An SDR 5G Stand-Alone Multi-Access Edge Computing (MEC) Network to Provide ViNR and VoNR using SIP Kamailio Server

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***Abstract*—This paper presents a significant contribution to the field of 5G networking through the development and deployment of a Software-Defined Radio (SDR)-based 5G Stand-Alone (SA) network leveraging the Multi-Access Edge Computing (MEC) paradigm. Designed to deliver high-quality voice and video services using the Session Initiation Protocol (SIP) Kamailio Server, our implementation significantly reduces latency by integrating Virtualized Network Functions (VNFs) and Docker containerized elements onto a single workstation, enhancing the efficiency of 5G Core operations. Built entirely on open-source projects, the proposed mobile network successfully provides both Voice-over-New Radio (VoNR) and Video-over-New Radio (ViNR) services using SDR. Notably, this work introduces the first publicly available ViNR prototype for a comprehensive 5G SDR solution, thus filling a gap in existing research and development. We further detail a complete end-to-end call flow for both VoNR and ViNR, utilizing SIP Kamailio, and provide a valuable resource for researchers and developers. The performance of the proposed network is evaluated through Quality of Service (QoS) metrics, and the computational resource allocation is analyzed. We utilize two smartphones as representatives of typical mobile users to simulate their behavior. The results are then comprehensively compared with those obtained from a high-tech radio communication test station platform, a platform commonly used for certifying terminals, chipsets, and devices against 3GPP standards. Our findings demonstrate that the proposed SDR MEC network exhibits performance closely aligned with that of the robust, established test platform, validating its effectiveness in controlled environments. This research significantly advances the state-of-the-art in 5G SDR MEC networks by providing a scalable, efficient, and cost-effective solution for delivering IP multimedia services, with a particular focus on enabling and optimizing Video-over-New Radio (ViNR).**

***Index Terms*—5G, Kamailio, MEC, SDR, VoNR, ViNR**

I. INTRODUCTION

THE Fifth Generation (5G) of mobile networks uses a novel air interface called New Radio (NR), which brings several improvements, including a much more robust signal, new network infrastructure, higher data rates, and the ability to handle a much better Quality of Service (QoS) for the target user. In addition, the new 5G network features range from industrial and augmented reality applications to Internet of Things (IoT) [1] and mobility services [2].

Traditionally, Mobile Network Operators (MNOs) have built their network infrastructure, including the core network and Radio Access Network (RAN), in centralized locations [3]. This means that data generated by mobile users is often processed in data centers far from where it was created. This distance introduces latency, which impacts the performance of applications such as gaming, augmented reality, and real-time video. To address this, there's a growing trend towards edge computing, which brings data processing closer to the end-user, resulting in faster response times and improved experiences. Therefore, with the continuous evolution of mobile networks and the growing demand for services and applications, methods are being developed to enable service processing closer to devices, thereby reducing latency and enabling faster, more efficient access to information. This process enables data to be processed and offered to the user from an edge structure located near the user.

Multi-Access Edge Computing (MEC) [4] is an alternative that combines Cloud Computing and Edge Computing, enabling information traffic to travel a shorter path to its destination and directly impacting the Quality of Experience (QoE) of users. This paradigm is directly associated with the improvements enabled by the 5G network architecture, which aims to deliver services with shorter response times for processes that require low latency. With the proposed improvements and the development of the 5G network, the IP Multimedia Subsystem (IMS) architecture improves data packet transmission services through the resources made available by the network elements, thus providing Voice over New Radio (VoNR) [2] and Video over New Radio (ViNR) [5].

5G network virtualization enables the use of Software-Defined Radio (SDR) equipment, allowing for flexible and cost-effective network deployments. Open-source platforms, such as 5G SA Open5Gs [6] and srsRAN project [7], facilitate this by emulating key 5G components. Open5Gs is an open-source implementation focused on the 5G Core Network (5CN) functions. In contrast, srsRAN is an open-source 5G RAN project that provides access to the Next Generation NodeB (gNB) via the NR air interface. Both projects adhere to 3GPP standards, offering a valuable platform for 5G research, development, and testing.

Based on the aforementioned open-source projects, this work introduces a Proof-of-Concept (PoC) functional 5G

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Stand-alone (SA) MEC network capable of delivering both VoNR and ViNR services. The implementation uses the Session Initiation Protocol (SIP) Kamailio Server [8] for session border control and signaling, coupled with SDR technology for flexible and programmable access to the air interface. This work notably presents the first operational ViNR prototype within a fully realized 5G SDR-based solution. A performance evaluation, utilizing two smartphones as mobile user equipment (UE), assessed QoS metrics and computational resource allocation within the 5G core network. Results, benchmarked against a high-performance, 3GPP-compliant radio communication test platform used for conformance testing, demonstrate that the proposed SDR MEC network achieves comparable performance characteristics in a controlled laboratory environment.

The remainder of this work is organized as follows. Section II identifies gaps in existing research. Section III provides background on the core concepts of 5G SA, SDR, and QoS metrics. Section IV details the methodology for capturing log files and data, as well as the specifications of the 5G SDR network setup and the radio communication test station platform. Section V presents a detailed analysis of the findings. Section VI discusses the challenges encountered and proposes solutions. Finally, Section VII summarizes the conclusions and outlines future approaches.

II. RELATED WORK

In [9], Ndassimba et al. proposed to implement a broadband network to enable quality teaching at the University of Bangui through a solution based on a private 5G network as infrastructure support and virtualization techniques with SDR, providing, in this way, a network that supports the problems of internet access faced in remote areas. Thus, this solution provides students with an alternative through digital education, making the knowledge offered by the internet more accessible.

In other studies, such as [10], Wojciech et al. present potential applications for implementing an SDR operating as a radio base station for 4G and 5G networks. Thus, the research aims to perform benchmark tests using open-source hardware, such as srsRAN, in conjunction with other radio module software. From this, the performance metrics are evaluated, and the problems encountered during the implementation stage of the hardware and software layers are analyzed.

In [16], the authors introduce a dual-modem solution to minimize downtime during inter-PLMN (Public Land Mobile Network) handovers, an adaptive bitrate system for reliable media streaming, and a WebRTC server as a gateway for vehicle communication. The study highlights the challenges of ensuring seamless connectivity amid mobility and the limitations of current 5G infrastructure, which may not fully support the stringent requirements of Connected, Cooperative, and Automated Mobility (CCAM) for Vehicle-to-Everything (V2X) applications. Critically, it highlights the need for additional solutions to address these gaps in 5G performance, particularly in terms of video streaming latency and packet loss.

The authors in [12] discuss how MEC enhances 5G networks by placing computational resources closer to end users (as virtualized elements), thereby reducing latency and improving service quality. The paper presents an architecture for edge-native applications that demonstrates the integration of MEC with existing network infrastructures. Key challenges include the complexity of implementing MEC and ensuring data privacy and security. Critiques focus on the difficulty of deploying and managing MEC at scale, as well as the need for standardization to reduce computational costs and mitigate latency.

The authors in [13] note that an initial deployment network is a soft transition from fourth-generation (4G) networks to 5G Non-Stand-Alone (NSA) networks. This article demonstrates that elements from different architectures can communicate with each other and establish the bearer and stream for each IP service. Furthermore, the evaluation of QoS metrics, including jitter, throughput, and round-trip time (RTT), was presented for a VoLTE call between two mobile users connected to an SDR network.

In [14], the authors demonstrated a prototype for voice-over-5G using open-source projects implemented at Technische Universität Berlin and provided initial performance measurements. Our work shares similarities with this approach but extends beyond their foundational study by offering a detailed analysis of VoNR calls and QoS metrics. While our methodology aligns with the outlined framework, we introduce additional layers of depth and specificity in assessing both network performance and user experience, thereby advancing understanding of VoNR functionality and its implications for SDR-5G-based communication systems.

In [15], it refers to our initial research, which was presented and provided an initial evaluation of VoNR QoS using a SIP Kamailio server. This preliminary work did not address Video over New Radio (ViNR) or the resource allocation of the Virtual Network Function (VNF). Our focus was exclusively on assessing the Mean Opinion Score (MOS) and the R-factor metrics.

In this context, we identified significant gaps in the literature regarding the provision of IMS multimedia services in 5G networks utilizing SDR technology. To reduce this gap, we introduce a PoC functional 5G SA MEC network capable of delivering both VoNR and ViNR services using SDR technology and SIP Kamailio Server. This work notably presents the first operational ViNR prototype within a fully realized 5G SDR-based solution. A performance evaluation, utilizing two smartphones as mobile UE, assessed QoS metrics and computational resource allocation within the 5G core network. Results, benchmarked against a high-performance, 3GPP-compliant radio communication test platform used for conformance testing, demonstrate that the proposed SDR MEC network achieves comparable performance characteristics in a controlled laboratory environment.

To facilitate a clearer understanding of the research landscape, Table I presents a comparative analysis of related works. The table highlights key characteristics, including research objectives, methodologies employed, limitations encountered, and significant contributions. This analysis reveals that SDR has been a prominent technology in mobile network research, frequently utilized to enhance the quality of service and

TABLE I
COMPARISON OF SDR AND RELATED TECHNOLOGIES STUDIES

Reference	Objectives	Methods	Limitation	Contributions
[9]	Implementing a broadband network for remote areas.	Virtualization with SDR to enhance access to digital education.	Ensuring accessibility in remote areas with limited infrastructure.	Improved internet access for students and faculty at the University of Bangui.
[10]	SDR as a radio base station for 4G and 5G networks	Benchmark testing using open-source hardware (srsRAN) with other radio module software.	Implementation complexity and challenges in ensuring seamless connectivity.	Successful completion of benchmark tests highlighting potential applications.
[11]	Dual modem solution for inter-PLMN handovers.	Adaptive bit-rate system, WebRTC server for vehicle communication.	Limited support for advanced features in 5G, challenges in mobility, and reliability.	Reduced downtime during handovers, reliable media streaming, and vehicle communication solutions.
[12]	MEC integration into existing network infrastructures.	Edge-native applications architecture to reduce latency and improve service quality.	Complexity of implementation, ensuring security and data privacy, and scalability issues.	Enhanced network performance through efficient resource management and reduced latency.
[13]	4G to 5G transitional deployment using SDR.	Evaluating QoS metrics (jitter, throughput, RTT) for VoLTE calls.	Integration complexity with existing systems limited the support for advanced features.	Successful deployment of a transitional network with improved call quality metrics.
[14]	Evaluate and assess the integration of open-source VoNR functionality within private 5G SA networks.	Compute QoS metrics, e.g., call setup time, Real Time Protocol (RTP), packets lost, and RTP-Jitter.	The experimental scope was focused on technical aspects rather than broader network performance. It is not evaluated in the ViNR scenario.	The study contributed to understanding the integration of open-source VoNR in private 5G SA networks by providing empirical data and analysis.
[15]	Evaluate VoNR performance using the SIP Kamailio server. This is our initial work. We evaluated the Mean Opinion Score (MOS) and R-factor.	A testbed using Open5GS as a core network and srsRAN as a gNB running on a B210 SDR. The Simplified E-model was used to compute the R-factor and estimate the MOS.	Limited to only two UE connected to the network and a single gNB stack. Not evaluated the resource allocation consumption on the Virtual Network Functions.	The first work that evaluates the QoE by computing the R-factor and MOS metrics in an SDR scenario.
This paper	Implementing a private 5G mobile network using SDR technology, the SIP Kamailio Server, and MEC-like PoC. Provide VoNR and ViNR.	QoS metrics, computational resource allocation, and network deployment are involved in making voice and video calls.	The SDR mobile network experiences instability; sometimes, mobile devices fail to detect the base station carrier. This issue arises from the impairments and limitations of SDR devices.	The successful deployment of VoNR and ViNR services ensures they are cost-effective and highly flexible, leveraging SDR to enable easy integration and customization. This work notably presents the first operational Video over New Radio (ViNR) prototype within a fully realized 5G SDR-based solution.

facilitate the creation of realistic test environments.

