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Low-Cost, Open-Source, Experimental Setup Communication Platform for Emergencies, Based on SD-WAN Technology

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Abstract: The rapid advancement of communication technologies underscores the urgent need for robust and adaptable emergency communication systems (ECSs), particularly crucial during crises and natural disasters. Although network-based ECSs have been extensively studied, integrating open-source technologies, such as software-defined wide area networks (SD-WAN) with private long-term evolution (LTE) base stations, is a relatively unexplored domain. This study endeavors to fill this gap by introducing an experimental ECS platform that utilizes a hybrid network, incorporating a VoIP network to enhance open-source and on-premises communications in targeted areas. Our hypothesis posits that a hybrid network architecture, combining SD-WAN and private LTE, can substantially improve the reliability and efficiency of ECSs. Our findings, supported by the open-source OMNeT++ simulator, illuminate the enhanced communication reliability of the network. Moreover, the proposed platform, characterized by autonomous wireless 4G/LTE base stations and an Asterisk VoIP server, demonstrates improved quality of service (QoS) and quality of experience (QoE), with minimal data loss. This research not only has immediate practical applications but also bears significant implications for the development of cost-effective, open-source communication networks, optimized for emergencies, critical infrastructure, and remote areas.

Keywords: 4G; LTE; SDWAN; VoIP; VoLTE; Asterisk; OMNeT++; critical infrastructures; emergency communication systems

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1. Introduction

The rapid advancements in communication technologies have opened new avenues for improving ECSs. Such systems play a pivotal role during crises and natural catastrophes, especially when conventional communication channels fail. While various solutions have been proposed in the literature, the integration of open-source technologies with private communication infrastructures remains an area ripe for exploration. This paper aims to bridge this gap and contribute to the scientific understanding of ECSs' potential and limitations, particularly in environments where conventional channels might be compromised. Therefore, our primary research hypothesis is to introduce a low-cost, open-source experimental communication platform based on hybrid network architecture that reliably supports emergency scenarios where traditional communication channels are ineffective or unavailable. These networks demand flexible, realistic, and scalable experimental platforms supported by simulation tools. In this direction, low-cost communication platforms have been developed, using an ExpressMIMO2 PCI Express (PCIe) board [1], but this option does not incorporate hybrid network scalability and voice transmission over a private mobile network. As far as network scalability is concerned, we have presented our work previously in [2]. Thus, in this article, we present the creation of a non-commercial, independent experimental communication platform for cellular mobile systems using SDR devices instead of ExpressMIMO2 PCI Express (PCIe) boards, which can make calls via a private network over LTE, called voice over LTE (VoLTE). To build the on-premises mobile base station, we have used open-source OAI Public License V2.1. software and state-of-the-art equipment. We have integrated the required operating code of a private 4G-LTE network into a portable experimental-based station that uses a general-purpose universal software radio peripheral (USRP) software-defined radio (SDR) device. We have also installed an Asterisk server, which uses open-source private branch exchange (PBX) Mizudroid V.4.0.2 software for voice transmission. The OMNeT++ simulation tool helped us to configure the network parameters and therefore to safely select our network devices and deployment topology.

Although a wireless sensor network can be reliably based on an LPWAN topology, voice communications require a mobile voice and data transmission system. In case of a disaster, an emergency communication network can help users, support the disaster relief center, achieve on-site data transmission, and enable other activities to support emergency rescue personnel [3]. To describe and test our ECS platform, we first consider an experimental scenario and two hypothetical search and rescue scenarios (Section 1). After that, we provide a summary of recent work on SD-WAN-based ECSs and experimental platforms (Section 2), then present the system's features (Section 3) and end up with the simulation of a private VoLTE network (Section 4), before concluding with the experimental implementation (Section 5) and discussion of our future research (Section 6).

Search and Rescue Scenario

In the following scenario, we consider a forest area where the regular communication network is out of cover. A lost hiker wanders through this area, while a search and rescue team, consisting of two equal subteams, is trying to find him. One or two portable private 4G base stations are placed inside the rescue area, near a forest road, providing a local 4G/LTE network for up to 10 users equipped with mobile devices in which a pre-registered proprietary network SIM card is installed. To create the above network, we have implemented two sub scenarios: a simulation and an experimental one, as seen in Table 1. The lost hiker is not able to communicate with the private mobile network. Every portable base station can be mounted on a vehicle, with antennas installed on a telescopic mast of variable length, achieving optimal network coverage.

Table 1. Simulation and experimental scenario parameters.

Parameter	Simulation Scenarios	Experimental Scenario
LTE Base Stations	1 - 2	1
Base Station TX Power	+16 dBm	+16 dBm (max)
Mobile Devices	10	2
Mobile Device TX Power	+24 dBm	+24 dBm (max)
Voice Codec	G.711	G.711
Coverage Area	2 km^2	100 m^2
Tested Services	VoLTE	VoLTE, data transmission

This implementation could also be used in military and other government applications. A similar private network with one, two, or more portable base stations could also be usable for forest firefighting forces, acting in variable area fields, or when public base stations are damaged. The advantage of the proposed private 4G/LTE network is that in addition to VoIP calls and sensor data transmitting (like GPS coordinates), photos, video, and other data files may be sent as well. Moreover, using an appropriate application, it can also make real-time video calls. Lastly, it is based on mobile network security standards, providing secure telecommunications to isolated network users.

2. Wireless Telecommunication Networks for Critical Infrastructures and Emergencies

The primary advantages of a private telecommunication network are high reliability and security while maintaining high speed and lower latency. The well-designed private network addresses issues that are difficult to handle for public infrastructures or Wi-Fi networks installed by businesses. Private networks, which will also be 5G-based in the future, will hold a powerful position in such solutions [4]. Below we present some private-based communication systems and experimental platforms using either SD-WAN technology or VoIP services. We also include some emergency voice communication networks.

Pedersen et al. [5], trying to replace the traditional public switched telephone network (PSTN) with a more modern solution, created a private network by implementing the concept of a walkie-talkie using voice over IP (VoIP) services and existing telephony infrastructure that supports the service. This project aimed at utilizing VoIP between mobile phones and a simple router. From the central router of a house, IP packets were forwarded through the voice channel on the Internet, allowing data exchange to occur through interconnected mobile devices within the private network of the house. The flexibility of this project lay in the fact that there was no need for new device purchasing, as a simple Wi-Fi connection to the router could serve the implementation need.

Yao Nan Lien et al. [6] designed a system consisting of multiple communication nodes, like a walkie-talkie, using the P2Pnet platform and portable electronic devices. During the critical early hours of a natural disaster, these nodes can communicate wirelessly with each other until they approach the area where rescue operations are accessible. During the system's design, it is mentioned that each IP packet, along with headers and frames, can be sent as a UDP packet without significant issues. The system is fully capable of receiving and converting all incoming and outgoing packets from the same node without filtering. Additionally, the use of PCM encoding was studied to address the scenario where more than two nodes communicate simultaneously, providing a solution to the aforementioned problem. PCM encoding reproduces data at a regular and relatively low rate, contributing to the system's functionality.

Through Radcliffe et al.'s [7] SD-WAN solution, businesses can enhance the quality of voice services for VoIP calls. They support this option in their research, as the activation of SD-WAN on a device via the Internet allows many employees to work exclusively from their homes. This implementation ensures better resource management for each user adopting this idea, while the central SD-WAN management eliminates traditional issues related to configurations, changes, and scalability. During their research, they conducted various test scenarios. One scenario involved a single communication line where two computers were connected through a simulated broadband connection without SD-WAN functionalities. Additionally, the IP telephony was controlled by a remote PABX (private automatic branch exchange) system. This asynchronous broadband network was used as the connection for the two computers. Subsequently, they conducted tests using a dual link for SD-WAN, focusing on the primary and secondary routes created within the WAN between Router A and Router B. The primary route was separated by a WAN simulator, to meet WAN connection needs, while a 4G-LTE connection simulator was used for the broadband connection requirements.

Another valuable reference on VoIP via the SD-WAN platform is presented in [8]. They propose a connection implementation between two central SD-WAN systems. This approach can lead to improved quality of service and increased bandwidth. They demonstrate that this solution can deliver better network traffic on VoIP calls while enabling more efficient management of network resources, resulting in the desired quality. The architecture of this implementation of the two interconnected central data systems was supervised by the software-defined data center (SDDC) software, i.e., Asterisk V16.1, which defines area networks with the ultimate goal of eliminating interconnection issues between these systems. To conduct their test scenarios, they used a server with the Asterisk operating system, which could record the calls made. For each scenario, they conducted 150 and 300 calls, respectively. The call quality with a bit rate of 80 Mbps was stabilized by applying a policy of traffic prioritization for IP calls. However, during high demand for calls, where there was a greater increase in call volume, the bitrate for the 150 calls scenario dropped to 52.12 Mbps, while for the 300 calls scenario, it was maintained at an average of 44.80 Mbps.

