Development of 4G base station for rural areas based on LimeSDR

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Abstract- Rural areas in Peru still suffer from a significant lack of mobile coverage, as operators do not find it profitable to invest in these regions due to geographical challenges, infrastructure requirements and economic constraints of the inhabitants. This research proposes the development of a 4G base station prototype for low population density rural areas using SDR technology using the LimeSDR model. Performance evaluation was carried out through local testing with the VOLTE service, using network parameter measurement tools, allowing optimizations for future deployments in rural environments.

Keywords-- rural areas, population density, 4G, SDR, VoLTE

I. Introduction

This paper addresses the development of a 4G-LTE base station prototype using software defined radio (SDR) technology for deployment in rural areas. The need to offer technological solutions for low population density areas is crucial, as traditional telecommunications operators face significant challenges to justify investments in these regions. Factors such as complex geography, high infrastructure and logistics costs, and low long-term profitability are barriers that contribute to digital exclusion. The importance of this research lies in the fact that access to voice and data services, including Internet access, are important for social and economic development, and a key means to reduce the digital divide in the country.

In recent years, research has begun based on Open Source environments and the use of SDR technology as a way to develop mobile networks, and with cost-effective and low-cost hardware. Reference [1] was the first to demonstrate this approach. For example, the development of 3G/4G networks using OpenUMTS, OpenLTE and OpenAirInterface codes, where they used a USRP NI 2901 equipment as SDR hardware, and also with the use of different hardware equipment such as the USRP B210 in a 2018 research by Francisco Garcia, from the UPG, and David Martinez, with a similar project, by the UPM, both in Spain.

Private sector companies presented initiatives such as OpenEPC, developed by Core Network Dynamics of Germany, which simulates an LTE Core in a Raspberry PI, one of the low-cost equipment, but with computational and portable capacity, for use in emergency areas. In addition, the company YateBTS launched a product called YateUCN, which is a unified Core for LTE that also offers voice service, and can be integrated to other software platforms.

Recently in Latin America, a thesis project developed by Mariela Codon [2], where she applies a recent software platform called srsRAN, also makes a comparison with a local commercial mobile network operator (Argentina); and a year ago, at the National University of Loja, Ecuador [3], Sergio Garcia developed an LTE base station using OpenAirInterface, but unlike the others, he used a BladeRF equipment as hardware.

II. Methodology

For the development of the 4G-SDR prototype, the following techniques were implemented:

a. SDR Hardware Selection: The available SDR hardware was evaluated, considering the existing research, the availability of equipment at the university and the experience of the developer community with the selected software.
b. Open Source Software Evaluation: Open Source codes for the construction of 4G Core and access networks were analyzed, paying attention to their documentation, versions, compatibility with operating systems and SDR hardware.
c. Subsystem Design: The energy, infrastructure and electrical protection subsystems required for the 4G-SDR prototype were designed.
d. Outdoor Validation: Prototype validation tests were performed in outdoor environments.

III. Design and Development

A. HARDWARE AND SOFTWARE SELECTION:

The proposed base station combines software that simulates the core of an LTE network with SDR equipment for the radio stage. This integration allows the system to function as a physical cellular base station, capable of transmitting and receiving wireless signals over the air interface. In this way, a mobile device can connect and access data and voice services efficiently.The hardware and OS characteristics required for an 4G solution based on SDR technology and Open Source software are listed below:

- ✓ SDR devices: SDR devices are needed that can operate in the bands allowed in Peru and, in addition, are compatible with the 4G network simulation software. The devices evaluated according to their availability are presented in Table 1.

TABLE 1
TYPES OF SDR EQUIPMENT

SDR equipment	Description
USRP 2920	An adjustable RF transceiver, 20 MHz of Bandwidth, Frequency range from 50 MHz to 2.2 GHz
LimeSDR	A 100 kHz to 3.8 GHz full duplex transceiver, used to develop and test software for GSM, UMTS, LTE or 5G.
BladeRF	BladeRF 2.0 Micro xA4 is a 47 MHz to 6 GHz 2x2 MIMO RF transceiver compatible with various SDR suites such as GNU Radio and MATLAB.