III. THEORETICAL CONCEPTS

This section outlines the theoretical foundations of this work. We begin by examining the 5G architecture, including key components such as SDR, MEC, and IMS, which are central to delivering voice and video services. The SIP Kamailio Server is also a potential solution for implementing a robust Voice-over-dedicated-IP communication system.

A. 5G Architecture

Network Function Virtualization (NFV) provides flexibility in managing software networks, allowing network functions to be decoupled from the hardware on which they run, thereby reducing resource consumption, including memory, processing, and energy. In 5G networks, the network core is cloud-native and programmable, enabling rapid behavior changes and the creation of virtual machines (VMs) that support applications such as virtual MNOs and Internet of Things (IoT) services. Another relevant concept for 5G networks is Software Defined Networking (SDN), an architecture that separates the control plane, which makes decisions, from the user plane, which executes network decisions [17].

The 5G network defines two types of architectures [1]: 5G Non-Stand-Alone (NSA) and 5G Stand-Alone (SA). In this work, SA option 2 was employed, corresponding to a fully 5G core (5GC) deployment and a next-generation node B (gNB) using the New Radio (NR) air interface [18]. Fig. 1 shows the 5GC service-based architecture.

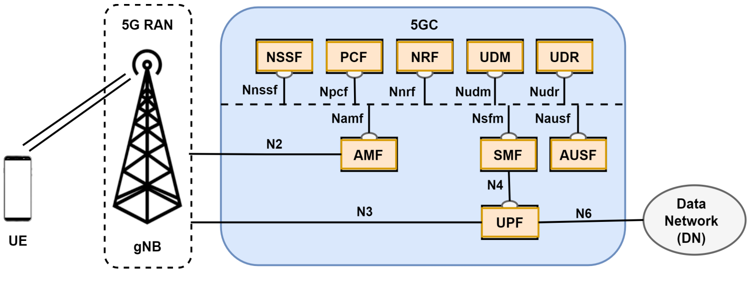


Fig. 1. 5G Core Architecture

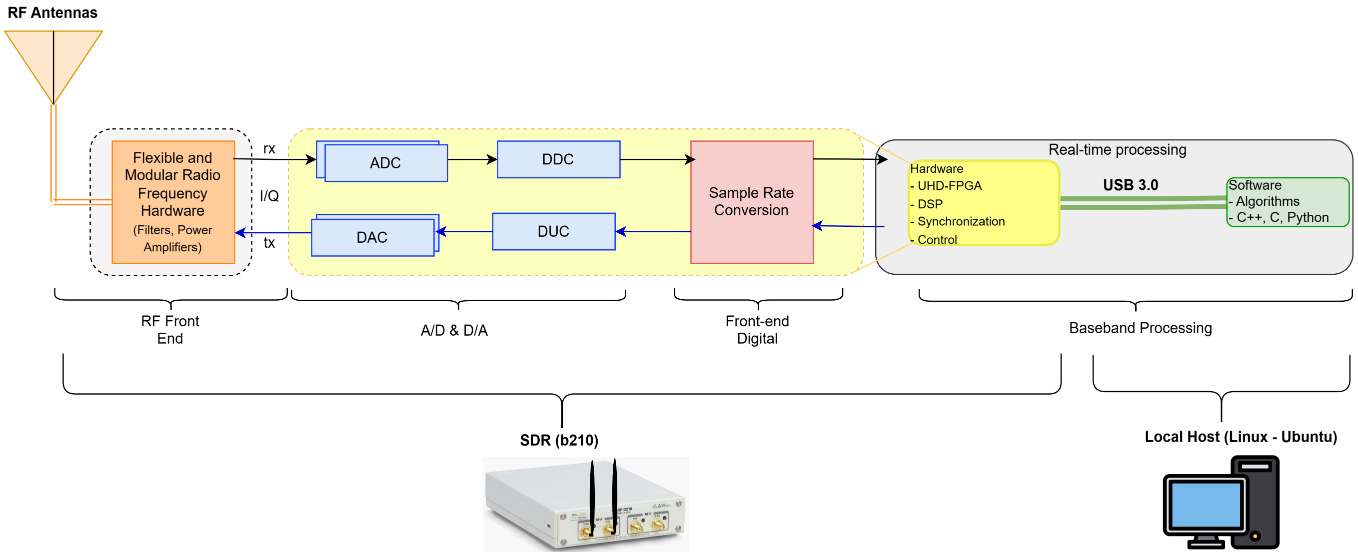


Fig. 2. High-level Scheme of an SDR device

In the user plane, the primary function is the User Plane Function (UPF), which processes and forwards user data, acting as an anchor point between the devices and external IP networks [18]. The functions of the 5G network control plane are defined below:

1) Access and Mobility Management Function (AMF): it allows users to register, be authenticated, and move between different radio base stations [19].
2) Session Management Function (SMF): It is responsible for establishing, modifying, and releasing Protocol Data Unit (PDU) sessions for IPv4, IPv6, Ethernet, and unstructured data, IP address allocation, and QoS control [19].
3) Policy Control Function (PCF): it makes policy decisions and provides rules for both the SMF and policy information to the user [20].
4) Unified Data Management Function (UDM): it manages user identity by generating authentication credentials [20].
5) Unified Data Repository (UDR): It stores various data types, including for other network functions, e.g., UDM and PCF [19].
6) Authentication Server Function (AUSF): An authentication server that provides this service using the authentication credentials created by UDM [20].
7) Network Slice Selection Function (NSSF): It can be used by the AMF to assist with the selection of the Network Slice instances. As such, the NSSF determines the Allowed NSSAI (Network Slice Selection Assistance Information) that is supplied to the device [20]. In this work, we used the default Network Slice.
8) Network Repository Function (NRF): it provides Network Function (NF) instance information, including function type, function ID, and network slice-related identifiers [21].
9) Binding Support Function (BSF): Supports binding information updates by NF service consumers [21].

B. Software Defined Radio (SDR)

This technology is used to perform radio signal processing functions implemented in hardware. Radio Hardware components include analog-to-digital converters (ADC), digital-to-analog converters (DAC), and antennas. Signal processing tasks in modern wireless communication systems are increasingly performed using programmable digital devices, notably Field-Programmable Gate Arrays (FPGAs). Unlike traditional Application-Specific Integrated Circuits (ASICs), FPGAs enable the reconfigurable implementation of radio functions via software frameworks such as GNU Radio [22]. This flexibility enables researchers and developers to rapidly prototype, test, and deploy new signal processing algorithms and wireless protocols without requiring hardware modifications.

SDR can have several applications in 5G mobile networks, ranging from supporting multiple network protocols to enhancing compatibility with MEC, which can reduce latency, a key requirement of 5G networks. Another relevant point is optimizing spectrum usage in 5G networks, which affects the allocation of radio resources in real networks [23]. The low cost of SDR platforms makes them essential for telecommunications solutions; as a result, numerous SDR solutions are available on the market. It is even more adaptable for 5G network applications that are already virtualized, as it does not require additional hardware components. The SDR device used in this work is the Universal Software Radio Peripheral (USRP) B210 equipment; technical specifications can be found in [24].

Fig. 2 illustrates a typical Software Defined Radio (SDR) architecture. The RF front-end comprises RF components, including bandpass filters and low-noise amplifiers (LNAs), to establish initial signal conditioning and minimize noise figure. Analog filters in the RF and Intermediate Frequency (IF) stages implement spectral shaping and channel selection, providing out-of-band rejection and mitigating spectral spillover. Following RF/IF amplification, a final anti-aliasing filter, typically a low-pass or band-pass filter, is crucial to satisfy the Nyquist criterion before digitization with an Analog-to-Digital Converter (ADC). The core of the SDR resides in the digital processing section, comprising the ADC/DAC, Digital Down Conversion (DDC), and Digital Up Conversion (DUC) blocks. DDC performs frequency translation to baseband via mixing with a digitally generated local oscillator (DLO), followed by digital filtering and decimation. Conversely, DUC performs the inverse operation, baseband signal filtering, interpolation, complex mixing with a DLO, and digital-to-analog conversion. These DDC/DUC blocks are commonly implemented on a Field Programmable Gate Array (FPGA) and/or Digital Signal Processor (DSP) to achieve real-time processing throughput. A key component enabling this functionality is the FPGA firmware, such as the USRP Hardware Driver (UHD), which provides a hardware abstraction layer and a suite of optimized DSP algorithms for signal processing tasks. UHD allows configuring the FPGA's internal resources, including multipliers, accumulators, and memory blocks, to implement efficient DDC/DUC pipelines and custom DSP blocks.

The USRP B210 [24] employs a direct-conversion architecture, leveraging a Spartan 6 FPGA for signal processing and control. The platform supports RF frequencies from $70\,\mathrm{MHz}$ to $6\,\mathrm{GHz}$, with two receive and two transmit channels, and is facilitated by Analog Devices. A 12-bit ADC and DAC operate at a maximum sampling rate of $61.44\,\mathrm{MS\,s^{-1}}$, enabling a theoretical maximum instantaneous bandwidth of $30.72\,\mathrm{MHz}$, limited by the Nyquist-Shannon sampling theorem. The observed performance is further constrained by the RF front-end's characteristics, including filter roll-off and impedance matching. The B210 achieves a wideband spurious-free dynamic range (SFDR) of 78 dBc, indicating its ability to discern weak signals in the presence of strong interferers. The platform's transmit power exceeds 10 dBm, enabling experimentation with short-range wireless communication systems. Data transfer to the host computer occurs over a USB 3.0 interface, supporting a host sample rate of $61.44\,\mathrm{MS\,s^{-1}}$ with 16-bit samples. However, sustained data rates depend on the USB 3.0 chipset's performance and the host system's resources.

C. Multi-Access Edge Computing (MEC)

Multi-Access Edge Computing (MEC) is an emerging paradigm designed to address the increasing demands of bandwidth-intensive, latency-sensitive applications, such as augmented and virtual reality and autonomous vehicles. By combining the capabilities of Cloud Computing, Edge Computing, and Mobile Technologies, MEC brings computation and data storage closer to end users. As depicted in Fig. 3, MEC servers are deployed at the edge of the network, in proximity to radio base stations, enabling low-latency connectivity to numerous mobile devices and offering localized processing capabilities. This approach has the potential to revolutionize real-time computing capabilities and elevate the overall user experience by minimizing data displacement.

The MEC host, which provides computing, storage, and networking resources for MEC applications, is deployed either at the edge or on the central data network. It is equipped with the UPF to manage network traffic direction [4]. The user plan for MEC applications is tailored for the data network. While MEC can be located in various places, ranging from near the base station to the central data network, the consistent feature across all deployments is the use of UPF to route traffic to the intended MEC applications and the network [11].

Integrating the MEC paradigm with SDR represents a significant advancement in 5G network architecture. This combination enables a highly flexible and scalable network that supports a wide range of applications within a single device, effectively enhancing its capabilities and reducing reliance on centralized infrastructure. SDR's inherent programmability enables dynamic resource allocation and customized data processing at the network edge, thereby minimizing latency and maximizing throughput. This is especially crucial for mobility-related applications, such as high-definition voice and video calls, augmented reality, and autonomous vehicle control, which require access to large volumes of data, low-latency connectivity, and real-time processing to ensure a reliable and responsive user experience. Furthermore, this architecture enables network slicing, allowing operators to allocate dedicated resources to specific applications and to prioritize performance based on their unique requirements.