Moreover, we should not overlook the possibility of making VoIP calls through 4G technology. Specifically, calls in 4G technology are made using mobile phones. These calls are known as VoLTE calls. To ensure good quality in VoLTE calls, further performance analysis is needed. Kassim et al. [9] performed such measurements, analyzing and comparing the performance in 4G networks. They presented results on bandwidth availability, jitter performance, and voice delay during VoIP calls. Through comprehensive analysis, they concluded that both jitter and delay values met the QoS requirements for implementing a VoIP calling system over a 4G-LTE network.

In 2018, Sevilla et al. [10] introduced CoLTE, an open-source implementation for private networks based on OAI, which is compatible with Debian 9 and Ubuntu 18.04 LTS. CoLTE is a lightweight LTE core network designed for small-scale community LTE networking, featuring on-site Evolved Packet Core (EPC) deployment with minimal cellular radio stations (eNodeBs). Its primary function is establishing a prepaid network management system that enables usage-based billing or IP traffic rate charging. By collocating the EPC in the field, CoLTE provides high-bandwidth local connectivity, supporting custom SIM cards for user coverage and LTE security. The implementation successfully served over 40 active users, offering cost-effective solutions, and ensuring economic sustainability by covering both operational and capital expenses.

In mid-2020, Thota et al. [11] established a private network supporting closed-loop control and video applications. The network consisted of three main components: a radio access network (RAN), a core network (CN), and a slicing gateway. They examined three applications: closed-loop control, involving a robotic arm receiving activation commands; event-driven control, where a human operator controlled a robotic arm; and video streaming using a commercial handset. The implementation used a USRP Ettus X310, Ubuntu 16.04, and the OpenAirInterface Public License V2.1. software, and Open Cells SIM cards. The demonstration showcased the successful coexistence of diverse applications with software-defined radio slicing.

Girmay et al. [12] introduced a coexistence scheme for private LTE networks in unlicensed spectrum alongside co-located Wi-Fi networks. Through utilizing LTE configurations and the Wi-Fi spectrum, the paper demonstrates that private LTE can successfully adapt to the presence of Wi-Fi, catering to both upload and download scenarios. Thus, the flexibility of LTE in adjusting to Wi-Fi requirements is emphasized in this implementation.

In summary, the reviewed studies exhibit both commonalities and distinctions in their approaches to communication network enhancement. Among the similarities, multiple investigations prioritize the utilization of modern technologies such as VoIP, SD-WAN, LTE, and Wi-Fi to elevate communication efficiency, quality, and reliability, especially in demanding scenarios like natural disasters or remote work environments. Additionally, there is a prevalent emphasis on ensuring QoS delivers satisfactory user experiences for voice and video communication. However, differences emerge in the specific technologies employed, ranging from private network configurations to SD-WAN solutions and LTE-based infrastructures. Moreover, each study targets distinct applications, encompassing disaster communication, business VoIP, community networking, and closed-loop control systems, indicative of diverse use cases. Lastly, while some studies prioritize performance analysis and optimization, others concentrate on practical implementations and demonstrations of proposed solutions. Despite these variations, collectively, these studies contribute significantly to advancing communication technologies and addressing multifaceted challenges across various contexts.

Considering the above implementations and the history of private mobile communications, we identified the need to develop a non-commercial experimental communication platform, with the following characteristics:

- Software-simulated.

- Open source.
- Easily deployed.
- Portable.
- Scalable.
- Low cost.
- Real-time voice and data transmission.
- Secure.

3. Materials and Methods in Designing Open-Source On-Premises Experimental Communication Platforms

After thoroughly studying the above tools and platforms, we focused on the development of a private mobile base station for the needs of the experimental platform. Until now, all the efforts to implement such an endeavor underscore the strategic adoption of modern technologies such as VoIP, SD-WAN, LTE, and Wi-Fi to improve communication efficiency and fidelity. Each study directs its attention to different applications, covering a wide range from disaster communication to corporate VoIP and community networking. Additionally, differences are observed in the specific technological methods employed and the thematic focuses of the research, with some prioritizing performance analysis and optimization while others focus on practical application and demonstration of solutions. Despite these nuanced distinctions, the collective body of research fosters perceptible progress in communication technologies, consistently addressing multifaceted challenges across various frameworks.

The solution presented below is based on the integration of open-source technologies within private communication infrastructures, focused on ECSs. It proposes a low-cost, open-source experimental communication platform designed for emergency scenarios where traditional channels may provide no services or functionality. This platform uses SDR devices to enable seamless voice communication over a private LTE network. The integration of OAI software and an Asterisk server facilitates the establishment of a portable mobile base station. It allows for sensor data transmission, image and video dissemination, and real-time video conferencing while adhering to stringent mobile network security protocols.

Given that we need to build a low-cost, open-source experimental platform, we have chosen to use the OAI Public License V1.1 software for the Evolved Node B (eNB) and EPC implementation. Thus, in our experiment, we used two laptops, 1 for the eNB and 1 for the EPC components, with the minimum system requirements of an Intel i5 6600 and 5600, respectively, with 16 GB memory and 256 GB SSD in each laptop. Table 2 depicts the acceptable experimental platform SDR device characteristics. We have selected the B210 SDR device, as a low-cost option that enables us to experiment in a large scale of frequencies including some unlicensed bands, depending on the deployment area regulations. USRPs B210 operation is based on software control and programming, giving users the ability to define and control the behavior of the radio spectrum [13].

Figure 1 shows the available implementation options for such a base station.

The dotted lines show the variety of available open-source available implementation options according to each implemented technology, according to the desired outcome, that were derived from the researched literature. The first column refers to the SIM card options, the second to the supported UE devices, the third to the eNB type, and the fourth to the EPC. For real-time voice and data transmission, the OAI LTE implementation was preferred instead of the OAI NB-IoT, which does not support voice transmission. “Open Cells” SIM cards and open-source UICC Programmer V3.2 with the necessary card reader have been used. These SIM cards are suitable for Android and iOS phones and even for SIM7000 modules for sensor data transmission.

Table 2. Acceptable SDR device characteristics.

Characteristic	B200	B210	N321
DC Input	6 V	6 V	12 V
Connection	USB 3.0	USB 3.0	Ethernet (gigabit)
MiMo	1 × 1	2 × 2	4 × 4
Bandwidth	56 MHz	56 MHz (1 × 1) 30.72 MHz (2 × 2)	100 MHz per channel
RF Coverage	70 MHz–6 GHz	70 MHz–6 GHz	10 MHz–6 GHz
TX Power (max)	+16 dBm	+16 dBm	+20 dBm
Full Duplex	Yes (half or full)	Yes (half or full)	Yes
Sample Rate	61.44 MS/s	61.44 MS/s	122.88, 125, 153.6 MS/s
ADC	12 bits	12 bits	16 bits
DAC	12 bits	12 bits	14 bits
FPGA Version	Xilinx Spartan 6 XC6SLX75	Xilinx Spartan 6 XC6SLX150	Xilinx Zynq 7100-Dual-core ARM Cortex-A9 800 MHz
RFNoC	No	No	Yes
Extra Notes	GPS (Optional)	GPS (Optional)	GPS
Open-Source	FPGA/Driver	FPGA/Driver	FPGA/Driver
Cost	EUR 1200.00 (approximately)	EUR 1200.00 (approximately)	EUR 10,000.00 (approximately)
Dimensions	97 × 155 × 15 mm	97 × 155 × 15 mm	357.1 × 211.1 × 43.7 mm
Weight	350 g	350 g	3.13 kg

