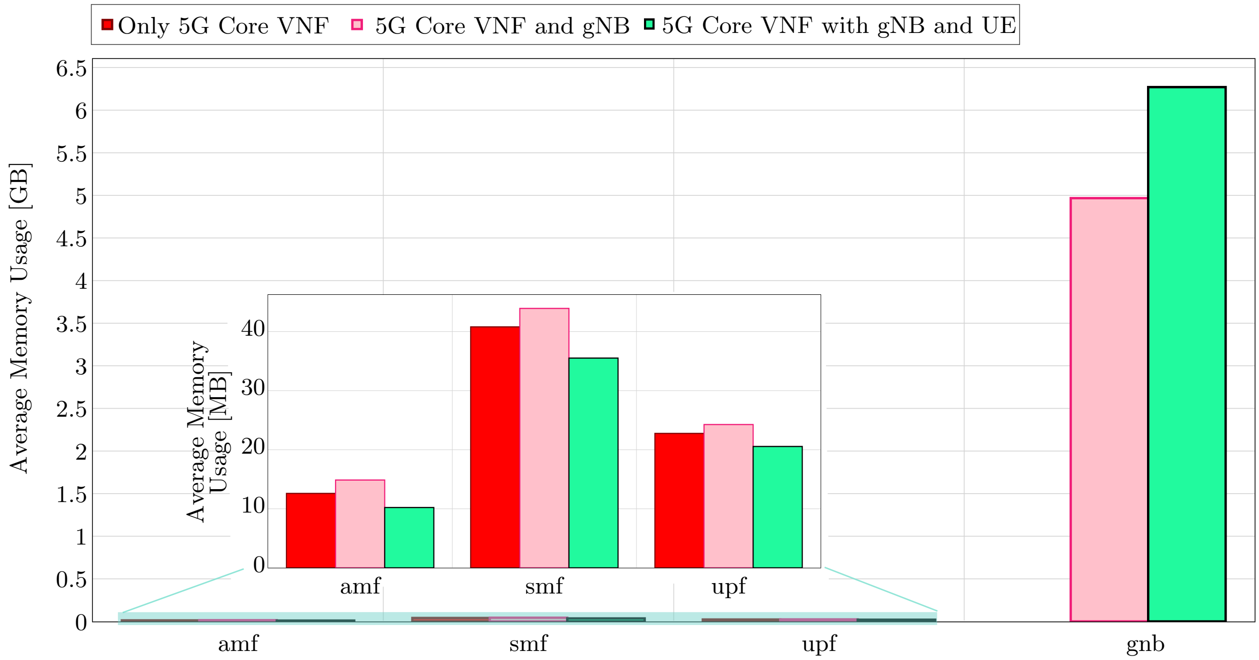

Fig. 8: Comparison of Memory Usage per container

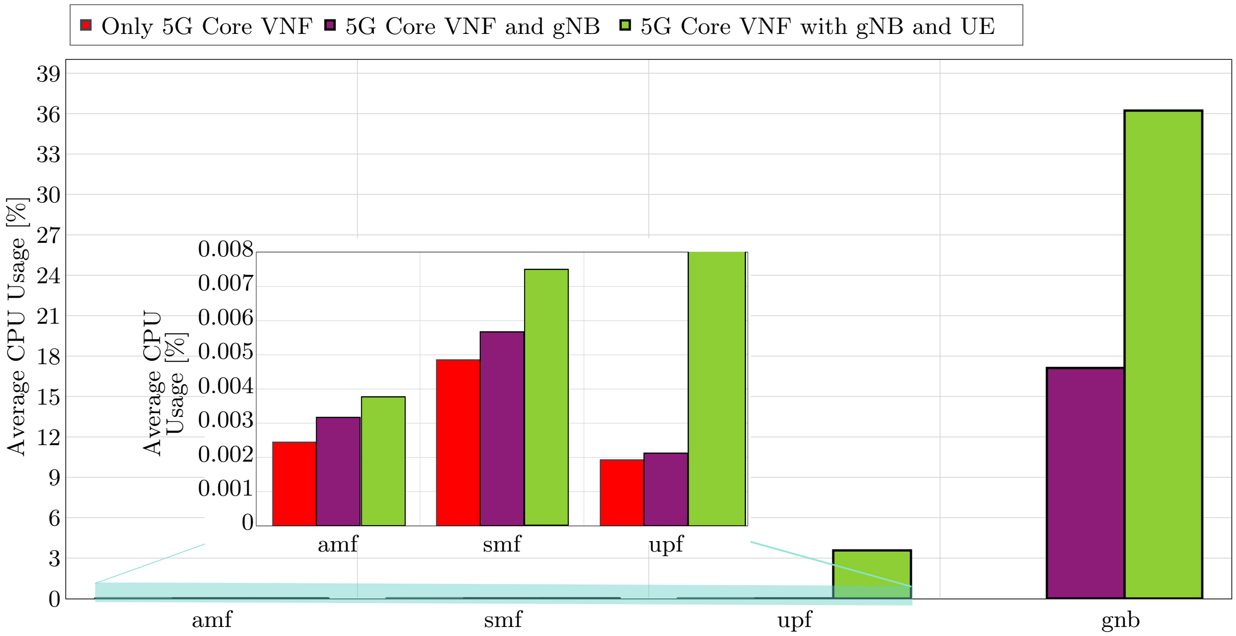

Fig. 9: Comparison of CPU Usage per container

values since the QoS was maintained, as explained in previous sections.

Fig. 9 presents the results of the average computational resource allocation for the 5G core containers; however, only for the AMF, UPF, SMF, and gNB NFVs. As explained previously, there were evaluated the same three scenarios. We can observe an incremental average CPU usage once the setup is fully deployed. For the AMF and SMF cases, and when only 5G Core VNFs and when the gNB are attached to the network, the average CPU usage is neglected since they are below 0.006%. In contrast, for the UPF case and when the UE is attached and the network throughput was evaluated, there was an incremental CPU usage equal to 3.57%, which represents an estimation of the energy consumption (EC) of CPU [28] equal to 1.31W (CPU in Idle State (CIS)) or 3.78 W (CPU in 100% Load (CL)). When the average CPU usage of the gNB was evaluated, we obtained 17.11% (EC of 6.30W and 18.14W in CIS and CL, respectively) and 36.22%

(EC of 13.33W and 38.40W in CIS and CL, respectively) when there is not a UE and when the network throughput test is evaluated, respectively. These values represented an incremental resource allocation equal to 111.69% since there is a demand for computational resource allocation to provide network throughput performance over the RF communication channel, and the 5GC SA private network is fully operating.

V. CHALLENGES AND RECOMMENDED SOLUTIONS

This section discusses potential challenges and recommended solutions for implementing an SDR-based 5G mobile network. SDR introduces essential flexibility and friendly scalability; however, it also presents challenges. Both approaches are presented as follows.

A. Challenges

- **High Data Rates and Low Latency:** 5G mobile networks require high data rates and ultra-low latency that inquire robust and efficient real-time processing capabilities. This work shows that a portable SDR-gNB can provide high data rates to users.
