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VISIÓN ELECTRÓNICA

Rural connectivity strategies based on the integration of 4G networks and IoT solutions

Estrategias de conectividad rural basadas en la integración de redes 4G y soluciones IoT

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Abstract

The integration of 4G private and Internet of Things (IoT) networks offers one of a transformative solution to address the connectivity challenges faced by rural areas in Colombia. This project easy to update to 5G, focuses on leveraging open-source tools, including srsRAN and Open5GS, along with containerization and visualization technologies such as Docker compose, Portainer and Grafana, to deploy, manage and visualize private 4G networks key performance indicators (KPI). Using general-purpose hardware and Software-Defined Radios (SDRs) like USRPs and Baicells eNBs, we aim to establish a robust Fixed Wireless Access (FWA) network for private 4G networks in rural areas traditionally unconnected. This FWA network will facilitate the connection of LoRaWAN gateways to IoT sensors deployed in agricultural environments and allow the deployment of wireless networks

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with excelent signal penetration and coverage. Also, It shows a viable and cheap proposal to Colombian government to accomplish its objective of connecting 85% of Colombians before 2026 without buying expensive hardware from traditional legacy providers and creating adding value.

The primary objective with the integration between 4G and IoT is to enhance agricultural practices by providing real-time data that allows farmers to optimize their harvests, manage resources efficiently, and reduce the use of pesticides and fertilizers. Additionally, the improved connectivity will enable farmers to market their products more effectively to urban consumers. Through this approach, we seek to bridge the digital divide in rural areas, fostering sustainable agricultural practices, improving economic opportunities for rural communities, and reducing the climate change impact.

Keywords: Integration, Key Performance Indicators, private networks, IoT, FWA, LoRaWAN, USRP, eNB, 4G.

Resumen

La integración de redes privadas 4G y de Internet de las Cosas (IoT) ofrece una solución transformadora para abordar los desafíos de conectividad que enfrentan las áreas rurales en Colombia. Este proyecto, fácil de actualizar a 5G, se enfoca en aprovechar herramientas de código abierto, incluyendo srsRAN y Open5GS, junto con tecnologías de containerización y visualización como Docker compose, Portainer y Grafana, para desplegar, gestionar y visualizar los indicadores clave de rendimiento (KPI) de las redes privadas 4G. Utilizando hardware de propósito general y Radios Definidos por Software (SDR) como USRPs y estaciones base (eNBs) Baicells, nuestro objetivo es establecer una red de Acceso Fijo Inalámbrico (FWA) robusta en áreas rurales tradicionalmente no conectadas. Esta red facilitará la conexión de gateways LoRaWAN a sensores IoT desplegados en entornos agrícolas y permitirá el despliegue de soluciones inalámbricas con excelentes cualidades de penetración y cobertura de la señal. Además, se presenta como una propuesta viable y económica para que el gobierno colombiano logre su objetivo de conectar al 85% de los colombianos antes de 2026 sin la necesidad de comprar hardware caro de proveedores tradicionales y creando valor agregado.

El objetivo principal es mejorar las prácticas agrícolas proporcionando datos en tiempo real que permitan a los agricultores optimizar sus cosechas, gestionar recursos de manera eficiente y reducir el uso de pesticidas y fertilizantes. Además, la mejorada conectividad permitirá a los agricultores comercializar sus productos de manera más efectiva a los consumidores urbanos. A través de este enfoque, buscamos cerrar la brecha digital en las áreas rurales, fomentando prácticas agrícolas sostenibles, mejorando las oportunidades económicas para las comunidades rurales y reduciendo el impacto del cambio climático.

Palabras clave: integración, Indicador clave de desempeño (KPI), Redes privadas, Internet de las cosas (IoT), acceso inalámbrico fijo (FWA), LoRaWAN, USRP, eNB, 4G.