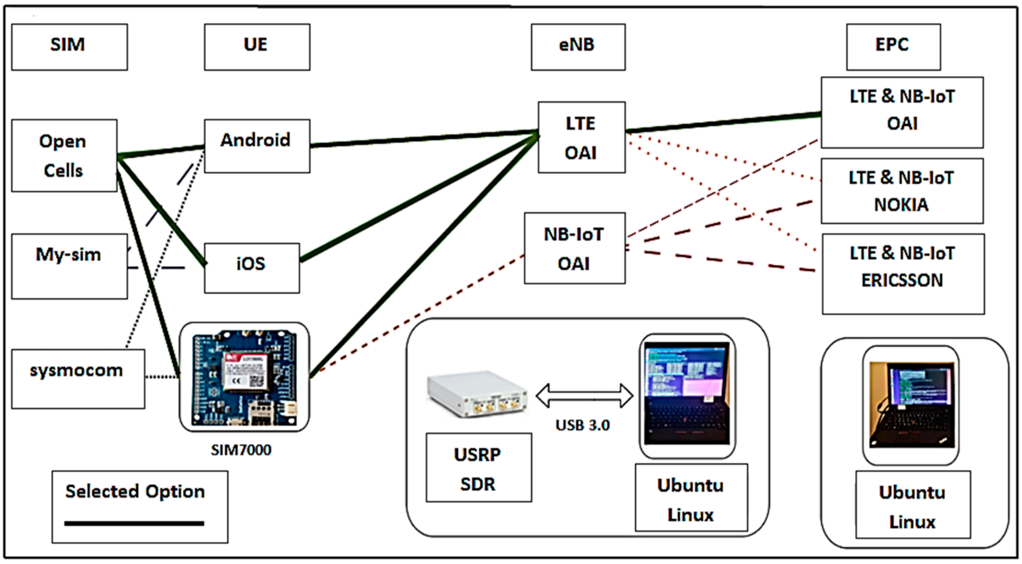

Figure 1. Available options to implement a private mobile base station.

4. VoLTE Scenario and Simulation Report

This section presents an OMNeT++ simulation-based investigation of the VoLTE performance of our SDR eNB and user equipment (UE) located outside a forest. In this simulation report, we present two main findings. Firstly, we examine the diversions of the simulation results while keeping the number of UEs constant and the quantity of eNBs variable. Secondly, we demonstrate that an increase in eNB variability leads to an improvement in the QoS and QoE of the VoLTE network. Therefore, the simulation models presented in this report can provide valuable data and information to evaluate the potential scalability, identify any weaknesses, and assess the usefulness of the experimental platform.

The simulation process was executed with utmost precision, using the devices' technical characteristics and specifications that we will use in the low-cost experimental platform. We meticulously considered every aspect, from the TX power to the software capabilities, to ensure that the VoLTE network performs at its real-life level. We selected a development area that contains various natural obstacles, making radio frequency (RF) propagation challenging. However, this will allow us to evaluate the network's performance and provide us with valuable insights into the network's performance and expansion potential.

Specifically, we conduct two types of simulations: one with a single eNB and another with two eNBs. For our simulations, we utilized the SimuLTE framework, a widely adopted simulation tool for the research of LTE networks [14,15] built for OMNeT++, serving as a discrete event simulation framework used for modeling and simulating communication networks [16]. The scenario comprises 10 UEs meant to represent moving rescuers across a forest area spanning 2 square km, while the eNBs are located in the middle of the forest. Thus, the primary objective of our simulation is to represent the deployment of our low-cost SDR-based system along with a first-level evaluation of its performance in this challenging forest environment.

4.1. Simulation Parameters and Setup

Our simulation setup emulates the data plane of the LTE RAN and EPC in frequency-division duplexing (FDD) mode with portable eNBs, utilizing omnidirectional antennas and realistic channel models, MAC, and resource scheduling in both directions. In this simulation, each UE establishes VoLTE calls through the eNBs. To replicate real-world scenarios, all UEs initiate VoLTE calls simultaneously, spanning 60 s, thus generating a burst of call setup requests. We adopt the G.711 codec, renowned for its high-fidelity audio transmission [17]. Unlike the native VoLTE AMR codec, the G.711 is supported by Asterisk V18.10 software to implement VoIP and VoLTE calls, therefore suiting our system, as its high-quality communication can enhance comprehensible communication in a search and rescue scenario, although the use of different codecs is feasible. To adhere to the specifications of the G.711 codec, we transmit voice data in packets of 214 bytes at 20 ms intervals where 160 bytes represent the raw voice data (data rate of 64 kbps) and 54 bytes of protocol overhead [18].

To replicate real-world wireless propagation and account for signal attenuation caused by obstacles and terrain variations, characteristic of forest environments, we integrate the log shadow path loss model featured on OMNeT++ into our simulation. This model has been used in research to represent the fluctuating signal strength due to factors such as forest vegetation [19–21]. The log path model features Equation (1), where we choose the path loss exponent (n) to be 2, showing only a few obstacles between UEs and eNBs when the standard deviation for X is set to 8 dB, meaning that shadowing effects may very likely take place, as in a mildly dense forest.

$$PL(d) = L(d\_0) + 10n \log\_\{10\}(d/d\_0) + X. \tag{1}$$

Table 3 presents the RF parameters of our VoLTE simulation scenarios. We use one channel with a center frequency of 2.69 GHz as in our SDR-based system for a single eNB scenario, and we shifted one eNB to 2.71 GHz for the dual eNB scenario.

4.2. Single eNB Simulation Scenario

The following report presents the results and analysis of the VoLTE simulation focusing on the single eNB scenario. In this scenario, a single eNB is located inside a dense forest. There are 10 UE units representing rescuers positioned along the edges of the forest in two groups, with five UE units in each group facing opposite directions. The UE units receive VoIP traffic generated by a server, while a router forwards this traffic to the eNB (Figure 2). The UEs move with a speed of 1.5 m/s (5 km/h), representing human movement at 1.5 m height towards the forest, whereas the eNB is stable at 2 m height, placed in a stationary vehicle. The average distance between UEs and the central eNB during the 60 s simulation is between 1200 and 1500 m.

Table 3. VoLTE simulation RF parameters.

Parameter	Single eNB	Dual eNB
Center Frequency/LTE Band	2.69 GHz	2.69 GHz, 2.71 GHz
Channel Bandwidth	20 MHz	20 MHz
Number of Channels	1	1 for each eNB
Antennas	Omnidirectional	Omnidirectional
UE Transmit Power	+24 dBm	+24 dBm
eNB Transmit Power	+16 dBm	+16 dBm
Path Loss Model	Log Shadow	Log Shadow
Codec	G.711	G.711
Call Duration/Simulation Time	60 s	60 s
Mean Distance (UE–eNB)	1200–1500 m	800–1100 m

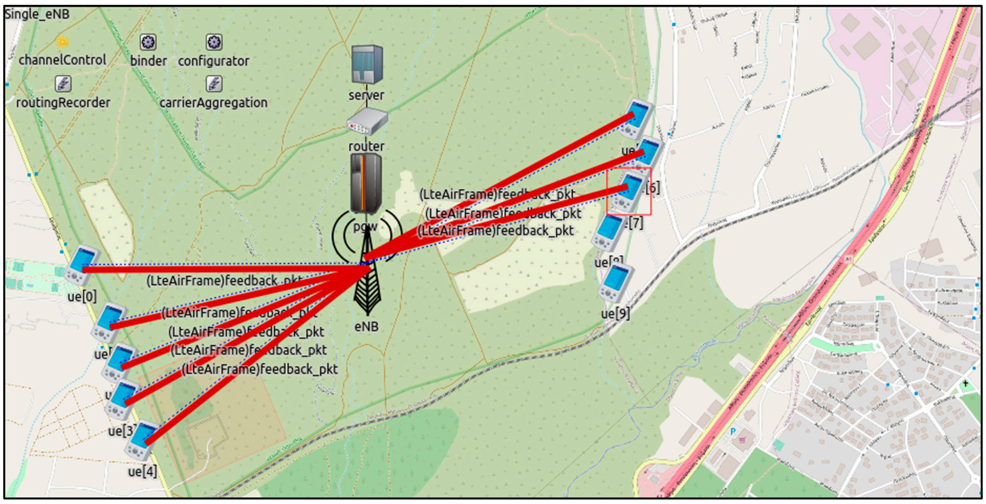

Figure 2. Single eNB simulation scenario.

4.3. Dual eNB Simulation Scenario

For the dual eNB scenario, we introduce a network deployment to enhance network capacity and coverage within the dense forest area. This setup involves two eNBs, each serving as a central communication hub, positioned approximately 700 m apart (Figure 3). The rationale behind this separation is to show the scalability of our system and to enhance network capacity. One eNB operates at the central frequency of 2.69 GHz while the other works at 2.71 GHz to avoid interference between the two, thereby ensuring seamless and reliable VoLTE communication for the rescuers deployed in the forest. Like in the single eNB scenario, the UEs move with a speed of 1.5 m/s (5 km/h) at 1.5 m height towards the forest, whereas the eNB is stable at 2 m height, placed in a stationary vehicle. The measured mean distance between UEs and their serving eNBs during the 60 s simulation is between 800 and 1100 m.