D. IP Multimedia Subsystem (IMS)

The IP Multimedia Subsystem was initially developed as a framework to enable access to many multimedia services, ensuring QoE to users [25]. This network architecture provides higher-quality data traffic, enabling voice and video transmission over mobile network technologies such as Long Term Evolution (LTE) and, more recently, NR. Thus, IMS uses the Session Description Protocol (SDP) to enable multimedia

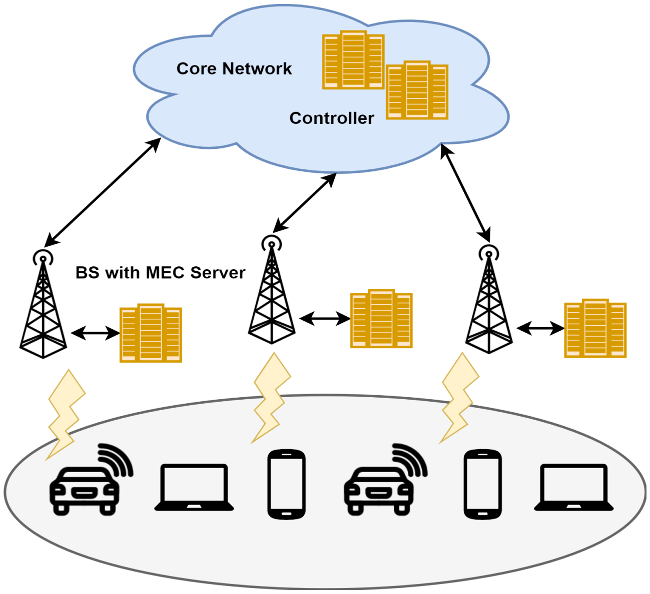


Fig. 3. Multi-Access Edge Computing (MEC)

mobile services, including Voice over IP (VoIP), video calls, multimedia conferencing, and supplementary services over dedicated streams [26].

IMS is a network architecture composed of three Call Session Control Functions (CSCF) and one element that performs the database function. The first element that can be identified is the Proxy CSCF (P-CSCF); this is the first access point of the network, routing SIP messages and acting as a security gateway, blocking unauthorized access to the network infrastructure [27].

Serving the CSCF (S-CSCF) has the functionality to control session status and register users in IMS. Thus, this element receives the user's registration request and consults the Home Subscriber Server (HSS) to check the user's profile and subscription type [28]. The HSS is the element that stores data, providing the CSCF with the user's IP address [26]. From this, the S-CSCF can, using the HSS, discover and direct the service request to the Application Server (AS) [2]. The third element, the Interrogating CSCF (I-CSCF), accesses the HSS to locate the device you want to contact. Once the consultation is made and the recipient's address is known, the I-CSCF forwards the SIP request to the S-CSCF [27]. Fig. 4 depicts a high-level architecture of IMS.

E. Voice and Video over New Radio

The transmission of voice over IP has improved over the years, reducing noise and minimizing packet delay, thereby ensuring a better user experience. Parameters aimed at leveling the quality of telephone services are analyzed to observe this aspect. From this, the QoS and QoE parameters serve as a reference for maintaining the quality of services offered by MNOs [3]. Thus, as mobile network generations evolve, reducing parameter values has led to a delay in data packet transmission, thereby enabling more efficient communication.

Among the various services that have emerged to improve mobile communication quality, we can mention those offered recently in some regions, such as VoNR and ViNR. VoNR is related to voice service in 5G NR. At the same time, ViNR is associated with real-time video calls, offering high-quality coded audio and video linked to Enhanced Voice Services (EVS) and H.264 codec required by 3GPP [5].

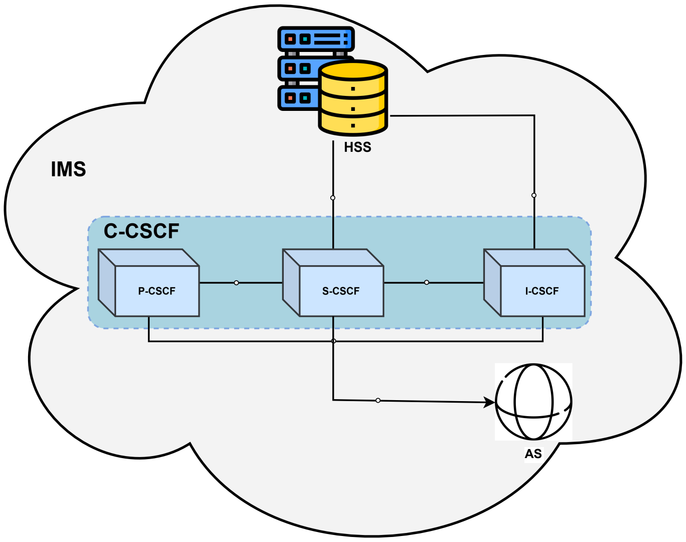


Fig. 4. High-level IMS Core Architecture

The IMS facilitates end-to-end traffic flows with specific QoS characteristics, defined by a Guaranteed Bit Rate (GBR) and categorized using 5G Quality of Service (5QI) values, ranging from 1 to 5 [2]. Lower 5QI values (e.g., 1) represent higher priority and are typically allocated to delay-sensitive applications, such as VoNR, to guarantee low latency and consistent performance. Conversely, higher values (e.g., 2) are assigned to applications with less stringent delay requirements, such as video transmission (ViNR), accommodating higher bandwidth but accepting potentially greater latency. These configurations were established within the HSS function of our 5G SDR MEC network, enabling differentiated service delivery.

Another key contribution of this work is the development of a fully customized UE, specifically, a smartphone capable of supporting both VoNR and ViNR services over a SIP Kamailio Server that acts as an IMS network. Achieving this required significant software engineering effort, including modifications to the device's core code snippets for IMS multimedia services. Furthermore, we leveraged and adapted the Samsung-specific IMS Settings application [29] to configure and validate the device's support for both service types. This smartphone customization goes beyond simple configuration, representing a substantial development effort and providing a uniquely instrumented platform for evaluating the performance and capabilities of VoNR and ViNR in a real-world setting.

F. SIP Kamailio Server

The IMS is a foundational architecture for delivering modern multimedia services over IP networks. At the heart of many IMS deployments lies SIP Kamailio Server [8], a highly scalable and feature-rich open-source SIP server. Kamailio handles signaling for multimedia sessions, including call setup, management, and teardown, using SIP. Its modular architecture allows for extensive customization and integration with various databases and applications, making it a popular choice for both service providers and researchers developing next-generation communication solutions.

In this work, we utilized the open-source SIP Kamailio Server as the core network infrastructure for our IMS implementation [8]. The IMS core comprises several key functional elements, the Call Session Control Functions (CSCFs), specifically the Proxy-CSCF (P-CSCF), Interrogating-CSCF (I-CSCF), and Serving-CSCF (S-CSCF). We selected Kamailio as the IMS core due to its compelling performance characteristics and robust feature set. Built using pure C for Unix-based systems, Kamailio leverages architecture-specific optimizations that deliver exceptional throughput and minimal latency, essential for real-time communication.

Beyond performance, SIP Kamailio Server's extensive suite of services supports a wide range of multimedia applications, including voice, video, and text messaging. Importantly, it

TABLE II
FEATURES AND CHARACTERISTICS OF THE SCENARIOS

Scenario	**Release**	**Open-Source**	**HW Requiremets**	**Frequency Band**	**Sub-Carrier Spacing (kHz)**	**Bandwidth (MHz)**
5G Setup Platform	17	No	Intel Core i7-3770 CPU 3.40 GHz RAM 16 GB	All	15, 30, 60	10, 20, 40, 60, 120
SDR 5G SA MEC	17	Yes	Intel Core i7-7700 Processor 3.2 GHz 4G RAM, 4 CPU 20GB HDD	All	15, 30	10, 20, 40
DuT	**Release**	**RF Modem**	**HW Requirements**	**Frequency Band**	**Storage**	**Chipset**
Android 14 OS	17	Snapdragon™ X65 5G	Octa-core 1x3.36GHz Cortex-X3 2x2.8GHz Cortex-A715 2x2.8GHz Cortex-A710 3x2.0GHz Cortex-A510	N78 (3.75 GHz) Brazil Regulatory framework.	8GB RAM	Snapdragon 8 Gen 2 (4 nm), 12 GB

adheres to established global standards such as the SIP RFC 3261 [30] and SIP Overload Control RFC 7339 [31], ensuring interoperability and scalability. This adherence to standards, coupled with its open-source nature and active community support, makes SIP Kamailio Server an ideal platform for both research and deployment of advanced communication services. Its flexibility allows us to accurately emulate a production IMS network, enabling comprehensive testing and evaluation of emerging technologies like VoNR and ViNR using SDR.

At its core, the Real-time Transport Protocol (RTP) Engine manages the real-time transmission of media packets, ensuring the timely delivery of voice and video data. This process begins with the RTP Engine directing these packets to the P-CSCF, which serves as the initial point of contact within the IMS network for the mobile device. The P-CSCF then forwards the SIP Register request, initiated by the mobile device, to the I-CSCF. The I-CSCF acts as a central focal point, orchestrating connections for the subscriber and routing requests to a suitable S-CSCF. The S-CSCF, in turn, communicates with the HSS to validate subscriber data and complete the registration process within the IMS network. This ensures that only authorized devices can access IMS services.

To emulate the complex functionality of an IMS network, we leveraged Kamailio, a powerful and versatile SIP server. Kamailio's ability to simulate various IMS network elements enabled us to create and manage QoS Flows tailored to voice and video multimedia services. By leveraging the full range of SIP capabilities in Kamailio, we successfully implemented and tested VoNR and ViNR services in conjunction with SDR technology. This allows us to explore and optimize the performance of these services under controlled and repeatable conditions, paving the way for further advancements in 5G multimedia communication.

IV. METHODOLOGY

A. Device Under Test (DuT)

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

B. Experimental Setup

Two experimental scenarios were configured. Fig. 5 shows the first setup configuration. This scenario comprises the DuT communicating with the Radio Communication Station via the RF interface, and the 5G core elements that the local host manages via an Ethernet Interface. On the one hand, a radio communication station [32] with 5G capabilities was set up in a controlled environment laboratory, and both 5GC and IMS servers were configured using the SmartStudio Manager program [33], which allows the configuration of the virtualized core network elements. The controlled environment is appropriately located inside a laboratory, away from interference signals and out-of-band emissions that can affect radio station performance and the deployment scenario. Additionally, the DuT is housed in a shield box to minimize external interference.