1. Introduction

In the evolving landscape of telecommunications, private networks powered by open-source software and Software-Defined Radio (SDR) technologies present a promising solution to the connectivity challenges faced by rural areas, particularly in Colombia where mobile operators do not see profit. These solutions not only offer a pathway to reduce implementation costs but also address critical issues faced by farmers in remote traditionally unconnected rural regions. In Bogota, researchers doing their master and PhD tesis [1][2] demonstrated that it is possible to deploy private cellular networks with services such as data, phone calls, videoconference, IPTV, and SMS as private celular operators do, but instead of proprietary hardware and software they used open-souce software such as Magma [3], srsRAN [4], OpenAirInterface [5], Open5GS [6], general purpose processor, software defined networks, and antennas.

Many farmers in Colombia's rural areas encounter significant obstacles in moving, marketing, and selling their products. The first challenge include connectivity issues where any rural regions lack reliable internet access or it is too expensive, making it difficult for farmers to obtain real-time market information, weather forecasts, and best practices. This connectivity gap jeopardizes their ability to make informed decisions that could optimize their production and sales. The second challenge is market access and sales where limited connectivity restricts farmers' access to urban markets, and the demand for their products is higher. This isolation results in missed economic opportunities and often forces farmers to sell their goods at lower prices in local markets. The third challenge is resource management that means without access to advanced agricultural technologies and data, farmers struggle with resource management, which can lead to inefficient use of water, fertilizers, and pesticides. The fourth challenge is money, cellular netwoks if available are expensive and with low quality of service. The final challenge is composed of logistical constraints related to the physical distance and lack of infrastructure that complicate the transportation of goods from rural to urban areas. This logistical challenge further exacerbates the difficulties in reaching broader markets.

Acknowledging previous problems, our objective of this article is to recognize the Role of Fixed Wireless Access (FWA) networks based on 4G and evolving to 5G to provide a cost-effective solution to these rural connectivity issues. Using open-source software such as srsRAN and Open5GS combined with SDRs like USRPs and antennas will enable the deployment of private networks at a fraction of the cost of the main Colombian traditional providers. These technologies reduce the need for proprietary hardware and expensive licenses, making connectivity more affordable. Open-source solutions are highly customizable and can be adapted in time to meet the specific needs of rural areas. The seamless transition to newer technologies like 5G ensures that infrastructure stays relevant and efficient over time, emphasizing software improvements rather than hardware upgrades. FWA networks provide a stable internet connection that supports various applications, including real-time data sharing, IoT sensor integration, online market access or even access points for rural community. This connectivity empowers farmers with the tools to improve their agricultural practices and engage more effectively with urban markets. By bridging the digital divide, FWA networks enable farmers to access digital platforms for marketing and selling their products. This enhanced connectivity facilitates better communication with buyers and helps farmers secure fair prices for their goods. Also, rural people can take virtual courses to learn how to be more proactive, resilient, creative, and competitive in a globalized world full of competition. Colombia in 2023 presented the achievements and the fulfillment of goals set out in the Action Plan of the Ministry of Information Technologies Information and Communications (MinTIC) and the

Single Fund for Information and Communications Technologies Communications during the 2023 term in accordance with its missionary structure according to the axes strategic of the Ministry. That document showed 8601 digital centers: 7056 in regin A and 1545 in region B, reducing part of the internet connection gap [7], however we need more hands to accelerate the wireless coverage in Colombia.

Finally, the Colombian government is committed to aggressively connecting 85% of its population by 2026 [8]. If the Colombian government considers our proposal of using private 4G networks, leveraging open-source software and SDR technologies, this will be a feasible and cost-effective approach to achieving this goal in a fraction of time the colombian government has forecasted in a record time. These networks can be rapidly deployed in underserved rural areas, providing essential connectivity that supports agricultural productivity and economic development. Additionally, the 5G spectrum allocated to regional operators can be leveraged for such initiatives, not only expanding connectivity and innovation but also generating additional revenue for the government through license fees. By optimizing the use of these unused frequencies ready to be assigned, regional operators can foster local development, while the government benefits from increased license utilization and potential long-term economic growth. Based on National Administrative Department of Statistics (DANE), in 2023, 63.9% of households had an internet connection reducing the connectivity gap, but connections are still focused on big cities and critical in rural zones [9].