4.4. Simulation Analysis

The present subsection engages the simulation analysis derived from both the single and dual eNB scenarios. The simulation process has been repeated several times to confirm the percentage of users showing satisfactory communication based on the considered factors. In VoLTE networks, delay, packet loss rate, and jitter are defined as QoS indicators while the mean opinion score (MOS) is a QoE indicator [22]. Thus, to compare the two simulation scenarios, we have statistically examined the following parameters:

- Frame delay.
- Frame loss ratio (FLR).
- Jitter delay.

- MOS.

Thus, to compare each parameter's simulation results, we undertook a statistical F-test followed by a statistical *T*-test [23]. Tables 4 and 5 present the acceptable values in VoIP communications [22,24,25].

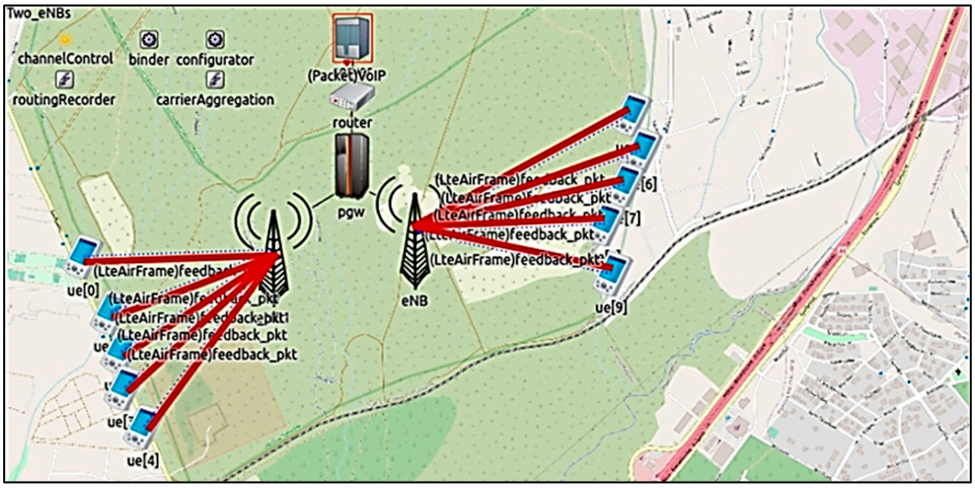

Figure 3. Dual eNB simulation scenario.

Table 4. VoIP QoS parameters.

Parameter	Good	Acceptable	Poor
Frame Delay (ms)	0–150	150–300	>300
FLR (%)	0–0.5	0.5–1	>1
Jitter (ms)	0–50	50–144	>144

Table 5. VoIP QoE parameters.

MOS	Quality
5	Excellent
4–5	Good
3–4	Fair
2–3	Poor
1–2	Bad

The mean and standard deviation values are presented in the following tables, while the vector analysis is observed in the figures. All data have been extracted from the OMNet++ simulation and have also been used to generate vector graphs. The statistical results are compared to the vector analysis, in which the following features apply:

- The boxes represent the frame's loss interquartile range (IQR) for each UE. The IQR measures the data spread between the two extremes of the distribution.
- The horizontal line inside each box indicates the median value. The median value is the numeric value separating the higher half of a sample from the lower half.
- The whiskers extend to show the range of the data, typically up to 1.5 times the IQR from the box (though this can vary depending on the data).

4.4.1. Frame Delay Analysis

VoIP frame delay measures the time taken for voice packets to reach their destination, reflecting the overall latency experienced by UEs during calls, which directly impacts call quality and user experience, approximating the mouth-to-ear delay [24]. Table 6 presents the single eNB frame delay mean and standard deviation values, while Figure 4 illustrates the vector analysis observed during the 60 s call.

Table 6. Single eNB frame delay values.

Frame Delay (ms)/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean Value	6.97	25.29	351.69	13.20	70.49	10.48	6.89	9.22	5.88	454.31
Standard Deviation	3.29	84.45	200.84	26.85	4.14	12.47	5.67	15.22	2.61	243.18

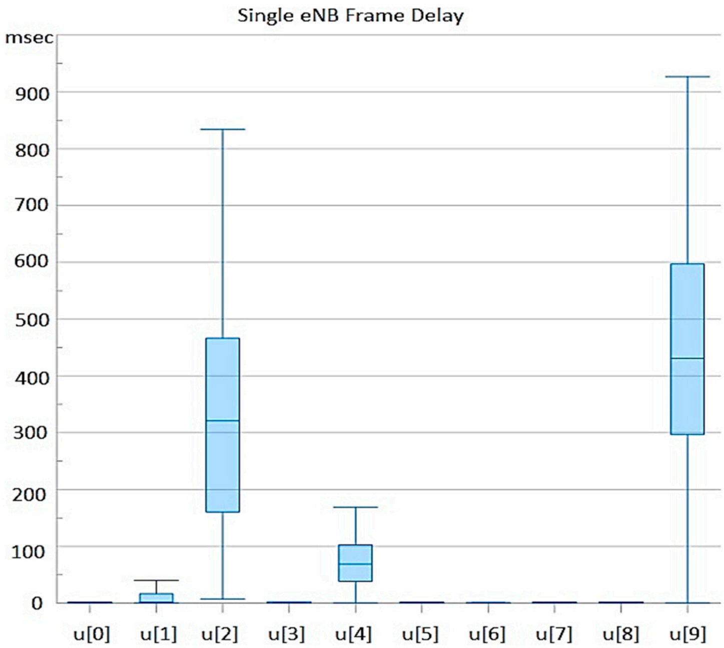

Figure 4. UEs' simulated frame delay (single eNB).

In our scenario, the "Two-sample F-test for Variances" is used to test the null hypothesis that the variances of the two mean datasets of each parameter are equal, while the "Two-sample *T*-test Assuming Unequal Variances" is used to examine the null hypothesis that the means of two datasets of each parameter are unequal. In the single eNB simulation, two out of ten UEs (UE[2], UE[9]) experience significant frame delays, while another two (UE[1], UE[4]) experience less significant delays. The other six UEs encounter insignificant frame delays. Table 7 presents the dual eNB frame delay mean and standard deviation values, while Figure 5 illustrates the vector analysis observed during the 60 s call.

Table 7. Dual eNB frame delay values.

Frame Delay (ms)/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean Value	6.09	4.65	4.82	4.88	4.75	6.34	11.80	5.41	5.67	4.93
Standard Deviation	3.02	1.18	1.43	1.46	1.26	5.52	33.59	2.11	2.60	1.47

In the dual eNB simulation, all UEs only experience a few frame delays. There is a significant improvement in the second scenario, which is also confirmed by the statistical analysis. The F-test showed that the F value (5723.54) > F Critical one-tail (3.44); thus, we reject the null hypothesis, proving that there are significant differences in the variances of the "frame delay" means across the two UE simulation groups. Moreover, the *T*-test showed that the t Stat (1.73) < t Critical two-tail (2.30); thus, we do not reject the null hypothesis, showing that the "frame delay" means of the two UE simulation groups are significantly different from each other. The above statistical differences are illustrated in the vector analysis of Figures 4 and 5.

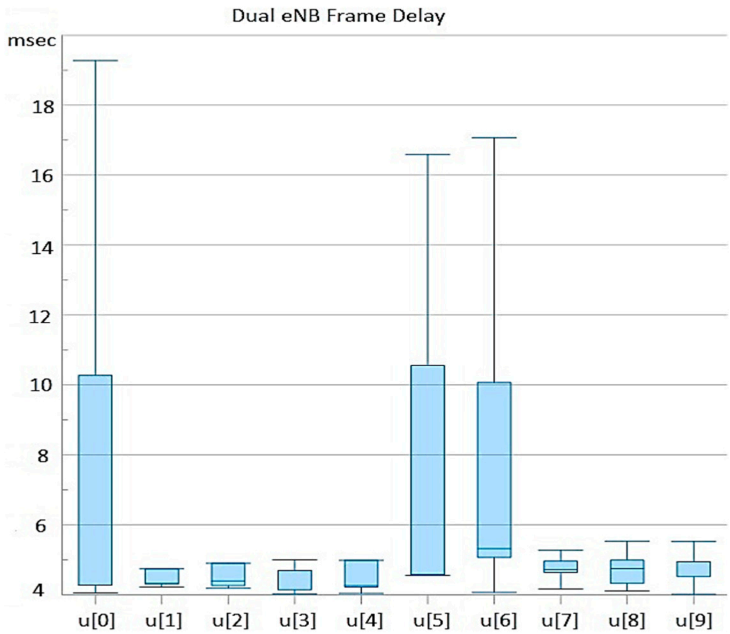

Figure 5. UEs' simulated frame delay (dual eNB).