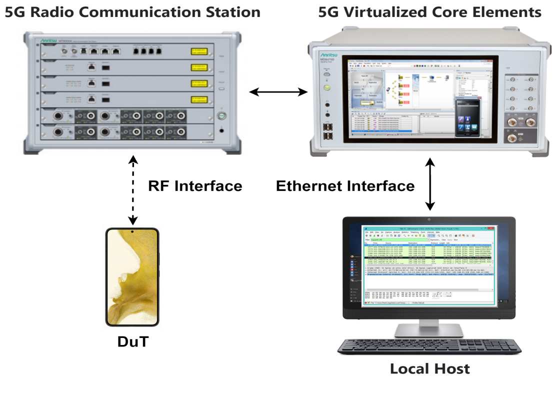


Fig. 5. 5G Setup Platform

In the second stage of the experiment, the scenario involves a configuration on a 5G SDR SA MEC (see Fig. 6). The 5GC runs on Linux Ubuntu 20.04, and an SDR B210 device is used as a gNB. In Table II, the SDR 5G SA MEC (USRP B210) exhibits a bandwidth range of 10 MHz to 40 MHz. This limitation is attributable to the transceiver (featuring an Analog Devices AD9361) and to system-level constraints on processing power and data transfer rates [24]. The 5GC and gNB are based on the Open5GS [6] and srsRAN [7]

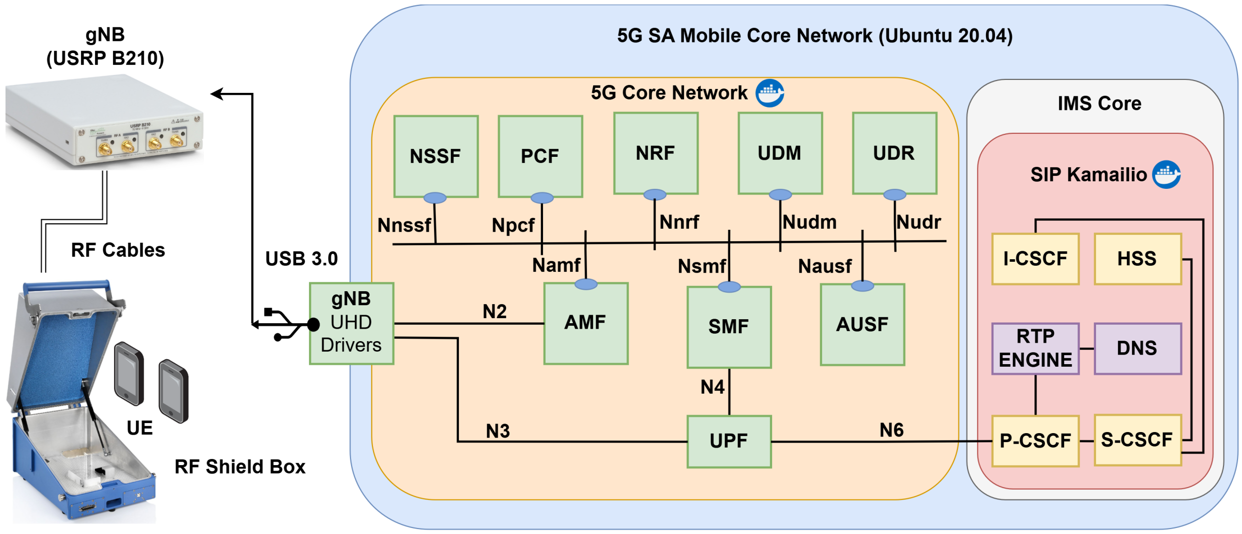


Fig. 6. SDR MEC 5G SA Testbed [15]

open-source projects, respectively. For the IMS server, the SIP Kamailio Server was used to provide VoNR and ViNR multimedia services. As seen in Fig. 6 [15], 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, as this function controls the RF and digital front-ends. At last, the 5G mobile network was set to 00101, corresponding to a Public Land Mobile Network (PLMN). It is located 1 meter from the base station in a controlled environment, free from external interference from local mobile operators and out-of-band emissions that can affect the deployment scenario's performance. In accordance with Brazilian telecommunication regulations [34], the 5G SDR operated at $3.75\,\mathrm{GHz}$ to enable a private 5G network with a bandwidth (BW) of $40\,\mathrm{MHz}$ and a sub-carrier spacing (SCS) of $30\,\mathrm{kHz}$. In Brazil, the regulatory framework for low-power private networks designates the N78 band ($3.7\,\mathrm{GHz}$ to $3.8\,\mathrm{GHz}$) for operation. To comply with these regulations and ensure accurate testing, our testbed is specifically configured to operate within this frequency range. Also, a 256 digital modulation scheme was configured. To be able to use the default network slice of the Data Network Name (DNN) [35], 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 [35]. The power transmission of the SDR and 5G radio test station was set to $\approx$ -10 dBm and -27 dBm, respectively.

In this context, by co-locating the gNB (USRP), the 5G core functions, and P/I/S-CSCF (SIP Kamailio Server) functions all on the same Linux-Ubuntu host, we are effectively pushing every VNF right up against the radio interface, which dramatically reduces delay for both signalling and data, and in principle, that is precisely what a MEC deployment is about. Therefore, this work deploys an MEC-like PoC because:

- **Edge placement:** all critical VNF (gNB on the USRP, 5G core functions, and SIP Kamailio Server as P/I/S-CSCF mainly) live on the same host beside the radio interface, providing the low-latency transport that MEC promises.
- **Service validation:** By verifying SIP predonditions, Diameter Rx interactions for QoS, and media anchoring with RTP engine, it is exactly what you expect in a real MEC trial.
- **Proof of workflow:** since we manually orchestrated Docker containers, we demonstrated the key control-plane and user-plane interactions that a production MEC would automate via an edge orchestator and standardized APIs.

In our deployment, the gNB (srsRAN plus USRP), Open5Gs, and SIP Kamailio communicate primarily over internal Docker bridges. Consequently, N2 (Next Generation Application Protocol-NGAP over Stream Control Transmission Protocol-SCTP), N3 (GPRS Tunneling Protocol User-plane-GTP-U over UDP), and SIP signaling traverse kernel-level virtual networking paths with minimal physical transport latency. This architecture is highly efficient for functional validation, particularly for VoNR and ViNR call flows, SIP precondition, Diameter-based Rx interactions, and RTP anchoring via RTPengine, because it collapses transport variability and eliminates external queuing effects. It does not expose realistic scaling constraints such as network interface card interrupt saturation, buffer congestion, Maximum Transmission Unit (MTU) fragmentation due to GTP encapsulation, or jitter induced by physical switching.

On the other hand, if the MEC node (hosting IMS and 5GC control and user plane) is physically separated from the gNB but remains within the same local edge domain (e.g., same Point of Presence-PoP or aggregation switch), the system transitions from Inter-Process Communication (IPC) dominated communication to true Layer 2 and Layer 3 transport. That can introduce a small but real Round-trip time (RTT), plus transport jitter. In this model, SCTP associations, GTP tunnels, and RTP streams traverse real Ethernet paths, introducing measurable propagation, serialization, and queuing delays. While this slightly increases latency, it significantly improves architectural realism and scalability. Control-plane functions (AMF/SMF/SIP Kamailio) can scale horizontally behind load balancers, while user-plane scaling can be achieved by deploying additional UPF instances closer to traffic anchors (local breakout). Meanwhile, the radio host can be optimized independently with real-time CPU isolation and UHD tuning. This separation enables clearer fault domains, better capacity planning, and slice-aware transport engineering (Differentiated Services Code Point (DSCP), traffic shaping, VLAN isolation). Therefore, the physically separated edge model more accurately reflects production MEC topologies, while the single-host model remains an efficient MEC-like PoC for validating signaling, QoS flows, and service call flows.

C. SIP Kamailio Server

In 3GPP architectures, a call session is classified as VoNR or ViNR when its signaling is anchored within the IMS domain, and its user plane (media traffic) traverses the 5G Core network, being carried over the 5G NR air interface. This represents a fundamental shift from previous generations, enabling seamless integration of multimedia services within the 5G ecosystem. The defining characteristics of VoNR and ViNR services extend beyond simple connectivity and encompass a comprehensive set of network features. These include: (1) End-to-end integration with core mobile network functions, specifically AMF, SMF, UPF, and PCF, ensuring seamless dedicated session establishment, management, and QoS policies. (2) SIP signaling routed through IMS entities, such as P-CSCF and S-CSCF, enabling robust call control and dedicated multimedia session management. (3) Tight coupling with subscriber management, policy enforcement, charging frameworks, and mobility management protocols inherent to cellular systems, ensuring secure, reliable, and personalized service delivery. This tight integration enables advanced features, including seamless handover between cells, QoS guarantees, and dynamic policy adaptation based on network conditions and user preferences.

Fig. 7 shows a full call-flow of our proposed solution to provide VoNR and ViNR using SIP Kamailio Server, and 5G Core. The first step in using SIP Kamailio server involves the authentication and authorization steps, where when the UE sends a REGISTER request to the P-CSCF, Kamailio uses the ims_request_auth function to issue a User Authentication Request (UAR) Diameter request to the UDM/AUSF, obtaining the Authentication and Key Agreement (AKA) and User Authentication Answer (UAA) challenge vectors. Upon receipt of these vectors, the ims_validate_auth function compares the Response (RES) from the UE with the expected value. If the response does not match, a 401 Unauthorized error is sent along with the challenge. Otherwise, a 200 OK is sent.

Then, in the call handling step, when the UE initiates a call with an INVITE containing audio and video media lines, the SIP Kamailio server invokes the ims_request_auth function again, sending a Diameter Multimedia Authentication Request (MAR) to authorize the multimedia session. The process is similar to REGISTER, with checks and sending 407 Proxy Authentication Required and authenticated INVITE messages. Meanwhile, Kamailio's Diameter client (from the auth_diameter.so module) handles the exchanges between MAR and Multimedia Authentication Answer (MAA) for the INVITE, as well as the UAR and UAA for the REGISTER. It maps SIP URIs to Diameter Attribute-Value Pairs (AVPs), and parses result codes into pseudo-variables that guide the authentication logic. After the authentication process completes, Kamailio performs a Domain Name System Service Record (DNS SRV) lookup (using lookup("srv") or the built-in resolver) to find the I-CSCF host and resolve the DNS entry. The result is stored in a pseudo-variable, and the destination URI is rewritten accordingly.

Next, Kamailio anchors the caller's Session Description Protocol (SDP) by calling rtpengine-offer (replace−origin replace−session−connection) from the rtpengine.so module. The RTPengine daemon responds with public IP addresses and ports, which Kamailio reinserts into the INVITE body and records in an AVP for later use during the answer phase. Using the ims_route() function, Kamailio determines whether to forward the anchored INVITE to the I-CSCF or directly to the S-CSCF. It applies ENUM lookups, dispatcher lists, or static service routes to configure the destination URI and destination URI variable before relaying the request with t_relay(). Once the INVITE reaches the I-CSCF, Kamailio proxies it to the S-CSCF (using route[RELAY]) without performing any additional checks, thereby preserving the branch and transaction identifiers. At the S-CSCF, Kamailio applies any service logic, such as user-profile filters or charging hooks, before proxying the INVITE to the callee's P-CSCF. When the callee responds with a 183 Session Progress and a 200 OK containing its SDP, Kamailio at the S-CSCF proxies both provisional and final responses upstream via t_relay() and updates the dialog state in the variable. At the caller's P-CSCF, Kamailio calls rtpengine_answer() to anchor the callee's SDP, again exchanging HTTP/UDP commands with the RTPengine daemon and rewriting the 200 OK body with the updated media endpoints. After this, Kamailio relays the ACK from the caller back to the callee, allowing RTP streams to flow through the UPF/gNB path under RTPengine's anchoring.

Kamailio determines whether to forward the INVITE directly to the S-CSCF or to the I-CSCF by performing ENUM lookups, using dispatcher lists, or following static service routes. The INVITE is then forwarded without performing any additional checks, preserving the branch and transaction identifiers. Upon reaching the S-CSCF, Kamailio applies service logic, such as user profile filters or billing hooks, before forwarding the INVITE to the callee's P-CSCF. When the callee responds with a 183 Session Progress and a 200 OK containing its SDP, Kamailio in the S-CSCF forwards both the interim and final responses to the caller, updating the dialog state. In the caller's P-CSCF, Kamailio calls rtpengine_answer function to anchor the callee's SDP, updating the media endpoints in the body of the 200 OK. After that, Kamailio forwards the caller's ACK to the callee, allowing RTP streams to pass through the UPF/gNB path under RTPengine anchoring.