- ✓ Open Source Software for LTE networks: There are codes in several repositories capable of simulating a mobile network, including the LTE standard, as shown in Table 2:

TABLE 2
SOFTWARE PLATFORMS FOR 4G MOBILE NETWORKS

OS	Characteristics
OpenLTE	It implements the access part, and a simulator for the EPC with the MME and HSS functionalities, through an XML file that establishes the bandwidth parameters, the distance between the eNB and the UE, among others.
Open Air Interface	Its platform is divided into two parts: OpenairCN, which implements the different equipment that make up the LTE backbone, such as the MME, HSS, SGW and PGW; and Openair5G for the access network.
srsRAN	This code has an eNodeB, EPC and UE solution, which acts as a mobile terminal from a computer. Being modularized, it allows the implementation of a hybrid network, using other eNB or external EPC solutions.
Open5GS	Enables the execution and management of an LTE/NR network, providing all the components of an EPC and Core 5G. Allows integration with other code solutions, such as srsRAN, for access in 4G or 5G networks.
Kamailio	It is an open source SIP server, where the most important features include: secure communication via TLS for VoIP (voice, video, text); IMS extensions for VoLTE.

For the selection of hardware and OS, the following criteria, listed in Table 3, were considered.

TABLE 3
SOFTWARE PLATFORMS FOR 4G MOBILE NETWORKS

	LimeSDR	USRP 2920	BladeRF
OpenAirInterface [8]	✓	x	✓
OPEN5GS [9]	✓	✓	✓
In Peru LTE bands B4, B7, B8, B9	✓	No - band B7	✓
Price	315 USD [7]	€ 2096/ 2409 USD [8]	€ 649 /674 USD [9]

Open5GS is compatible with all SDR models, while the USRP2920 is not compatible with OpenAirInterface (OAI). In search of a cost-effective solution, it has been decided to prioritize the testing of the LimeSDR module in combination with the Open5GS platform.

B. SUPPLEMENTARY EQUIPMENT:

The equipment required for the installation and configuration of an LTE operating system is detailed below, organized in a clear and concise manner:

TABLE 4
SOFTWARE PLATFORMS FOR 4G MOBILE NETWORKS

Component	Specifications / Function	Justification
Computer equipment	Lenovo, Processor: Intel Core I5, RAM 16GB, Storage: 240 GB, Interface USB 3.0	Base equipment to run software, meeting minimum performance requirements.
USIM LTE Programmer	SIM card reader, 2FF/3FF/4FF, programable, 4G, VoLTE, ISIM, OYEITIMES brand.	Can be written ICCID, IMSI, KI, OPC, OP, GSM.
SIM CARDS	SIM card reader, 2FF/3FF/4FF, programmable, 4G, VoLTE, ISIM, OYEITIMES brand.	SIM CARD for cell phone use.
Multiband Antennas	Omnidirectional antennas with 10 dBi gain.	Improve coverage.
Additional Accessories	USB 3.0 cable for connection to the LimeSDR	They ensure connectivity between the SDR equipment and the computer equipment.
Mobile Devices	Huawei Mate Lite 20, 4G connectivity: B2 (1900), B4 (1700/2100), B7 (2600), B28 (700) bands.	Used to insert registered SIMs, connect to the network and measure key parameters.

C. ARCHITECTURE AND COMPONENTS

The architecture designed for the development of the VoLTE prototype integrates specific hardware and software components, following 3GPP standards to ensure the functionality and efficiency of the system. The integrated elements are presented below, see Fig. 1.

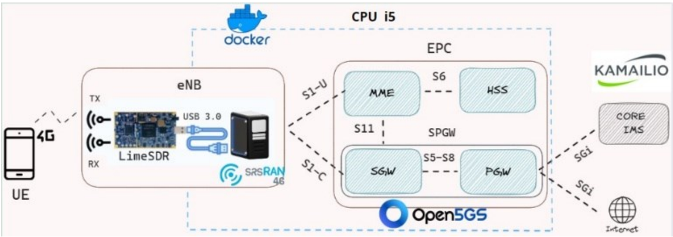

Fig. 1. VoLTE solution diagram

The integration of these components into the 4G network with VoLTE support, using SDR technology and open source software, involved several technical steps. First, a computer with an Intel Core i5 processor and the Linux operating system was used. Docker had to be installed and configured for container management. For the access network (eNB), the LimeSDR (USB 3.0) device was used, with srsRAN platform to operate as a base station. As for the 4G network core, Open5GS was implemented, which manages the EPC functions (MME, SGW, PGW). VoLTE functionality was enabled by Kamailio, which acts as the IMS core and connects to both Open5GS and srsRAN. To guarantee the connection of the mobile terminals, programmable LTE SIM cards configured with an OYEITIMES programmable USB reader were used. The test station used can be physically observed in Fig. 2 of the document.