4.4.2. Frame Loss Ratio Analysis

The FLR calculates the percentage of lost frames in a communication network. It is used as an indicator to evaluate the network's QoS. As lost frames in real-time communication can lead to a worse user experience, FLR is a crucial indicator in VoIP networks. A voice application should have less than 1% end-to-end FLR and 150 ms mouth-to-ear delay [25]. Table 8 presents the single eNB frame loss mean and standard deviation values, while Figure 6 illustrates the vector analysis observed during the 60 s call. In the single eNB simulation, four out of ten UEs (UE[1], UE[2], UE[4], UE[9]) experience significant frame loss, while the other six UEs do not experience significant frame losses.

Table 8. Single eNB frame loss values.

Frame Loss (Ratio)/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean Value	0.00	0.09	0.16	<0.01	0.24	0.01	0.00	<0.01	0.00	0.09
Standard Deviation	0.00	0.13	0.21	0.03	0.23	0.06	0.00	<0.01	0.00	0.19

Table 9 presents the dual eNB frame loss mean and standard deviation values, while Figure 7 showcases the dual eNB frame loss results experienced in the simulation.

In the dual eNB scenario, all UEs only experience a few frame losses. There is a significant improvement in the dual eNB scenario, which is also confirmed by the statistical analysis. The F-test showed that the F value (20.39) > F Critical one-tail (3.44); thus, we reject the null hypothesis, proving that there are significant differences in the variances of the "frame loss" means across the two UE simulation groups. Moreover, the *T*-test showed that the t Stat (2.05) < t Critical two-tail (2.30); thus, we do not reject the null hypothesis, showing that the "frame loss" means of the two UE simulation groups are significantly different from each other. The above statistical differences are illustrated in the vector analysis of Figures 6 and 7.

4.4.3. Jitter Delay Analysis

Jitter reflects the variability in the timing of signal transmissions and is a crucial factor in evaluating the QoS in mobile communication, particularly during VoIP calls, as it is usually caused by network congestion [26]. Table 10 presents the single eNB jitter values experienced in the 60 s simulation, while Figure 8 shows the vector analysis. In the single eNB simulation, four out of ten UEs (UE[1], UE[2], UE[4], UE[9]) experience significant jitter delay values, while the other six UEs encounter insignificant jitter delay values.

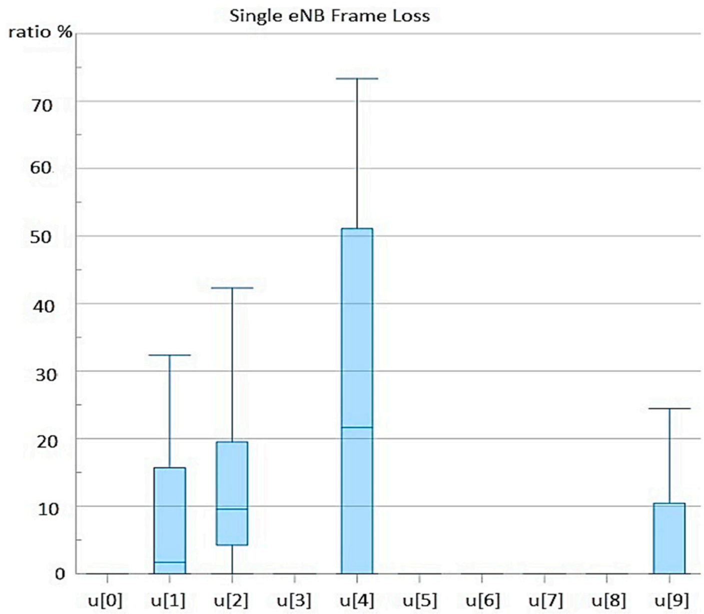

Figure 6. UEs' simulated frame loss (single eNB).

Table 9. Dual eNB frame loss values.

Frame Loss (Ratio)/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean Value	0.00	0.00	0.00	0.00	0.00	<0.01	0.06	0.00	0.00	0.00
Standard Deviation	0.00	0.00	0.00	0.00	0.00	0.01	0.14	0.00	0.00	0.00

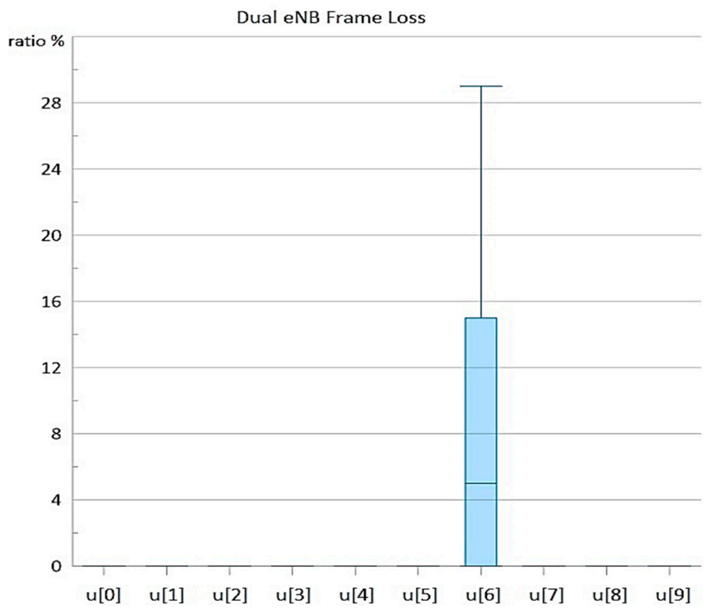

Figure 7. UEs' simulated frame loss (Dual eNB).

Table 10. Single eNB jitter delay values.

Jitter Delay (ms)/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean Value	4.29	491.32	1345.00	21.39	655.26	6.09	6.68	12.78	3.04	1317.00
Standard Deviation	3.24	662.67	1311.00	57.01	1044.00	11.16	8.22	26.03	2.54	1419.00

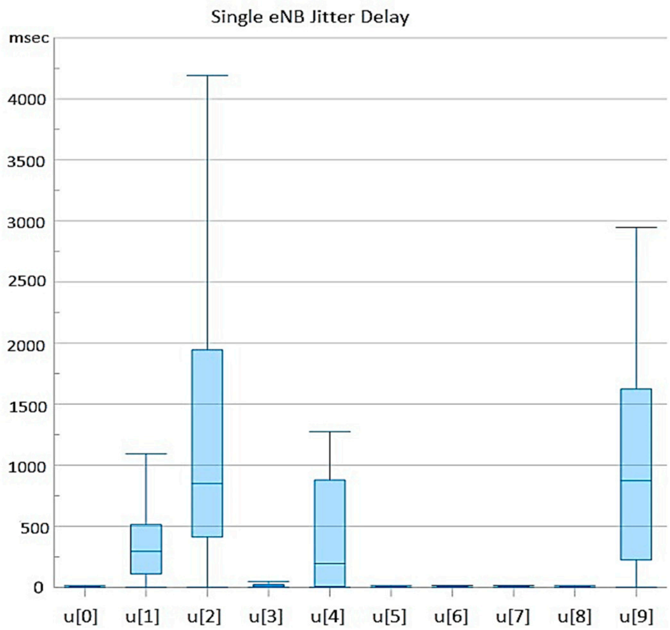

Figure 8. UEs' simulated jitter delay (single eNB).

Table 11 presents the dual eNB jitter delay mean and standard deviation values, while Figure 9 showcases the dual eNB jitter delay results experienced in the 60 s simulation. In the dual eNB scenario, all UEs only experience a few jitter delays. There is a significant improvement in the dual eNB scenario, which is also confirmed by the statistical analysis. The F-test showed that the F value (5459914) > F Critical one-tail (3.44); thus, we reject the null hypothesis, proving that there are significant differences in the variances of the "jitter delay" means across the two UE simulation groups. Moreover, the *T*-test showed that the t Stat (2.23) < t Critical two-tail (2.30); thus, we do not reject the null hypothesis, showing that the "jitter delay" means of the two UE simulation groups are significantly different from each other. The above statistical differences are illustrated in the vector analysis of Figures 8 and 9.

Table 11. Dual eNB jitter delay values.