- **Radio Spectrum Efficiency:** Efficiently utilizing vacant spectrum to support the wide range of 5G services, including eMBB, mMTC, and URLLC.
- **Interoperability:** Guaranteeing seamless interoperability among different SDR hardware devices and NFV functions, which can be intricate due to the continuous improvement of mobile network standards.
- **Security:** Protecting the 5G SDR network from cyber attacks, in particular, given the critical role of a 5G network in offering vital services and infrastructure.
- **Power Consumption:** Managing the power consumption of an SDR 5G network, mostly in Mobile Edge Computing (MEC) deployments.

B. Recommended Solutions

- **Advanced Digital Signal Processing:** Utilizing field-programmable gate array to handle the real-time signal processing requirements, enabling high data rates and low latency.
- **Dynamic Radio Spectrum Management:** Implementing a 5G SDR network with Cognitive Radio (CR) capabilities to dynamically allocate radio spectrum considering real-time demand, fading, and interference conditions, improving spectrum efficiency.
- **Software Flexibility:** Leveraging the flexibility of a 5G SDR-based network to adapt and update to new technical standards and technologies utilizing software updates and upgrades, guaranteeing future interoperability.
- **Enhanced Security Protocols:** Integrating advanced encryption, authentication, and anomaly 5G SDR-base network detection systems to secure the SDR network against potential cyber-attacks and threats.
- **Energy-Efficient Design:** Employing power-efficient algorithms and optimizing hardware design to reduce the energy consumption of 5G SDR-based deployments.

SDR-based 5G networks offer a versatile, scalable, and adaptable solution for satisfying the requirements of technical standards and mobile users' inquiries. Addressing potential challenges through advanced digital signal processing, dynamic radio spectrum management and techniques, software flexibility, security, and energy-efficient architectures ensures robust and 5G scalable SDR-based deployments that support a wide range of applications from high-speed internet access to the Internet of Things (IoT) and Industrial 4.0 applications.