Finally, during the in-call phase, any UPDATE or OPTIONS messages (such as those used to hold a ViNR session) are relayed using the same route[RELAY] logic. At call termina-

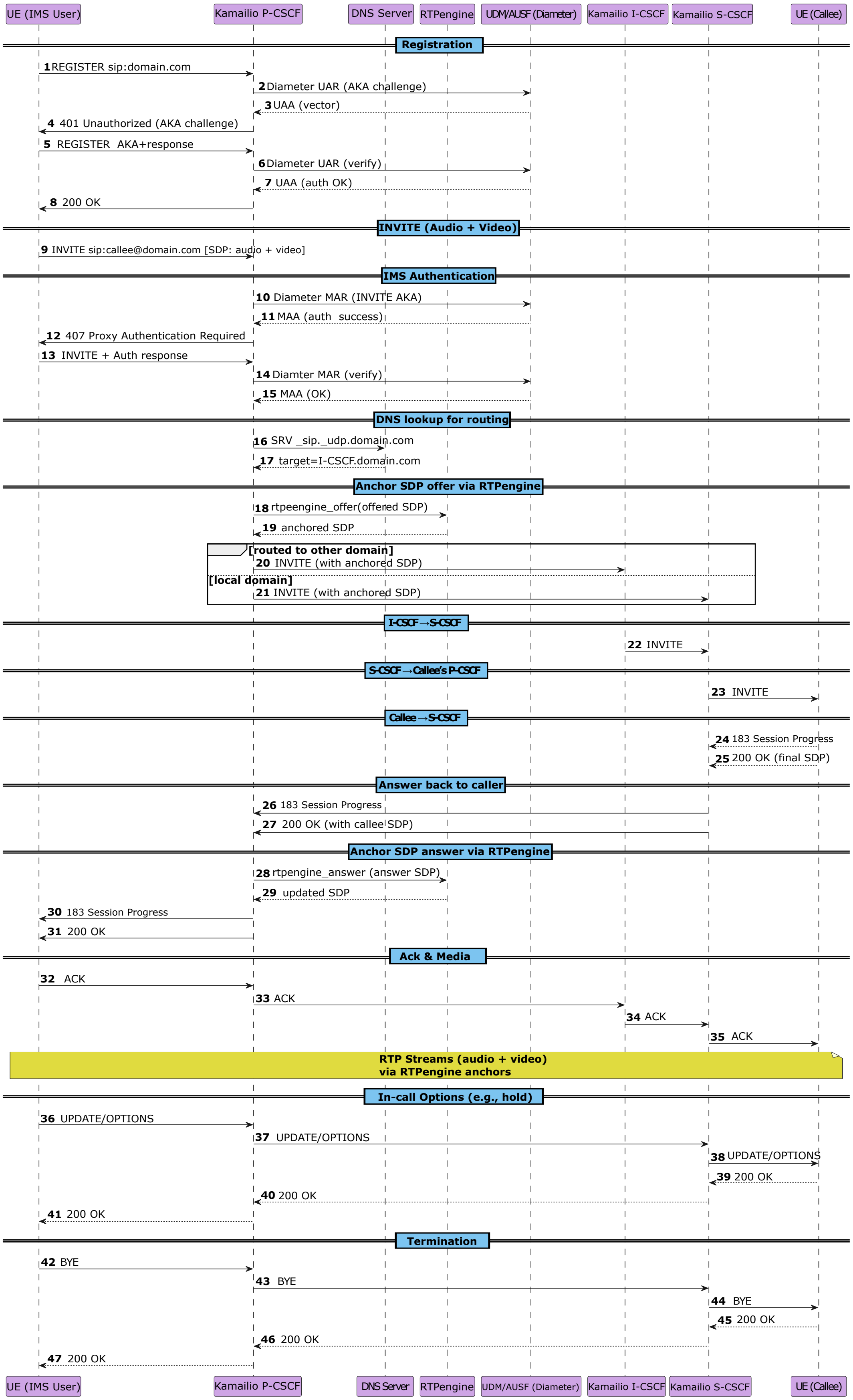


Fig. 7. Call-Flow of VoNR and ViNR using SIP Kamailio

tion, Kamailio invokes the rtpengine_delete function to tear down the media anchor, then relays the BYE and sends the final 200 OK response.

VoNR and ViNR calls in 5G networks are fundamentally distinct from generic VoIP, regardless of whether QoS flows are fully guaranteed. VoNR and ViNR require the voice session's SIP signaling to traverse IMS and its media to be carried end-to-end over the 5G NR radio interface and 5GC. The core network orchestrates mobility, authentication, policy enforcement, lawful intercept, and end-to-end quality of service, using cellular-grade security and standardized 3GPP procedures. In this architecture, establishing voice and video services leverages reserved network identities, subscriber databases, and tightly controlled QoS flow management, ensuring seamless operation. Generic VoIP, in contrast, typically involves best-effort packet delivery over unmanaged IP networks, lacks deep integration with mobile core functions, and is not subject to policy and regulation, charging, or standardized QoS enforcement.

As long as the session is anchored in IMS and uses 5GC and 5G NR, with policy and mobility control provided by the SDR network, the call session remains a VoNR or ViNR session rather than a generic VoIP session. The distinction is architectural and functional, not solely dependent on precondition negotiation.

Therefore, SIP Kamailio Server enables flexible, scalable SIP signaling, registration, and routing, enforcing 3GPP IMS standards and ensuring seamless interoperation with mobile core elements. Its modular architecture ensures that VoNR and ViNR signaling traverses a fully standards-compliant IMS core, integrated with the 5G Core network. While Kamailio manages QoS flows, it ensures that all signaling, policy triggers, and service logic concerning 5G IMS requirements are met. In this scenario, SIP Kamailio serves as a central enabler for VoNR and ViNR services, ensuring that voice and video sessions are established, managed, and terminated in accordance with the 5G architecture. This differs from generic VoIP, which lacks the rigorous operator-managed control and integration characteristic of 5G.

The deployment of the SDR 5G network and SIP Kamailio Server in this paper maintains the essential properties of VoNR and ViNR: the session is established, managed, and secured according to 3GPP 5G and IMS specifications, leveraging operator-managed policies, subscriber databases, and core network resources. As a result, voice and video services remain architecturally and operationally distinct from generic VoIP, whose signaling and media are not subject to such comprehensive core network control, IMS authentication, QoS, dedicated flows, or standards-driven service logic.

D. Video over New Radio (ViNR) using SDR

While significant research has focused on VoNR within 5G networks, the delivery of Video over New Radio (ViNR) remains a relatively unexplored area, particularly within the realm of SDR implementations. The existing literature lacks Proof-of-Concept (PoC) demonstrations of ViNR using SDR, creating a notable gap in the current state of the art. This work addresses this critical limitation by presenting the first SDR prototype capable of delivering ViNR services using the SIP Kamailio Server. This contribution is significant because it unlocks new avenues for research and development in areas such as optimized video codecs for 5G, dynamic resource allocation for multimedia streams, and end-to-end QoS evaluation in real-world wireless environments. By providing a flexible, programmable platform for ViNR experimentation, this work paves the way for innovative applications and services that leverage the full potential of 5G multimedia capabilities, moving beyond voice-centric communication to a truly immersive, visually rich mobile experience.

The code snippets in this Section demonstrate how smartphone software was configured to enable ViNR support using the Java programming language. In the code snippet of the algorithm 1, the JSON representation is shown, which enables essential IMS features, such as voice and video over the NR air interface, for the default network operator used in the test ($carrier\_default$). Notably, the command $enableVideo$ is crucial to enable support for video calls over 5G NR using IMS, allowing the system to offer this functionality to mobile users.

```
{
  "carrier": "carrier_default",
  "enableVoice": true,
  "enableVideo": true
}
```

Listing 1. Algorithm 1: Communication Services Configuration

In addition, the code snippet of the Algorithm 2 also enables the ViNR service in another JSON file, in which the ViNR service is explicitly listed in the services variable, indicating that the system must support ViNR calls. Furthermore, in this file, the supported network types (NR and LTE) are defined, ensuring the system can operate in environments with high data transmission capacity, which is essential for the quality of video calls.

```
{
  "carrier": "carrier_default",
  "network_type": ["NR", "LTE"],
  "services": ["voice", "video"]
}
```

Listing 2. Algorithm 2: Network and Services Configuration

V. EXPERIMENTAL RESULTS

The proposed 5G SDR SA MEC testbed, alongside a commercially 5G Testbed Platform, provides an environment for comprehensive experimentation with both VoNR and ViNR calls within a fully functional 5G network. To assess network performance and efficiency, we analyzed key QoS metrics, with a focus on jitter, which is the rate of variation in packet delay and directly impacts the perceived quality of real-time multimedia streams. Following successful UE attachment and authentication within the 5G SA MEC network, QoS metrics, as defined by 3GPP standards [35], were evaluated over both short-term (1 minute) and extended-duration (30 minute) periods. This approach enabled a detailed assessment