Jitter Delay (ms)/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean Value	5.28	6.00	6.00	6.00	6.00	5.94	9.71	12.77	6.34	5.98
Standard Deviation	2.28	0.00	0.00	0.00	0.00	1.94	16.00	48.31	1.72	1.62

4.4.4. MOS Analysis

The QoE of a voice application is typically represented by the MOS, which shows the extent to which the end user accepts the voice service. The MOS as a QoE is calculated by several QoS parameters, such as packet loss, packet delay, jitter delay, and jitter buffer dimension [27]. The term MOS is scalar, ranging from 1 (worst case) to 5 (best case) [22]. Table 12 presents the single eNB MOS indicator values experienced in the 60 s simulation, while Figures 10 and 11 show the users' MOS indicator during the 60 s simulation. In the single eNB simulation, four out of ten UEs (UE[1], UE[2], UE[4], UE[9]) experience bad indicator values, while the other six UEs seem to be quite fair.

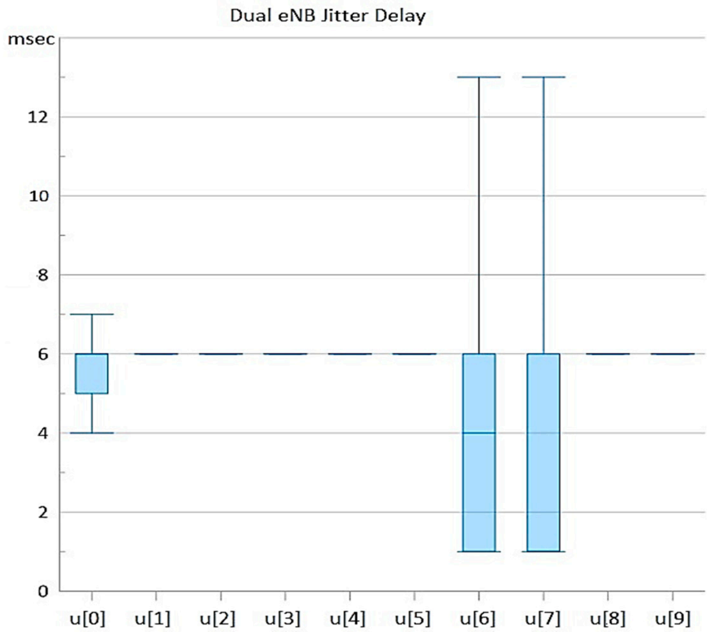

Figure 9. UEs' simulated jitter delay (dual eNB).

Table 13 presents the dual eNB MOS indicator values experienced in the 60 s simulation, while Figure 11 shows the MOS vector analysis. In the dual eNB scenario, five to ten UEs (UE[0], UE[3], UE[5], UE[6], UE[7]) experience fair MOS, while the other five experience good MOS. A significant improvement is acknowledged in the dual eNB scenario, which is also confirmed by the statistical analysis. The F-test showed that the F value (8.98) > F Critical one-tail (3.44); thus, we reject the null hypothesis, proving that there are significant differences in the variances of the "MOS" means across the two UE simulation groups.

Table 12. Single eNB MOS values.

MOS/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean	3.33	1.96	1.21	3.13	1.83	3.02	3.38	3.60	3.85	1.27
Standard Deviation	1.32	1.31	0.79	1.32	1.35	1.39	1.27	1.13	1.02	0.79

Moreover, the *T*-test showed that the t Stat (−3.68) < t Critical two-tail (2.26); thus, we do not reject the null hypothesis, showing that the "MOS" means of the two UE simulation groups are significantly different from each other. The above statistical differences are illustrated in the vector analysis of Figures 10 and 11.

4.5. Simulation Conclusions

The statistical results show that in the single eNB scenario, the simultaneous communication of 10 UEs inside the specific area shows weaknesses in both QoS and QoE due to network congestion. The dual eNB scenario seems to be more stable. Latency remains low, and the frame loss is sustainable to non-existent for our simulated devices. Likewise, jitter remains acceptable to promise good voice quality. In cases where we must cover small areas and a limited number of users, the dual eNB proposal is more effective. Moreover, an optimal eNB placement and TX power amplification will provide better QoS and QoE results. Therefore, according to the simulation results, our low-cost, open-source SDR-based system proves to be a promising solution for reliable and practical implementations, such as emergency scenarios. Moreover, it is scalable, fulfilling the communication network needs within specific deployment areas.

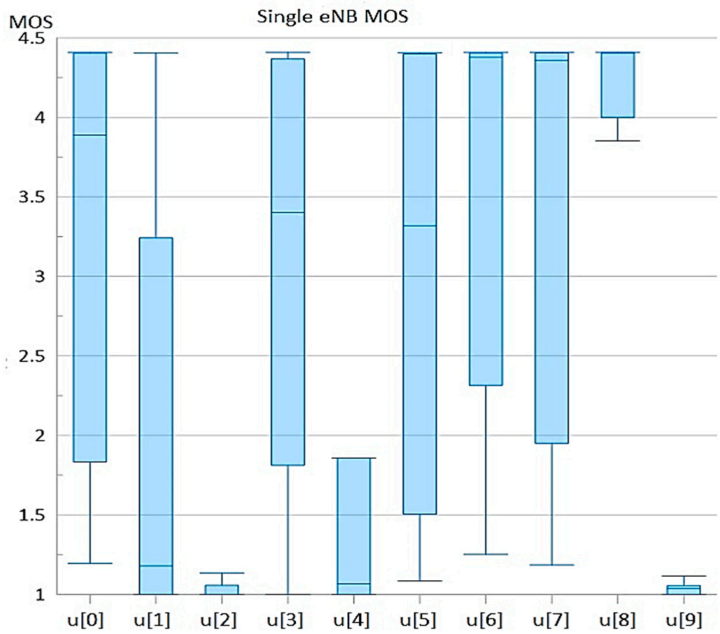

Figure 10. UEs' simulated MOS (single eNB).

Table 13. Dual eNB MOS values.

MOS/UE	UE[0]	UE[1]	UE[2]	UE[3]	UE[4]	UE[5]	UE[6]	UE[7]	UE[8]	UE[9]
Mean	3.72	4.00	4.28	3.94	4.08	3.73	3.10	3.85	4.01	4.13
Standard Deviation	1.03	0.78	0.40	0.86	0.75	1.02	1.44	1.05	0.81	0.63

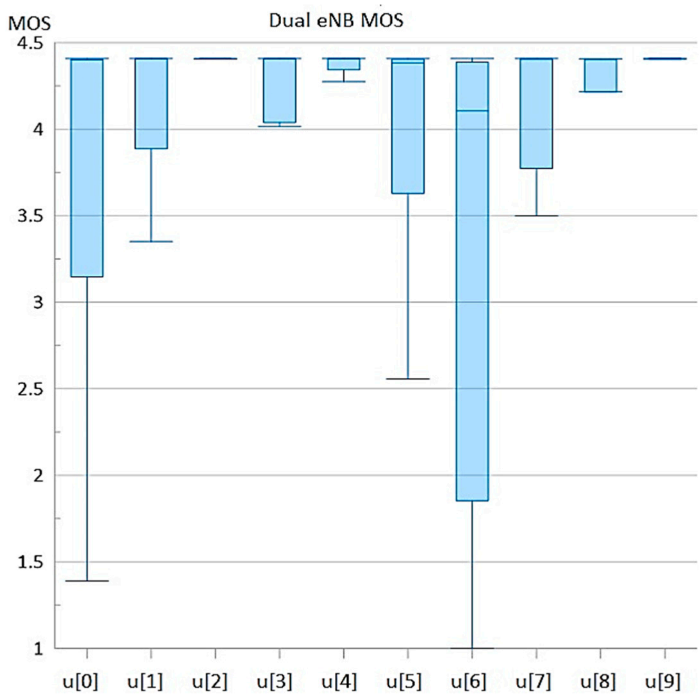

Figure 11. UEs′ simulated MOS (dual eNB).

5. VoLTE Network Experimental Implementation

5.1. Experimental Platform Topology

Our experimental endeavor is dedicated to the exploration of open-source technologies within private communication infrastructures, with a specific focus on ECSs. This research introduces a cost-effective, open-source experimental communication platform grounded on a hybrid network architecture, tailored to address emergencies where conventional communication channels may prove inadequate. While LTE networks conform to principles responding effectively to the growth of communication demand without lowering their QoS, attention should be paid to RF rules and the available unlicensed spectrum. Looking from a holistic perspective that considers the coexistence of all current and future cellular and IEEE 802.11 standards in all accessible unlicensed spectrum bands, the authors of [28] give an extensive survey on the coexistence of cellular and IEEE 802.11 standards. Having analyzed the simulation results and following the above rules, we plan to construct a single eNb experimental platform to assess its performance. Our objective is to test the network's efficacy in terms of making VoLTE calls between two users and transferring data among them. Figure 12 represents the proposed private network architecture based on such standards.