VI. CONCLUSION

This paper evaluated the network performance in terms of QoS for the eMBB network slicing of a private SA network operating at 3.75GHz using the Software Defined Radio approach and b210 model, which was set as a 5G SA gNB. The contributions of this work were the evaluation of the computational resource allocation of a private 5G SA network and the comparison of the QoS performance of this network with a controlled laboratory testbed (Radio Test Station, RTS) and the UERANSIM simulation tool. Additionally, open-source monitoring systems were used to collect the memory and CPU usage of the network during the experimentation. The results also evaluated throughput, jitter, round trip time, and propagation delay to validate the private 5G SA network performance. Fig. 4 compared the throughput for the downlink side. The theoretical approach obtained a value of 158.79 Mbps for approximately 70% of the symbols slots allocated for the user channel in TDD mode. For the UERANSIM simulation tool and the controlled environment setup, similar results were obtained. For the private 5G SA network, the maximum network throughput value was equal to 144 Mbps, approximately 6 Mbps below the MAC and IP layers of the average throughput. Therefore, the results of the SDR approach represented an important achievement. Moreover, analysis for RTT, propagation delay and jitter for the SDR SA network and the RTS setup were done. The std presented values equal $6.06ms$ and $2.37ms$ for SDR and RTS, respectively. There was a difference in IQR and std for both scenarios since the SDR approach was running on a generic Ubuntu OS kernel and without using an external clock signal generator, factors that can directly impact its performance. Even though the 5G SDR testbed obtained a mean value of around $37.32ms$, it satisfies the requirement, which is $600ms$ for the RTT budget and N-GBR. In addition, Fig. 6 presented the results of the propagation delay. As expected, the RTS approach had a more stable performance; nevertheless, even though the 5G SDR testbed was less stable, satisfies the requirement, which is $300ms$ for delay budget and N-GBR. Similar results were obtained for RTT jitter, showing that the proposed SDR case offered mobile users a private 5G SA mobile network and a low-cost gNB. Therefore, using an SDR Private 5G SA network, we obtained a high QoS performance system that provided a higher downlink bit rate to the UE (approx. $144Mbps$) using a portable gNB. In this work, we also evaluated the computational resource allocation for the deployed network, mainly for the AMF, UPF, SMF, and gNB 5G core elements, which are involved in the network throughput performance. For the AMF, UPF, and SMF VNFs, the average memory usage was neglected since the highest value was approximately 42 MB of memory usage (for the SMF case). For the gNB, on the other hand, the average memory usage was higher than the 5GC. When there was no UE connected to the 5G SDR private network, there was an increment of the average memory usage, which was 4.97 GB. Furthermore, when the UE was attached, and the network throughput was evaluated over the radio communication channel, there was an incremental of 26.23% of memory usage (6.27 GB), which impacts the performance of the setup but with neglected values since the QoS was maintained. Additionally, Fig. 9 presented the results of the average computational resource allocation. For the AMF and SMF cases, and when only 5G Core VNFs and the gNB were attached to the network, the average CPU usage was neglected since they were below 0.006%. In contrast, for the UPF case and when the UE was attached and the network throughput was evaluated, there was an incremental CPU usage equal to 3.57%, which represents an estimation of the energy consumption of CPU equal to 1.31W (in Idle State) and 3.78W (CPU in 100% Load state). When the average CPU usage of the gNB was evaluated, we obtained 17.11% (energy consumption of 6.30W and 18.14W in Iddle State and 100% Load State, respectively) and 36.22% (energy consumption of 13.33W and 38.40W in Iddle State and 100% Load State, respectively) when there was not a UE and when the network throughput test was evaluated, respectively. These values represented an incremental of the computational resource allocation equal to 111.69% since there was a higher demand for resources to provide higher network throughput performance over the RF communication channel, and the 5GC SA private network was fully operating. Finally, this work intended to show a low-cost 5G SA network based on the SDR approach to provide downlink service using a portable gNB. Future research attempts to utilize an external clock signal generator to improve the performance of the gNB for the SA Option 2 configuration and to collect accurately the energy consumption of the 5GC NFVs.

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VII. BIOGRAPHY SECTION

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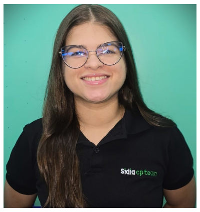

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