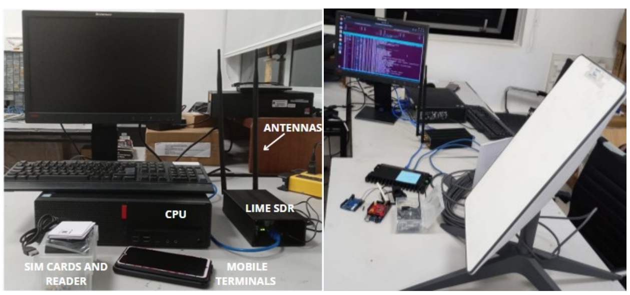

Fig. 2 Prototype test station

D. CODE

To carry out the implementation of the 4G-LTE base station prototype based on SDR, a process divided into three main phases was developed, structured as follows:

- Phase 1.Installation on a single unit: The entire network environment was implemented on a single computer with Intel Core i5 processor, 16 GB of RAM and Linux Ubuntu 22.04 LTS (64 bits) operating system. This configuration was decided due to hardware availability and to facilitate centralized management of the system.
- Phase 2.Configuration of the Docker Container: To facilitate the administration of the different services and ensure portability, a Docker environment was configured. The necessary images were downloaded from the official repositories on GitHub (docker_open5gs) and separate containers were created for each network component (Open5GS, srsRAN, Kamailio IMS). Key steps included:
- Installation of Docker and Docker-Compose
- Creation of an ".env" file with the key network parameters (MNC, MCC, APN).
- Construction of the service images. Prior to this second phase, the installation of packages/libraries must be performed for the correct installation of the software in a GitHub repository, which are detailed in the flow of Fig. 3.

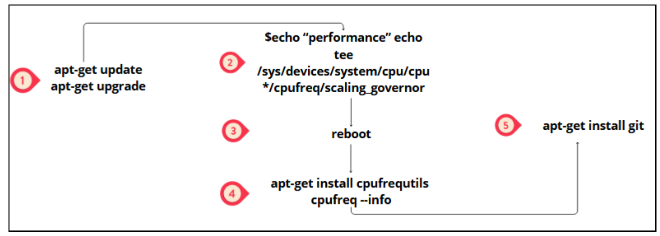

Fig. 3. Sequence of previous steps for the software

Whereas, in Fig. 4, we start by building the Docker images for the services from the repositories on GitHub:

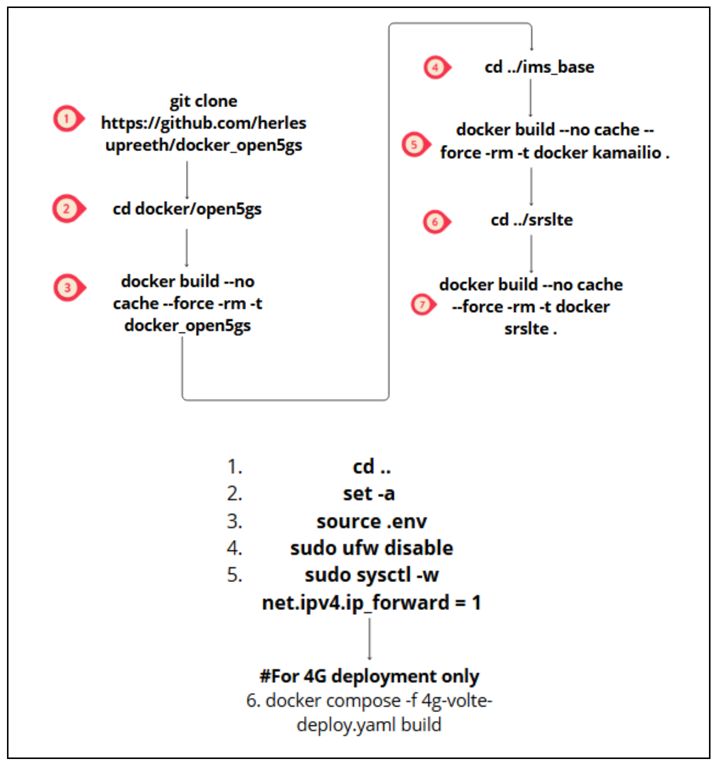

Fig. 4 Sequence of steps for downloading and installing the packages

After applying and saving the changes, we proceed to execute the commands shown in Fig. 5, distributing them in different terminal windows to carry out the execution of the network [4]:

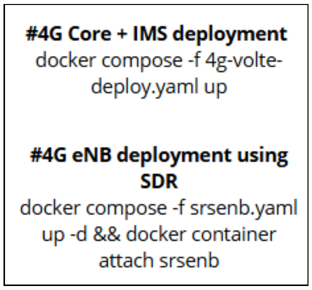

Fig. 5 Implementation of both networks (access and Core 4G)

Phase 3: Open5GS Configuration (LTE/5G Core)

Open5GS was implemented as the core of the LTE network, providing MME, SGW and PGW functions. The configuration included:

- The creation of users in the Open5GS database, associating SIMs with IMSI, Ki, OPc. Fig.6 shows an example of SIM creation, with the parameters to be configured:

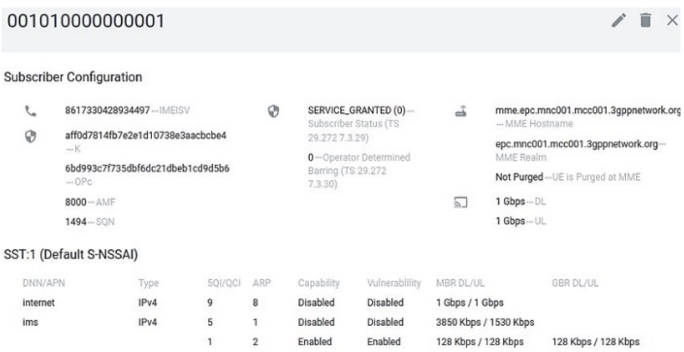

Fig. 6. Creation of SIM parameters

- For the configuration of IP ranges for Internet and VoLTE APNs, it can be deployed in two ways:
  - The eNB and (EPC+IMS)/Open5GS are deployed on a single host computer, or multihost in which the eNB is deployed on a computer other than (EPC+IMS)/Open5GS [4]. Due to the number of available hosts, the first alternative is chosen, which is configured in the ".env" file, considering the following parameters:
  - MCC: 001 / MNC: 01 → These values were used because they are test standards, to avoid conflicts with commercial operators and to enable VoLTE.
- IP address range: 192.168.100.0/24 for Internet APN and 192.168.101.0/24 for VoLTE, which are assigned to the mobile terminals. And are detailed in Fig.7, in addition to indicating that for the output to the Internet through one of the physical interfaces of the computer with the segment 172.19.4.0/24.

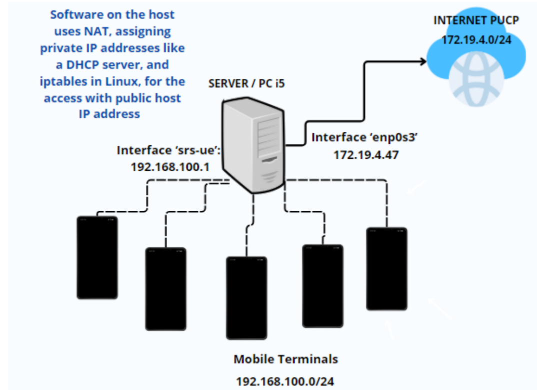

Fig. 7 Network addressing of installed software

E. ENERGY, INFRASTRUCTURE AND ELECTRICAL PROTECTION SUBSYSTEMS

In rural areas of Peru, where access to electricity is limited, a photovoltaic system is proposed to guarantee a reliable and continuous supply to telecommunications equipment with a load of 162 watts (see Table 5). This system, based on solar technology, ensures uninterrupted 24-hour operation, in addition to two days of autonomy (48 hours), sized according to the design suggested by the Rural Telecommunications Group [10]. Based on the sizing, 500 Wp solar panels, 10 100AH batteries, an advanced controller and a 12V/220VAC inverter adapted to the needs of the equipment are required. With this sizing, we guarantee 2 days of autonomy.