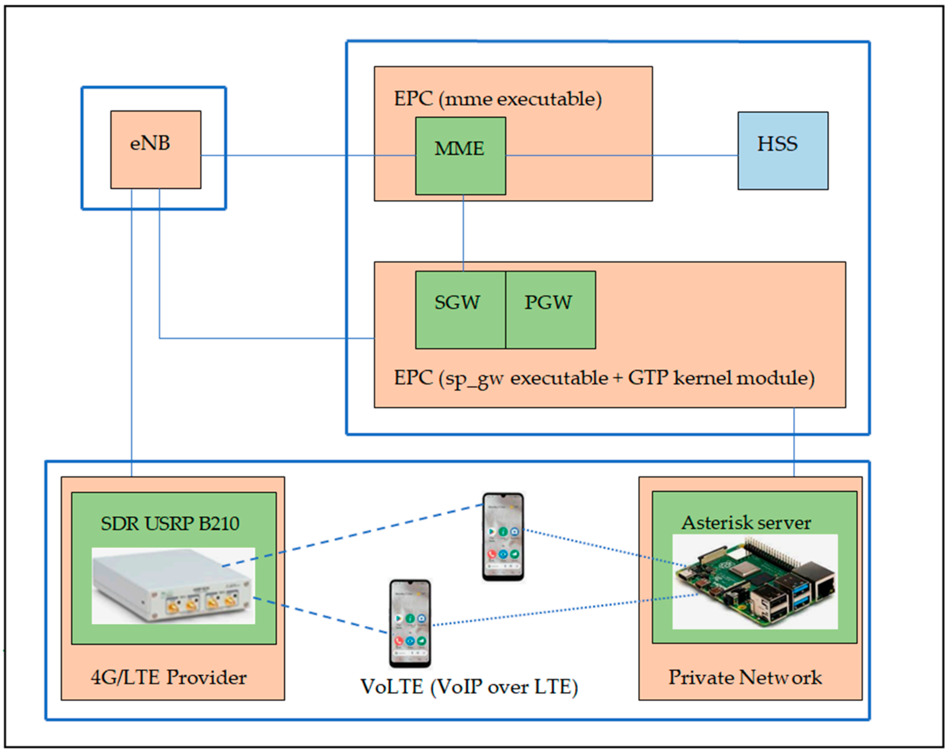

Figure 12. The proposed private network architecture.

The sophisticated EPC packet system is the basic routing computing system of the private LTE network. The terminals receive control and good operation signals through the base stations originating from the mobility management entity (MME). The MME performs several functions, such as managing and storing UE connection details, generating temporary identifiers, controlling authentication functions, and selecting the service gateway (S-GW) and the packet network gateway (P-GW). There is no data traffic through the MME. S-GW's role is to adapt UE handovers between the eNBs and route the required information between the P-GW and the Evolved Universal Terrestrial Radio Access Network (E-UTRAN). P-GW is the default router that undertakes the transfers between 3GPP and non-3GPP services and gives corresponding IP addresses to the connected devices, allowing them access to the packet data network (PDN). UEs connect to E-UTRAN to send data to the core network. The E-UTRAN complex of network connections consists of base stations. A base station, or eNB, adjusts and modifies the radio wave signals to connect to the user's equipment. They take on the relay role to create and send IP packets through the cellular network, passing the connection from one point of the network to another as the user changes location. This mode ensures a constant and seamless connection. The eNBs utilize the X2 interface to exchange communication control signals with each other, enabling the user equipment to move within the LTE network [29].

The implementation of eNB functions utilized the open-source Ubuntu Linux 18.04 software distribution. Power management and low-latency kernel installation crucially addressed processing speed and overall system performance optimization. Measures were taken to deactivate the CPU frequency scaling and constrain processor power dissipation for optimal functionality. Accessing the eNB code repository on Eurecom's GitLab [30] required the installation of a designated certificate. Once installed, access was granted, enabling the acquisition of the eNB's source code and procurement/installation of USRP Spartan V.6XC6SLX75 driver software. We also had to configure the "enb.band7.tm1.50PRB.usrpb210.conf" file to facilitate seamless interfacing of the SDR USRP B210 with the eNB via USB, enabling LTE frequency transmission on LTE Band 7, commonly deployed across Europe.

For EPC operations, Ubuntu Linux 18.04 was additionally used. The general packet radio service (GPRS) protocol, including the GPRS Tunneling Protocol User plane (GTP-U), proved to be vital for transferring GPRS packets across LTE 5G networks and others. The "nproc" command in Linux that determines the number of available processing units was applicable, leading to increased available modules, thus enhancing parallel processing capabilities. To activate the GTP-U, an adjustment of the "nproc" command preceded the installation of the Generic Kernel version 4.7.1. The EPC configuration included updating software, installing Git software, and acquiring a certificate for access to Eurecom's GitLab [30]. The certificate installation allowed access to download Eurecom's library source code.

An Ubuntu Linux 22.04 was utilized to implement network calls, with the operating system downloaded and the image transferred to a USB stick for installation on the Raspberry Pi 4. Asterisk, an open-source communication software, was installed after completing the software installation. This software server uses the G.711 codec to implement VoLTE calls between UEs. Call routes within the private network were organized using the "sip.conf" protocol, assigning a four-digit number to each subscriber (e.g., 7001 and 7002) and security codes. The "extensions.conf" file defined the call plan, specifying how Asterisk handles incoming and outgoing calls. It organizes the calling plan into environments, each consisting of extensions (telephone numbers) with priorities and applications. The voicemail service, configured in "voicemail.conf", handles unanswered calls by forwarding them to an automatic voicemail. Samsung Galaxy S40 with Android 12 and S32 with Android 10 were used as test phones. The Mizudroid client was installed on each device, with the server hosting Asterisk's address, the four-digit number, and the security code configured for future testing.

Apple, IP phones, and tablets could also be used instead of Android phones. Mobile phone UEs are radio-connected to eNB base stations via radio frequencies, while the stations receive and transmit IP packets to and from the core network. The mobile devices are the terminal nodes of the network, and they should be programmed to be able to work in LTE standards, as well as have the corresponding SIM network identification card installed. In the LTE network, the SIM cards are known as universal integrated circuit cards (UICCs) and are Java-programmed cards with an encrypted key. SIM7000 experimental modules can also be used for IoT applications, sensor networks, and data transmission. For SIM card programming, we have used blank "Open-Cells" SIM cards, UICC open-source programming tool V3.3 software [31,32], and a USB card reader/writer. To enable the connection of UE to the private network, a new APN profile must be defined, as it has been created in the HSS database. After entering the USIM into the mobile device, we set the new APN through the device settings. To summarize, we point out that the ability to clone a SIM card is not provided, and, therefore, unauthorized users' network access is impossible.

5.2. Experimental Platform Configuration and Test Tools

This section presents the configuration, preparation, and test tools that we have used in our experimental platform. OAI Public License V2.1. software can combine all the relevant functions of the structural elements of SGW and PGW into the same executable program, while HSS and MME are separate entities. The above elements have been installed on the EPC host PC. The only physical connection made during our experimental stage was the connection between the EPC and the eNB. The HSS serves as the database containing subscriber and UICC connection information for network access. MySQL local and PhpMyAdmin (apache2) databases were installed on the EPC for "HSS.PhpMyAdmin's" graphical user interface for ease of use. After defining the user and password for database access, installation was completed, and accessibility to the database was checked at "http://127.0.0.1/phpmyadmin/". A new database named "oai_db" was created, and its data were imported from the HSS path (openair-cn\src\oai_hss\db\oai_db.sql) into PhpMyAdmin. The "mme_identity" component facilitates connection and mobility management for LTE networks while supporting subscriber identity control. Before the UICC card programming, a user was registered for network access. Operational entities of the EPC (MME, HSS, SPGW) were configured for the network, and necessary certificates were ensured to be active before starting tests.