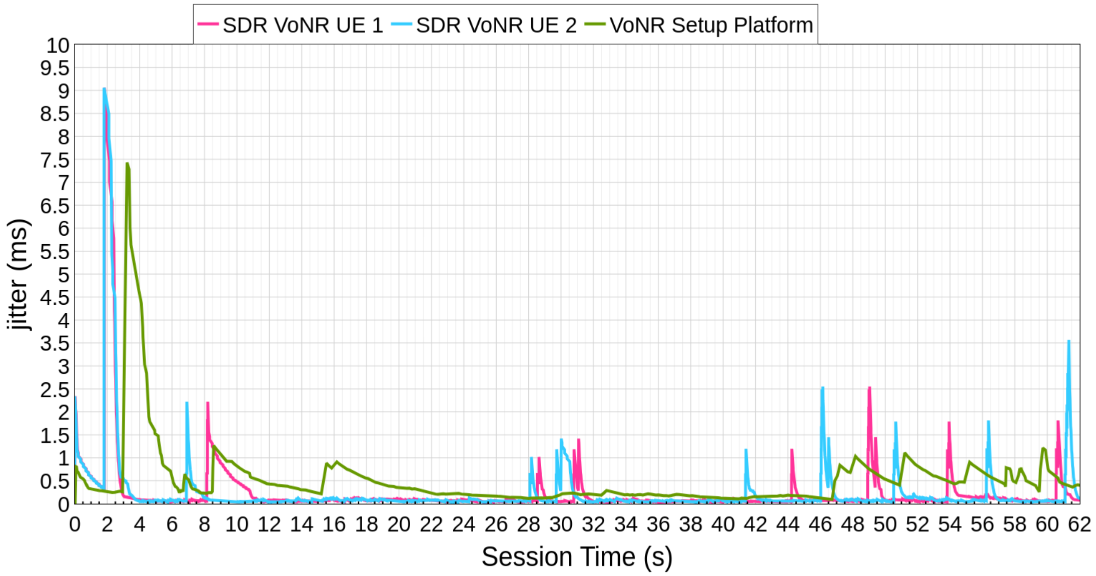


Fig. 8. Comparison of Jitter for VoNR

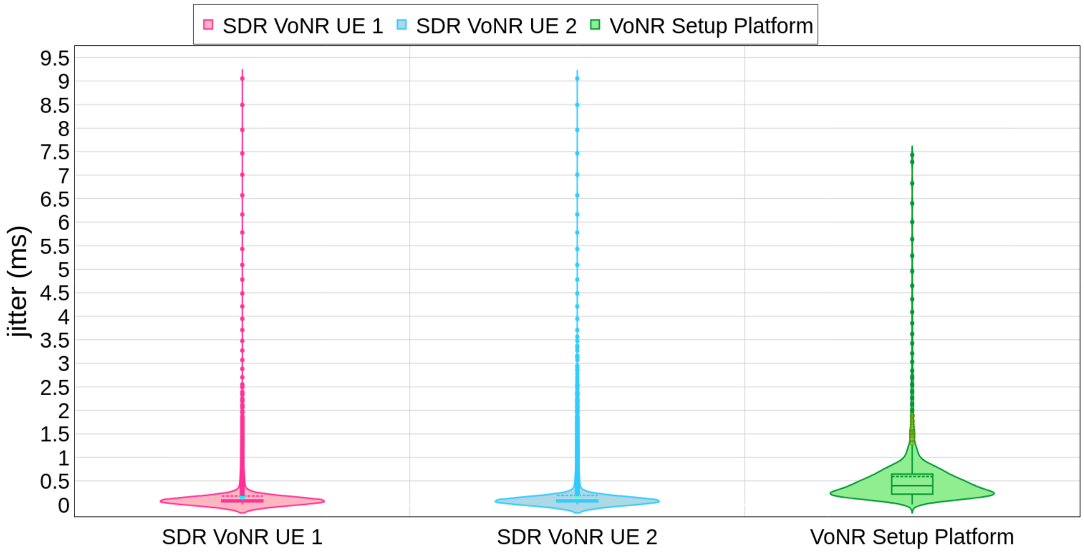


Fig. 9. Violin plots for VoNR

of computational resource allocation, providing insights into the network's ability to maintain consistent performance under varying traffic loads and extended usage scenarios. By examining both instantaneous and long-term behavior, we aimed to characterize the stability and scalability of the SDR 5G SA MEC network for delivering high-quality multimedia services.

Fig. 8 shows the jitter evaluation during a voice session (VoNR) between two mobile users using two physical smartphones that call each other, in pink and blue colors for user 1 and user 2, respectively. Additionally, the 5G Setup Platform is displayed in green. The VoNR voice session lasted approximately 60 seconds. On the one hand, for the SDR MEC 5G SA Testbed, at the beginning of the VoNR call, we have a peak of approximately $9.05\,\mathrm{ms}$ and $9.07\,\mathrm{ms}$ for User 1 and User 2, respectively, corresponding to the resource allocation of the SIP Kamailio Server. In this context, the jitter threshold is satisfied since the maximum acceptable value is $20\,\mathrm{ms}$ [36]. The packets are usually generated every $20\,\mathrm{ms}$, but arrive at the other end with inconsistent intervals due to different kinds of delay along the communication path. On the other hand, for the 5G Setup Platform, two mobile users were also used, one with a physical smartphone and the other with a virtual one. As we can observe, there is similar behavior at the beginning, as the IMS server allocates resources. Throughout the VoNR session, jitter peaks at $7.43\,\mathrm{ms}$ and yields results comparable to those in the SDR case.

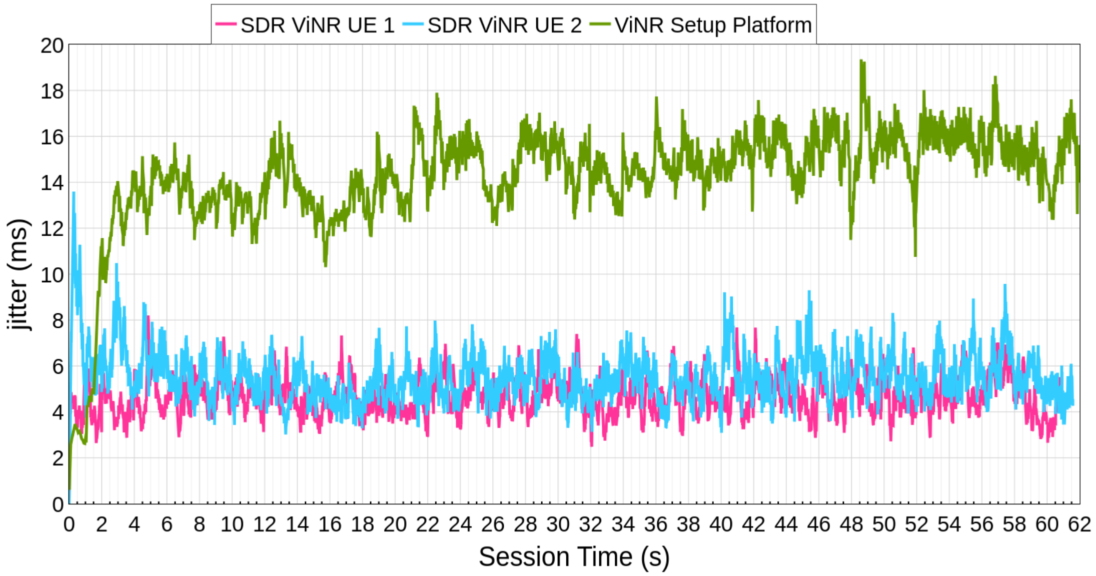


Fig. 10. Comparison of Jitter for ViNR

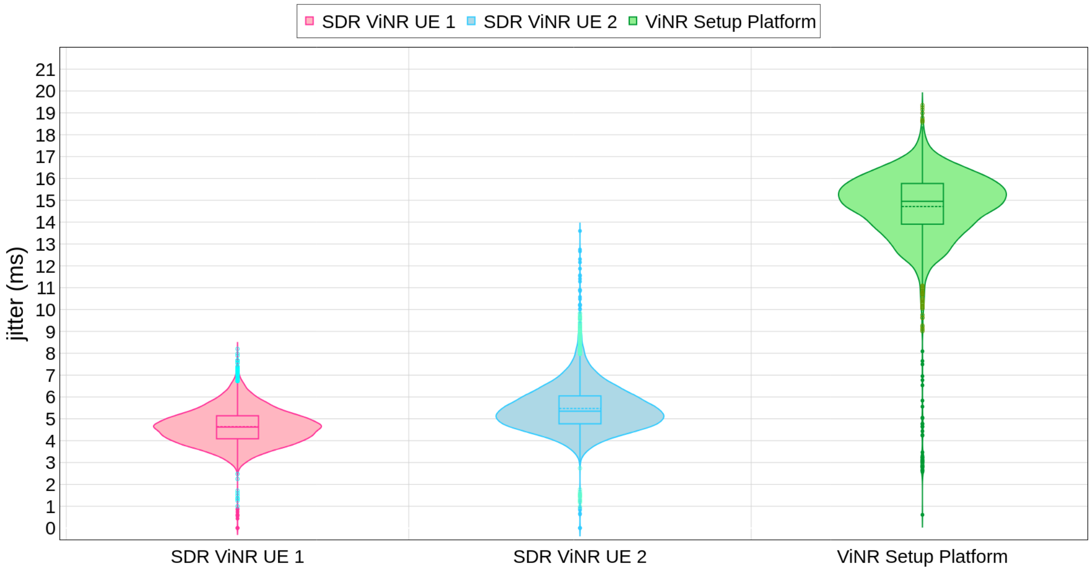


Fig. 11. Violin plots for ViNR

In Fig. 9, the statistical evaluation is performed using the Violin and Box Plots graph, comparing the statistical behavior during the VoNR session for each mobile user and the 5G Setup Platform user. The average values are $0.18\,\mathrm{ms}$, $0.19\,\mathrm{ms}$, and $0.59\,\mathrm{ms}$ for User 1, User 2, and the 5G Platform, respectively. The presence of outliers in all cases corresponds to the moment when the resources of the SIP Kamailio and IMS servers are allocated to guarantee the VoNR voice session. For the SDR MEC case, there is an asymmetric distribution to the right since the mean value is greater than the median for both users, approximately $0.07\,\mathrm{ms}$. On the other hand, for the 5G Setup Platform, there is also a right-skewed positive asymmetry, with a median of $0.40\,\mathrm{ms}$.

Fig. 10 and Fig. 11 assess jitter for the ViNR video session between two users (physical smartphones) and for a single user (physical smartphone) on the 5G Setup Platform (green). The video session was approximately $60\,\mathrm{s}$. It is noteworthy to observe that the average jitter values are approximately $4.64\,\mathrm{ms}$, and $5.47\,\mathrm{ms}$ for User 1 (pink) and User 2 (blue), respectively. The average jitter value for the 5G Setup Platform was $14.71\,\mathrm{ms}$. This occurs because the 5G Setup Platform has fully deployed a dedicated QoS flow throughout the video call session. In contrast, in the SIP Kamailio Server, the dedicated QoS flow is not entirely constant in an end-to-end path. When the UE sends an INVITE to the SIP Kamailio Server, the SDP includes RFC 3312 'preconditions', which inform the network that media cannot start until the resource reservation is successful. Kamailio's P-CSCF parses these with its precondition modules and then generates a Diameter Rx request, using the auth-diameter modules, toward the PCF, carrying the mobile operator's profile and the requested 5QI, ARP, GBR/MBR values. When the PCF returns its decision in a Diameter Rx-Answer, SIP Kamailio maps those AVPs back into the SIP dialogue by annotating the 200 OK's SDP with the granted QoS parameter or sending a SIP Update. Only then does SIP Kamailio forward the final 200 OK to the caller, at which point the UE's 5G NAS stack and SMF coordinate to establish the actual QoS flow in the UPF, providing the UE with the guaranteed bitrate and prioritized voice and video packet handling required by VoNR/ViNR. Therefore, we used all the capabilities of the SIP Kamailio server to provide VoNR and ViNR over 5G. Furthermore, the 5G SDR network deployed an MEC network, which further reduces various communication delays between VNFs and SDR devices compared to the 5G setup platform. In Fig. 11, the maximum values are $8.19\,\mathrm{ms}$, $13.60\,\mathrm{ms}$, and $19.35\,\mathrm{ms}$ for the User 1 (pink), User 2 (blue), and 5G setup platform scenarios (green), in that order. As explained earlier, it is worth noting that the jitter values meet the $20\,\mathrm{ms}$ threshold [36] to ensure voice and video services.

The throughput was computed for the radio test station (see Fig. 5) and the SDR MEC 5G SA Testbed (see Fig. 6). These results are based on our previous work [37]. The Iperf [38] tool, utilizing the TCP protocol, was employed to evaluate network performance in the Downlink direction. The throughput was calculated between the UE and the User Plane Function (UPF). After the UE was successfully attached to and authenticated with the 5G SA network, throughput was measured for 5 minutes, followed by post-processing analysis. The radio test station (see Fig. 5) was used to evaluate the MAC layer and determine the upper bound on throughput. The primary distinction between MAC and IP layer throughput at the radio station is that the MAC layer manages the transfer of data frames that contain both control and data payloads, whereas the IP layer encapsulates data payloads within an IP header, including the IP address and Time-to-Live. For the theoretical analysis, Eq.1 was applied to estimate the approximate maximum data rate for downlink [39]:

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

where in [39]: 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.