TABLE 5
ENERGY DIMENSIONING

Cargas	Cantidad	Cantidad de horas	Potencia	Constante	W-h/día
Router	1	24	12.0	1	288
Estación base 4G opensource + PC	1	24	50.0	1	1,200
Sensor E meter (current)	1	24	1.0	1	24
Inversor	1	24	8.5	1	204
Starlink - SATELITE	1	24	90.0	1	2,160
Controlador Solar (self consumption)	1	24	0.5	1	12
			162.0		

Total de energía necesaria en un día	3,888	W-h/día
Pérdidas	1.2	%
Total energía necesaria	4,665.6	W-h/día

Numero de paneles	3		**Numero de Baterías**	10	
Potencia pico del módulo	500	Wp	Capacidad de una batería	100	Ah
Radiación a 1000w/m2(peor mes) en horas	4.27	h/día	Voltaje de batería	12	V
Total energía generada	6,405	W-h/día	Capacidad banco de batería	12,000	W-h
Relación carga/descarga	1.37		Profundidad de descarga	0.8	
			días de autonomía	2.1	

These components work together to optimize energy collection, storage and distribution, shown in Fig. 8.

The infrastructure system will consist of a tower and an outdoor cabinet with IP65 degree of protection. The cabinet will house the main equipment, including the base station (consisting of a PC, LimeSDR and other routing components, see Fig. 8) and the batteries required for its operation.

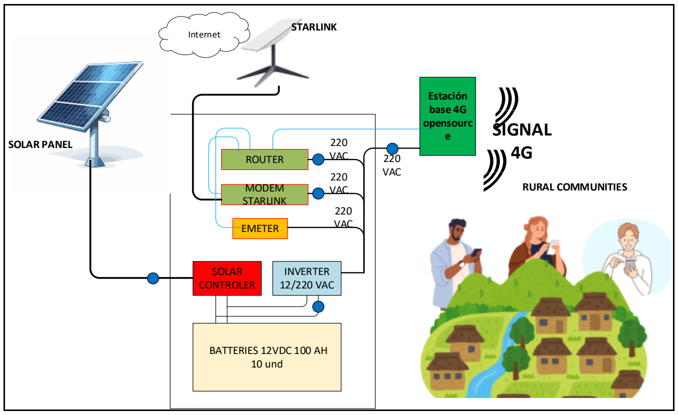

Fig. 8. Prototype connection system

As for the tower, a key aspect to consider is its height, which has been defined as 12 meters. This decision responds to the characteristics of rural environments, where most of the houses are usually one-story, with average heights between 4 and 5 meters.

For the electrical protection subsystem, according to the suggestion of the GTR in rural areas [10], a grounding well with a resistance of 10 Ohm, a lightning rod system, line protectors for coaxial cable for external antennas will be considered.

IV. RESULTS AND TESTS

For the tests, the following aspects were considered:

- **Outdoor test scenario**, specifically on the rooftop of a nearby building, as this location offers an open environment with line of sight, simulating the conditions of a rural environment.
- **Test Terminals**: Five Huawei cell phones were used, selected because they have VoLTE functionality enabled from the factory, without the need for additional permissions from an operator in their internal configuration. Table 6 details the specific models of the phones used during the tests.

TABLE 6
HUAWEI CELL PHONE MODELS USED FOR TESTS

Model	Description
Mate 20 Lite	Use for data and voice
P30 Lite LP	
P Smart 2019	
P30 Lite CP	
Y7 2017	Monitoring equipment

For the tests performed in the test scenario (Fig. 9), it was necessary to optimize the transmit and receive stages using the prototype. For this purpose, key parameters, such as tx_gain and rx_gain, were adjusted in the LimeSDR equipment. After these adjustments, a better performance was achieved in terms of the maximum distance reached by the connected mobile devices, obtaining the best results with a configuration of tx_gain=80 and rx_gain=40.

Fig. 9 Outdoor test environment

- **Performance of the test terminals**. Considering the parameters tx_gain and rx_gain, coverage measurements were carried out based on the behavior of the mobile terminal, such as signal level, latency and download and upload speeds respectively. Tests were performed from 2m to 16m, see Table 7, which shows results using a single mobile terminal.