The three terminal windows correspond to HSS, MME, and S-PGW, providing us with information about the status of our network and the stations connected to it, including the connection between eNB with the USRP and eNB with the UEs. The Asterisk server provides a console that displays the necessary Session Invitation Protocol (SIP) peers of the network's registered and connected UEs. Also, it presents the traffic of the UE's listening port. Moreover, it reports the UE's status (online/offline). The Asterisk console is one of the most essential tools for monitoring calls and real-time issues, as it enables the detection and resolution of any problems that may arise. During the experimental procedure, we used Asterisk to make VoIP calls over the LTE network, leveraging VoLTE technology. Through Asterisk's console, we gained a comprehensive view of the call's duration and timestamp per call when they were made, as well as any errors that occurred.

After the successful UE network registration, we ensure the monitoring of LTE packets on our private network by using the WireShark application, a useful LTE network analysis tool. In this experimental part, we monitored the packets exchanged between LTE layers, confirming the established network QoS. Additionally, using the WireShark open-source V3.6.22 software, we can prevent many security issues by monitoring the network traffic and packet losses. To provide internet services to the UEs, we had to connect the EPC to a public internet provider, as seen in Figure 13.

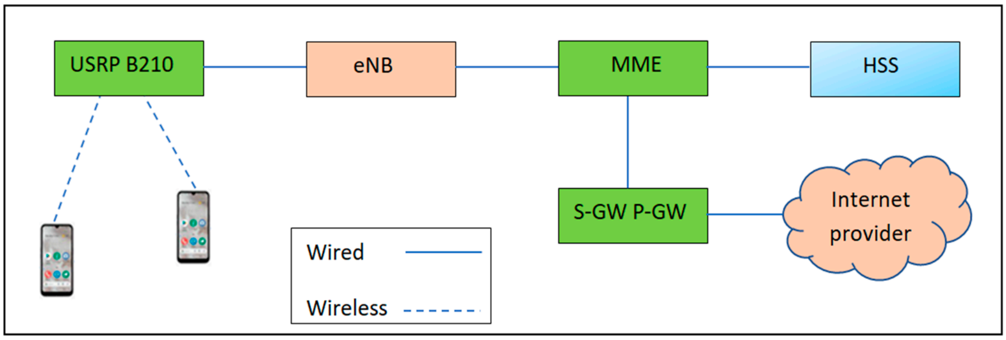

Figure 13. Public Internet provider diagram.

To conduct a study on the network's speed, both in terms of download and upload, as well as losses, we used the free SpeedTest application installed on each device. Table 14 depicts the SpeedTest results for two UEs, while other parametrizations should be tested to reduce the ping time.

Table 14. SpeedTest results.

Device	Ping	Download	Upload	Jitter
UE[1]	51 ms	17.74 Mbps	4.72 Mbps	9 ms
UE[2]	58 ms	18.32 Mbps	5.34 Mbps	13 ms

Finally, we used the OAI Soft Scope, a tool provided by OAI, to analyze and visualize the functionality of wireless communication systems. To test the above network tools and perform tests, an SDR base station, two smartphones, and a local host PC were used. The registered smartphones were separated 4 m from each other and 2 m from the base station, inside an RF laboratory.

5.3. Experimental Platform Conclusions

Our experimental scenario took place inside a laboratory without eNB's signal amplification. The implementation of both the EPC and eNB initially utilized Linux version 16.04. However, challenges arose due to issues regarding required libraries that could not be upgraded to newer versions. This led to the need for additional installations of parallel libraries to resolve the problem. During initial testing, the base station failed to meet network requirements adequately, resulting in frequent loss of range and communication regardless of the device used. This caused the station to shut down, leaving it unable to re-coordinate, and often necessitated the reprogramming of UICC cards. Moreover, when connecting a second device, tests had to be conducted very closely to the station, while instances occurred where simultaneous connections were not supported. These issues significantly delayed the implementation process. Upon investigation, it was discovered that the specific Linux version was unsupported and could not be upgraded. Attempts to upgrade the existing version proved to be unsuccessful, leading to upgrading to Ubuntu Linux 18.04 to address the problem.

By leveraging SDR devices instead of PCIe boards, the platform facilitates voice communication over a private LTE network. The integration of OAI software and an Asterisk server streamlines the development of a portable mobile base station, enabling seamless voice transmission and ensuring secure telecommunications. We found that the network remains stable for a small amount of UEs conducting VoLTE calls, thereby maintaining satisfactory levels of QoS and QoE. VoLTE calls between users were achieved without experiencing any delays or interruptions inside the experimental area. To achieve an improvement in the eNB's coverage area and to reach the simulation results, an intermediate amplifier needs to be applied. The output limitation of the SDR's transmit power is one of the primary causes of this constrained testing environment. In [33], the authors demonstrated how varied 4G/5G cell sizes may be created by utilizing the proper external devices, such as amplifiers, antennas, and filters that have been calibrated by the SDR device specifications. A second eNB can also help to reduce network congestion and delays and increase the coverage area, as seen in the simulation section. In our experiment, UEs were also able to send text messages and other data (e.g., photographs and video files) to each other using appropriate applications without facing any problems. Data transfer was fast without any lags or errors. Therefore, in the case of a search and rescue mission or emergency cases, the coordination center could use a laptop to manage the configured situation, enabling live communication and data transfer through the network's UE devices.

6. Conclusions

The article demonstrated that the use of IoT in conjunction with mobile telecommunications technologies can support critical infrastructure networks. Utilizing simulation and experimental scenarios, the paper culminates in the affirmation of the proposed platform's capacity to furnish secure voice services and data transmission, while also hinting at the potential for hybrid communication networks integrating LPWAN, Wi-Fi, and BLE technologies [2]. Implementing a private 4G LTE network using SDR technology proved to be feasible, covering the needs of critical networks with VoLTE capability and access to websites and videos. The use of open-source software and the Linux operating system (OS) enhanced the low-cost implementation, while SDR technology emerged as a significant advancement due to its low cost and flexibility. Finally, the OAI platform provided all the necessary tools for the study's implementation. Focusing on the simulation and experimental scenarios, we conclude that the proposed experimental platform network setup can provide secure voice services and data transmission in a specific area.

The article meticulously delineates the system's capabilities, encompassing the transmission of sensor data, images, videos, and real-time video calls, all while upholding stringent mobile network security standards. Therefore, the proposed experimental platform, in addition to ECSs, may help researchers and developers cover a multitude of communication applications, as below:

- In rural, private, and isolated areas with limited Wi-Fi coverage, a private network of wireless sensors with the possibility of calls could be very useful, enabling workers' direct communication, while enabling real-time status monitoring of the products.
- For patients in intensive care units (ICUs) and other clinics in hospitals, a wireless sensor network, including wearable devices, can be realized, in collaboration with the private network, to transfer patients' heart rate, oxygen data, and other vital data on a 24 h basis in a central system to which doctors and nursing staff have immediate access, while patients and attendants will be able to call them for immediate help by pressing a button. Moreover, we can build early warning systems (EWSs) based on sensor networks [34].
- In critical event situations on ships located far from the land, using a suitable digital signage application, safety personnel could guide passengers to muster stations by taking the least dangerous route. Moreover, an entire network of wireless sensors can also be created, along with the private network, to help ship managers monitor the ship's system in real-time [35].

We plan to extend our communication network by adding a second 4G/LTE base station and testing the VoIP application under variable circumstances. Moreover, we plan to install amplified base stations into cars with variable height antenna masts, thus improving their gain and making them more flexible. This improvement will allow us to test the experimental platform inside critical infrastructures and larger off-grid areas. Furthermore, we will expand our network by adding an isolated LoRaWAN subnetwork for sensor monitoring and data gathering [2]. At the same time, we will continue conducting simulation tests using the OMNeT++, and MATLAB tools to improve the scalability of the on-premises network and its QoS. We will also conduct more experiments in variable terrains using video calling and image transfer applications, testing at the same time network viability by scheduling network attacks and extracting security reports. Finally, we intend to present an open-source testbed implementation employing SDR technology to deliver both VoLTE services and an internet connection using 5G architecture, followed by an appropriate simulation tool.

Author Contributions: Conceptualization, V.C., S.P., N.P. and A.T.; methodology, V.C. and S.P.; software, V.C. and A.T.; validation, V.C., S.P., N.P. and A.T.; formal analysis, V.C., S.P., N.P. and A.T.; investigation, V.C. and S.P.; resources, V.C. and S.P.; data curation, V.C. and S.P.; writing—original draft preparation, V.C. and S.P.; writing—review and editing, V.C., S.P., N.P. and A.T.; visualization, V.C., P.P., D.D.P. and R.A.M.; supervision, V.C., P.P., D.D.P. and R.A.M.; project administration, V.C., P.P., D.D.P. and R.A.M. All authors have read and agreed to the published version of the manuscript.

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