Given the similarity of the configurations, as detailed in Table II, these results extend our previous work [37], which evaluated a private 5G Stand-alone SDR-based network and compared its quality of service metrics. The earlier study provided an initial exploration of 5G SDR mobile networks, focusing on raw data rather than an in-depth analysis of the IMS' services. The present study provides a comprehensive analysis of VoNR and ViNR services. Fig. 12 compares downlink throughput for the 5G setup platform (both MAC

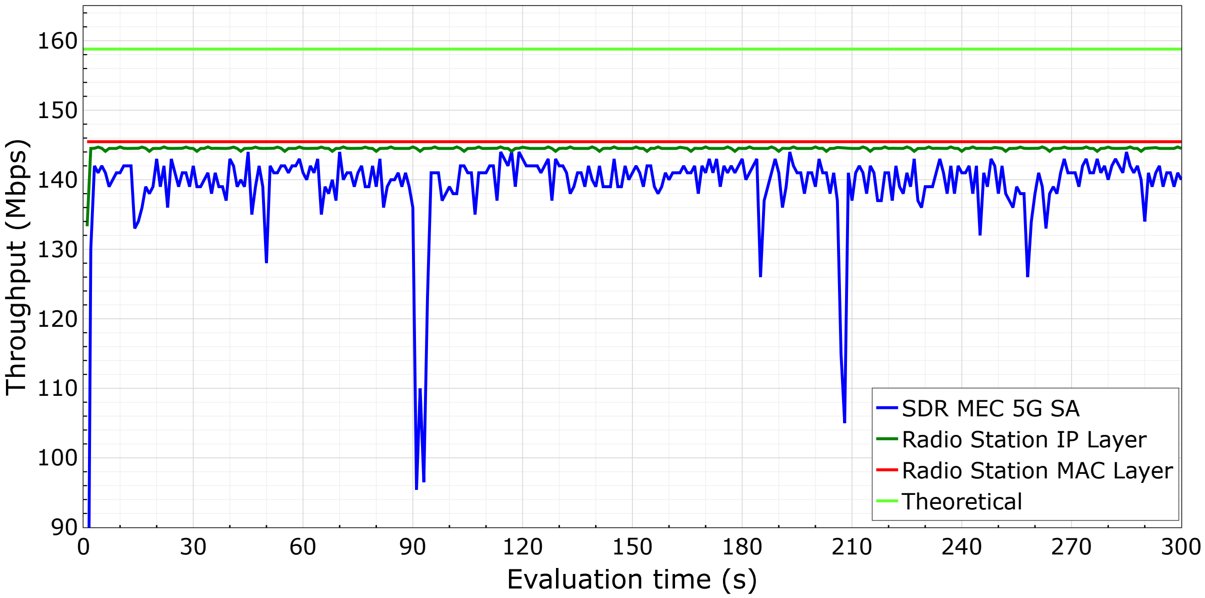


Fig. 12. Comparison of Throughput

and IP layers), the MEC SDR-based solution, and the theoretical approach. The theoretical approach, depicted in light green, shows a value of $158.79\,\mathrm{Mbit\,s^{-1}}$ for approximately 80% of the symbol slots allocated to the user channel in TDD mode. For the radio station, throughput is shown in red and green for the MAC and IP layers, respectively. As anticipated, the MAC-layer throughput evaluation yielded a higher value ($145.47\,\mathrm{Mbit\,s^{-1}}$) than the IP-layer evaluation ($144.52\,\mathrm{Mbit\,s^{-1}}$), with only a minimal difference between these values. The SDR MEC 5G SA network, represented in blue, achieved mean, minimum, and maximum throughput values of $139.13\,\mathrm{Mbit\,s^{-1}}$, $45.4\,\mathrm{Mbit\,s^{-1}}$, and $144\,\mathrm{Mbit\,s^{-1}}$, respectively.

Fig. 13 shows the smartphone display and icons during VoNR (left) and ViNR (right) sessions in experiments with the 5G SA SDR MEC testbed.

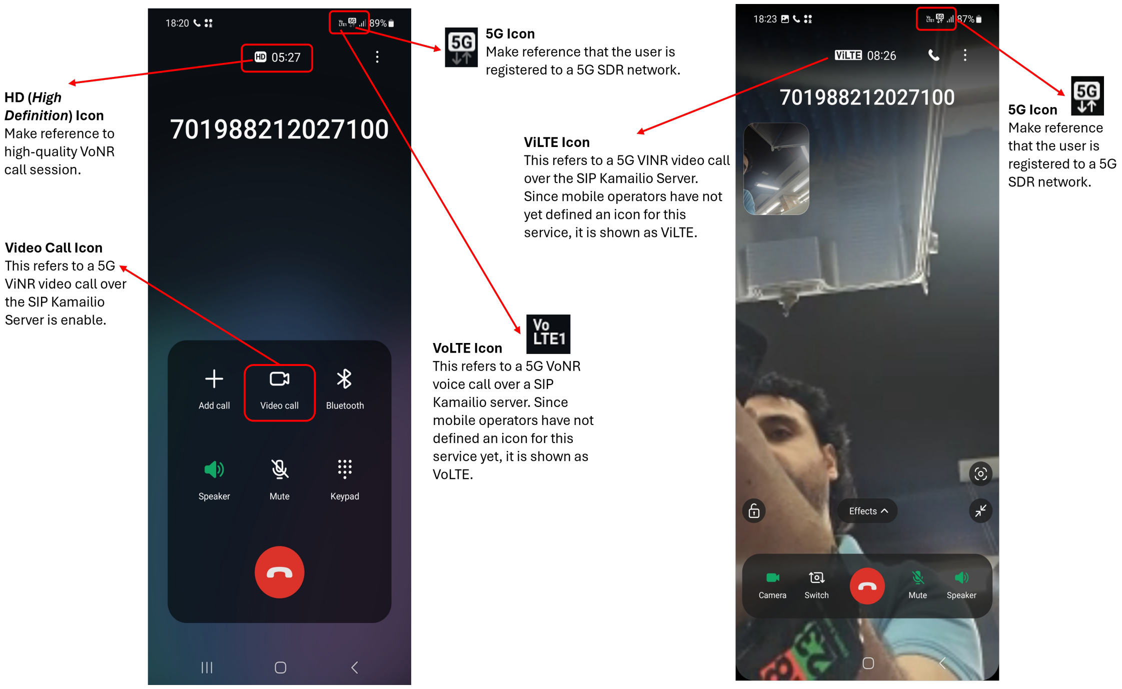
The consumption of computational resources was also evaluated, but only for the SDR scenario throughout the experimentation. We could not do the same for the 5G Setup platform since it is not an open-source solution. An important aspect of deploying network functions as VNFs in an SDR scenario, particularly within an MEC architecture, is evaluating their computational resource consumption. Unlike traditional hardware-based network functions, VNFs rely on shared computing infrastructure, which encompasses resource demands that include CPU cycles, memory allocation, and network bandwidth, a key determinant of overall system performance, scalability, and cost-effectiveness. Throughout our experimentation, meticulous monitoring of VNF resource consumption is therefore evaluated.

Fig. 14 shows the average CPU consumption for the cases with only one user registered to the network, with two registered users, and with both users browsing the Internet and watching a YouTube video [40] during the VoNR and ViNR video sessions. As we can observe, most of the computational resources were allocated to the gNB, with negligible consumption by the other 5G core VNFs. The main VNFs in the core network related to multimedia services are the AMF, SMF, and UPF, as well as the P-CSCF, I-CSCF, S-CSCF, MySQL, and RTP Engine on the IMS server. The average CPU usage values are presented in Table III. For the gnB case with only one registered user, the average CPU consumption was $24.10\,\%$. With two users, it was $26.95\,\%$; with internet traffic, it was $26.84\,\%$; with VoNR voice calls, $28.02\,\%$; and with ViNR calls, $29.22\,\%$.

Fig. 15 shows the results regarding memory resources for all evaluated cases. For the gNB, the average memory allocation was approximately $5.02\,\mathrm{GB}$, $5.06\,\mathrm{GB}$, $5.10\,\mathrm{GB}$, $5.20\,\mathrm{GB}$, and $5.27\,\mathrm{GB}$ for one user and two users surfing the internet, VoNR, and ViNR calls, respectively. As shown previously, the gNB is the VNF that consumes the most memory, with an average of approximately $5.13\,\mathrm{GB}$. Table IV presents the result for the most important VNFs regarding voice and video calls over the SIP Kamailio Server.

TABLE III
AVERAGE CPU USAGE (IN %) FOR 5GC AND IMS VNF

VNF	UE 1	UE 2	Internet	VoNR	ViNR
AMF	<0.01	<0.01	<0.01	<0.01	<0.01
SMF	<0.01	<0.01	<0.01	<0.01	<0.01
UPF	0.01	0.07	0.08	0.18	0.19
P-CSCF	0.02	0.01	0.01	0.01	0.01
I-CSCF	<0.01	<0.01	<0.01	<0.01	<0.01
S-CSCF	0.01	0.01	0.01	0.01	0.01
MySQL	0.08	0.07	0.08	0.08	0.08
RTP Engine	0.04	0.038	0.05	0.13	0.15



HD (*High Definition*) Icon
Make reference to high-quality VoNR call session.

Video Call Icon
This refers to a 5G ViNR video call over the SIP Kamailio Server is enable.

5G Icon
Make reference that the user is registered to a 5G SDR network.

VoLTE Icon
This refers to a 5G VoNR voice call over a SIP Kamailio server. Since mobile operators have not defined an icon for this service yet, it is shown as VoLTE.

ViLTE Icon
This refers to a 5G VINR video call over the SIP Kamailio Server. Since mobile operators have not yet defined an icon for this service, it is shown as ViLTE.

5G Icon
Make reference that the user is registered to a 5G SDR network.

Fig. 13. Smartphone's Display Left) VoNR Right) ViNR using SDR technology [37]