TABLE 7
OUTDOOR PARAMETER RESULTS (P30 LITE LP)

Distance (meters)	RSRP (dBm)	Donwlink (Mbps)	Uplink (Mbps)	Latency (ms)
2	-99	12,5	3,98	23
4	-109	2,41	2,04	40
8	-113	1,33	4,32	20
12	-113	2,39	4,09	32
16	-113	2,37	0,15	33

- After the test with a single mobile terminal, we proceeded to increase to two mobile terminals (see Fig. 10), and evaluated the signal level versus distance, achieving a maximum distance of 16m for the P30 LP equipment, while the SMART equipment only achieved a connection of 12m.

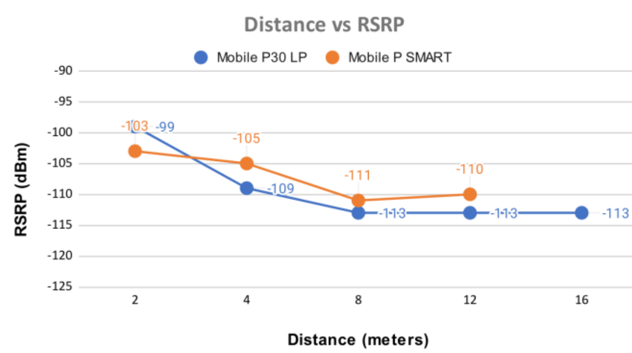

Fig. 10 Distance vs. RSRP outdoors (P30 LP vs P Smart)

- Then, it was increased to four mobile terminals, where both download and upload speed measurements were performed. The results are shown in Fig. 11.

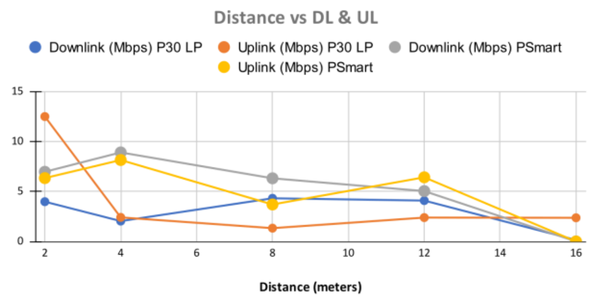

Fig. 11. Distance vs DL & UL outdoors (P30 LP vs P Smart)

- **Voice call quality**. The quality of voice calls via VoLTE was evaluated, considering the user's perception in aspects such as delay time when establishing the connection and audio clarity at different distances from the SDR equipment. For these tests, two cell phones with assigned numbering were used, and the MOS (Mean Opinion Score) parameter was used to measure call quality on a scale of 1 to 5, where 1 represents very low quality and 5 represents excellent quality, as recommended by ITU-T P.800 [11]. The methodology consisted of initially establishing a call near the prototype and then keeping it on speakerphone while one of the devices progressively moved away. This allowed to analyze if the voice transmission remained clear and stable at longer distances. The results reflect how call quality varies as a function of distance, that from 8m onwards is call establishment starts to have drawbacks. See table 8.

TABLE 8
RESULTS MOS, 2 USERS.

Distance (meters)	MOS	Established Call?	Can you hear voice?
2	5	YES	YES
4	5	YES	YES
6	4	YES	YES
8	4	YES	YES
16	1	NO	NO

V. CONCLUSIONS

We successfully implemented a 4G access network based on SDR technology, using LimeSDR equipment as hardware and srsRAN software, as well as OPEN5GS as the main platform. This development included the integral design of the power and infrastructure subsystems, consolidating a functional architecture for the 4G network prototype for a rural area in Peru.

The prototype was subjected to controlled performance tests, connecting two mobile terminals simultaneously with Internet access, obtaining measurements of 12.5 Mbps in uplink and 8Mbps in downlink. In addition to establishing voice calls up to 8 m away from the 4G station, after that distance there were quality problems and finally the connection was cut off.

RECOMMENDATIONS

As future work, it is proposed to improve the coverage of the SDR system by evaluating more advanced equipment, such as the USRP X310 and X410, to analyze their performance in terms of measurement parameters and the capacity for simultaneous connection of more than five devices. In addition, it is suggested to incorporate an amplification stage respecting the limits established by national regulations, as well as the use of higher gain antennas to optimize the range. It would also be important to explore solutions to overcome internal configuration restrictions in brands such as Samsung and Xiaomi to enable VoLTE, since this has currently only been achieved with Huawei devices. Finally, it is recommended that the necessary permits be obtained from the MTC (PERU) for the use of an LTE band spectrum, especially if this prototype is to be implemented in rural environments.

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