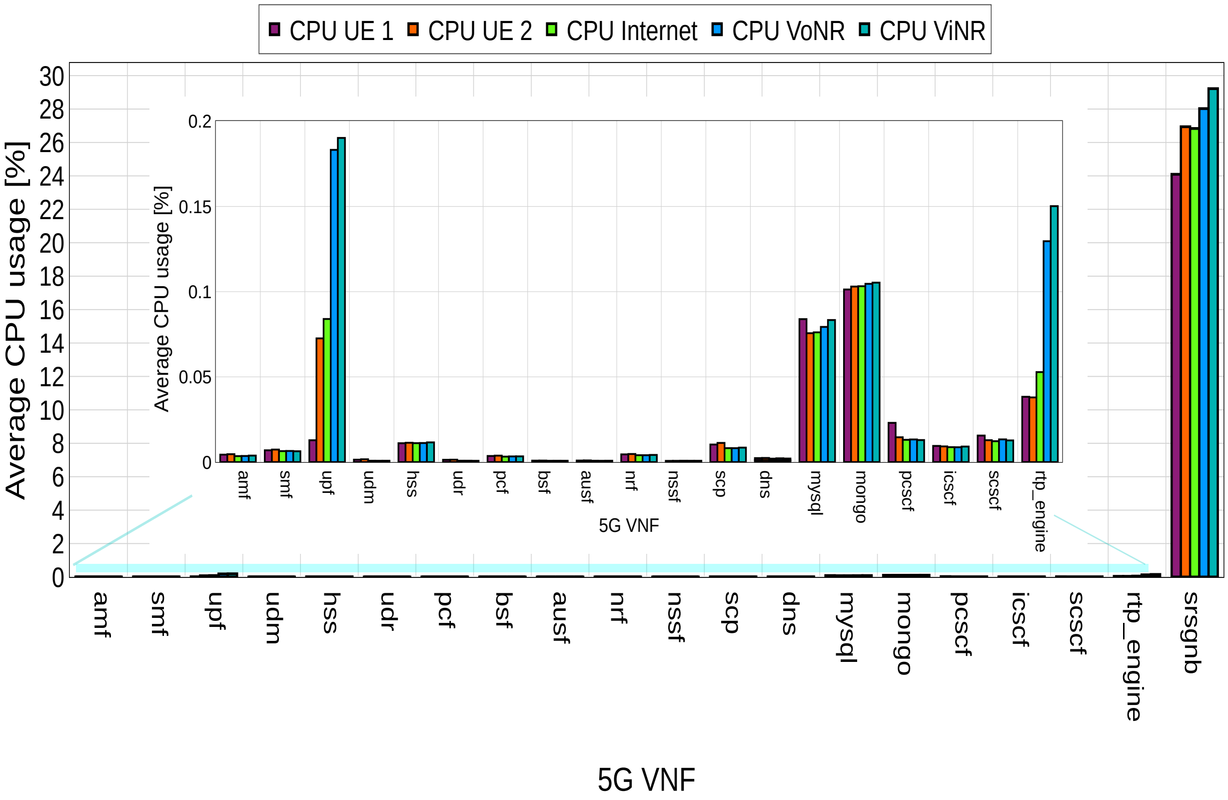


Fig. 14. Comparison of CPU Usage per container

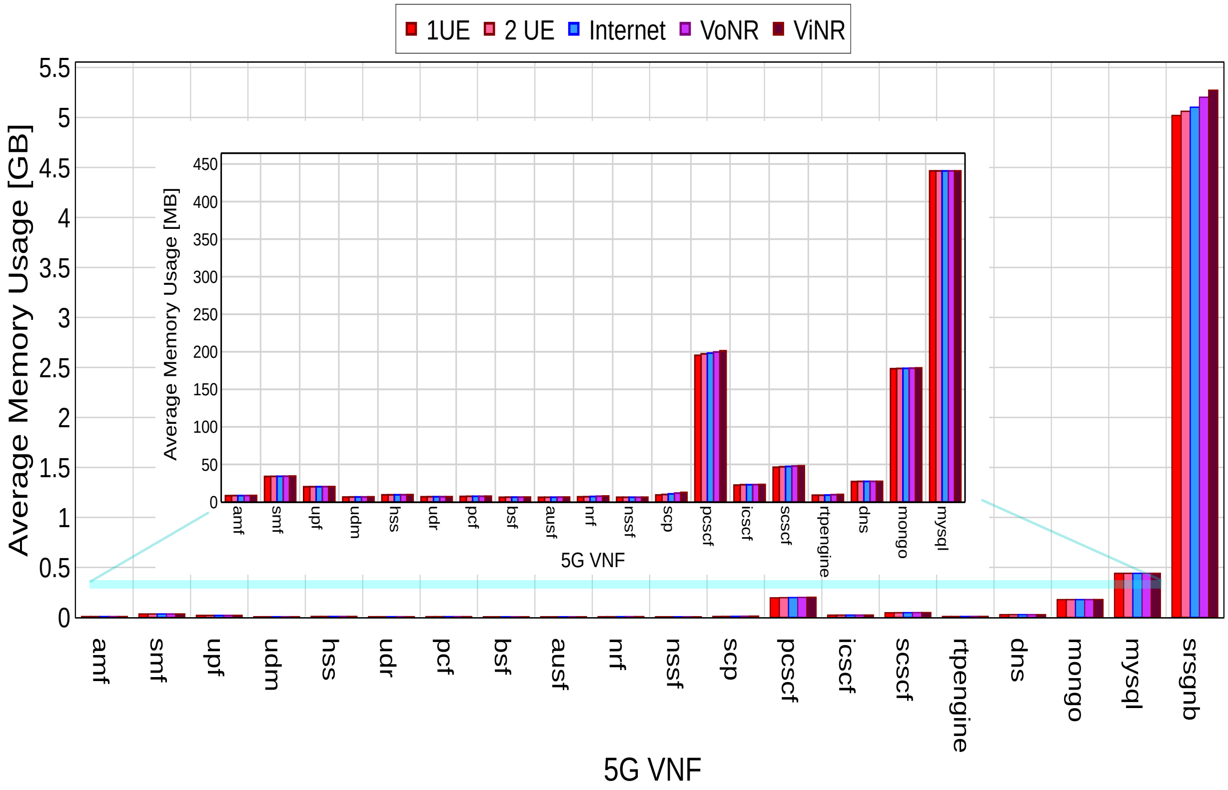


Fig. 15. Comparison of Memory Usage per container

TABLE IV
COMPARISON OF MEMORY USAGE PER CONTAINER (IN MB)

VNF	UE 1	UE 2	Internet	VoNR	ViNR
AMF	<10	<10	<10	<10	<10
SMF	30	30	30	30	30
UPF	20	20	20	20	20
P-CSCF	190	200	200	200	200
I-CSCF	22	23	23	24	25
S-CSCF	46	47	48	48	49
MySQL	441	441	441	441	441
RTP Engine	<10	<10	<10	<10	<10

VI. CHALLENGES AND RECOMMENDED SOLUTIONS

This section discusses potential challenges and recommends solutions regarding an SDR-based 5G SA MEC mobile network with the SIP Kamailio Server to provide IMS multimedia services.

1) **Real-time Performance and Deterministic Latency**
   - **Challenge:** SDR-based gNB (srsRAN using USRP) and RTP engines require a tight timing (sub-millisecond) to meet 5G radio and VoNR/ViNR latency budgets; nevertheless, Docker containers' default CPU scheduling and virtual networking can introduce jitter.
   - **Solution:** Evaluate critical containers (e.g., srsRAN, UPF, RTPengine) to dedicated CPU cores using `-cpuset-cpus`. Use `-network=host` or macvlan networks to bypass bridge delays. Deploy a real-time or low-latency kernel and enable CPU isolation via the `isolcpus=` boot parameter.
2) **Clock Synchronization**
   - **Challenge:** 5G timing (gNB frame alignment) and SIP transaction timers rely on accurate clocks, which can drift inside Docker containers.
   - **Solution:** Run Network Time Protocol (NTP) or Precision Time Protocol (PTP) on the host and mount its configuration into containers (e.g. `-v /etc/ntp.conf:/etc/ntp.conf:ro`); for sub-µs accuracy, pass through a PTP-capable NIC and enable PTP in the container.
3) **QoS Enforcement and Dedicated Bearers**
   - **Challenge:** SIP Kamailio Server can request QoS via SIP preconditions and Diameter Rx, but does not itself reserve or enforce 5G QoS flows bearers. Docker networks do not reflect bearer-level isolation.
   - **Solution:** Ensure PCF and SMF VNF processes Rx-Answer AVPs to schedule the QoS flows. Then tag using Differentiated Services Code Point (DSCP) on RTP via RTPengine. Also, you should map UPF Docker container interfaces to host bridges or VLANs.
4) **Resource Contention on a Single Host**
   - **Challenge:** 5G Core network functions, RAN, IMS signaling, media proxy, and SDR drivers compete for CPU and memory, risking starvation under load.
   - **Solution:** Profile each Docker container's resource usage; use groups limits (`-memory`, `-cpus`) to guarantee minimum resource. Offload heavy tasks to GPU-enabled Docker containers or separate hosts.
5) **Networking Complexity and Isolation**
   - **Challenge:** Multiple protocols (NGAP, N3, N4, SIP/TLS, RTP) on overlapping subnets can conflict, and Docker's NAT breaks GTP-U requirements.
   - **Solution:** Create Docker macvlan networks or use host networking with specific port binds. Bind the UPF container's GTP-U port directly to a host virtual Ethernet cable (veth). Enforce network policies with `iptables` to isolate SIP, GTP, and management traffic.
6) **Orchestration, Scaling, and MEC Integration**
   - **Challenge:** A manual Docker Compose lab lacks self-healing, autoscaling, and MEC exposure, preventing dynamic edge placement of functions.
   - **Solution:** Migrate to Kubernetes to register P-CSCF, and UPF as edge services. You can also use Helm charts for Open5GS and SIP Kamailio server to scale S-CSCF or UPF pods on demand.
7) **Hardware limitation**
   - **Challenge:** Evaluating MIMO and full 5G NR with a 100 MHz bandwidth presents a significant computational demand, potentially leading to excessive CPU utilization and hindering real-time processing.
   - **Solution:** To address this, we should recommend utilizing a USRP platform configured to offload computationally intensive tasks from the CPU. This will enable real-time processing and accurate evaluation of the 5G NR system.

VII. CONCLUSION

This paper evaluated the network performance in terms of QoS, primarily for VoNR and ViNR multimedia services over IMS in a SA network operating at 3.75 GHz, using the USRP B210 model as a 5G SA gNB and the SIP Kamailio server to emulate the IMS network. Additionally, a comprehensive 5G Setup Platform was deployed to facilitate a comparison of the results. This platform tests 5G communications terminals, chipsets, and devices.

In this regard, open-source monitoring systems were also used to collect network memory and CPU usage during the experiments. The results also evaluated jitter, round-trip time, and propagation delay to validate the performance of the SDR 5G SA MEC network. This work's contributions are diverse, ranging from assessing the allocation of computational resources for VoNR and ViNR multimedia services to comparing its QoS performance with that of a more robust laboratory test bench. It is also worth highlighting the contribution of the work on configuring the DuT source code to enable the ViNR service, demonstrating that Android devices can support this type of functionality. The network successfully provides Voice-over-New Radio (VoNR) and Video-over-New Radio (ViNR) services via open-source projects, introducing the first ViNR prototype for 5G.

We propose conducting future research and experiments under more realistic network conditions. This can involve:

- Simulation of Real-World Interference: Implementing mechanisms to emulate common sources of interference, such as signal degradation or packet loss caused by adjacent network devices or environmental factors. Tools like open-source emulators can introduce controlled interference patterns.
- Incorporation of Traffic Fluctuation: Designing and integrating scripts or algorithms to simulate sudden spikes or drops in data traffic, mimicking real-world network dynamics. This will help assess how the system performs under unpredictable conditions.
- Cross-Platform Testing: Conducting experiments across multiple hardware setups and network configurations to ensure compatibility and robustness in diverse environments, so that tests are more comprehensive in different scenarios.
- Validation Against Industry Standards: Comparing the results with established benchmarks or performance metrics from industry studies to establish a baseline for evaluation.
- Analysis of ViNR under Varying SNR Conditions: Evaluate the performance of ViNR video streams across a range of Signal-to-Noise Ratios (SNRs). It would quantify video quality degradation and the frequency of call drops and timeouts.

To sum up, this SDR-based implementation of an MEC 5G Stand-Alone network, leveraging virtualized network functions, occupies a unique position within the broader 5G landscape. Traditional 5G networks typically rely on dedicated hardware for network functions, offering performance predictability but limiting flexibility and scalability. In contrast, our approach embraces the principles of network virtualization, mirroring the disaggregated architecture of Open RAN (O-RAN). O-RAN promotes interoperability and vendor diversity through open interfaces, and our MEC VNF-based implementation similarly allows for flexible deployment and customization of network functions.

Furthermore, while some commercial solutions offer ‘all-in-one’ 5G network packages, these often represent closed, proprietary systems. Our SDR-based approach, built on open-source components, provides a fully programmable, extensible platform that enables researchers and developers to experiment with novel network designs and algorithms. It effectively offers a ’sandbox’ environment for innovation that complements and potentially accelerates the development of both traditional and Open RAN deployments. In essence, our proposed PoC provides a versatile setup for exploring the benefits of virtualization and disaggregation, paving the way for more agile, customizable, and cost-effective 5G networks.

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