2. 4G private and IoT networks integration

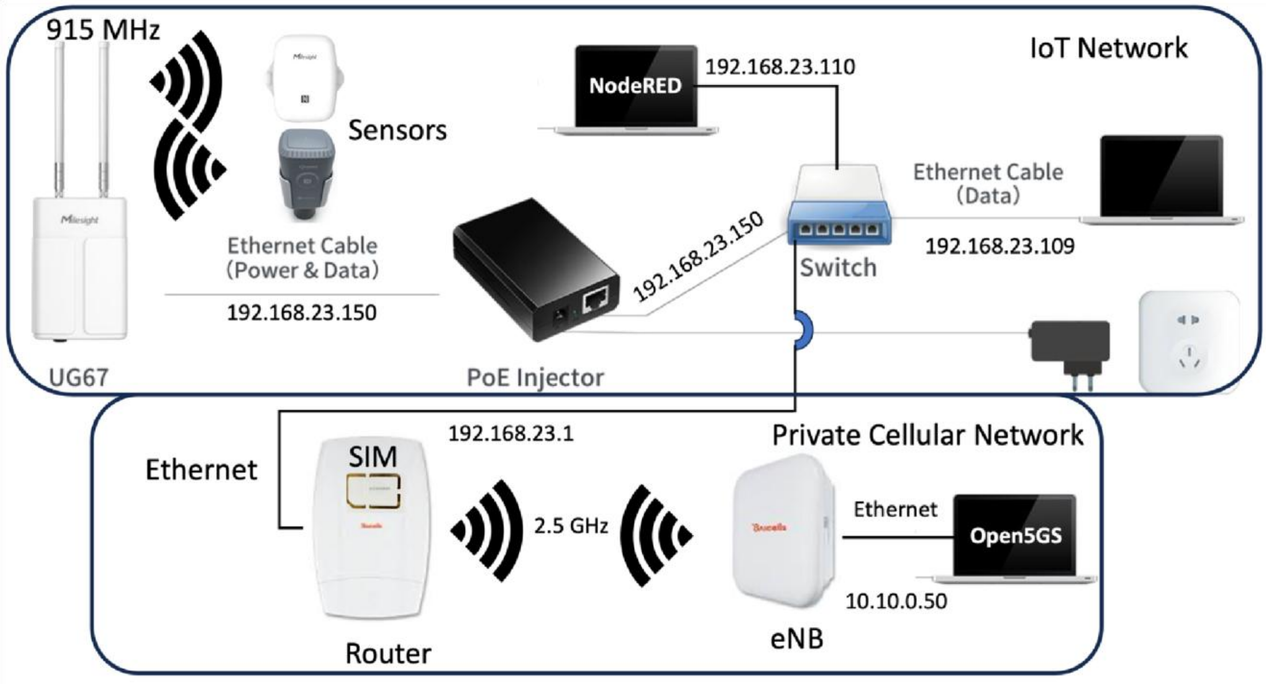
The stable proof of concept (POC) deployed by us for this article is illustrated in **Figure 1**. It demonstrates a 4G Fixed Wireless Access (FWA) connectivity using the Open5GS Core, the Baicells eNB and the Baicells CPE that will be the last mile for the gateway LoRAWAN. The implementation using general-purpose computer paired with a USRP and antennas can be established and were deployed as well, but with lower stability and signal coverage. That is the reason why we selected the setup with Baicells hardware that provides robust and stable internet access to connect the LoRaWAN gateway, and enabling communication with both fixed (Routers, Customer Premises Equipment (CPE) with 4G MOdulator-DEModulator (MODEM)) and mobile users within any rural coverage deployed area.

The deployment of the POC requires a set of steps. They are the following:

1. SIM cards configuration
2. Software compilation and installation
3. Private cellular network configuration
4. IMSI and MSISDN registration in OsmoHLR
5. Registration of APNs, AUCs, subscribers and ims_subscribers
6. Private cellular network and LoRaWAN integration

In following sections, we explain in a broader way.

Figure 1. 4G private and IoT networks integration with Baicells hardware.



2.1. SIM Cards configuration

In the context of integrating 4G private and IoT networks to enhance rural connectivity, SIM card configuration plays an important role in enabling different devices with 4G MODEM to connect to the private cellular network seamlessly. For example, cellular phones, 5G routers, CPE, or even directly to LoRaWAN gateways. We studiend two options of SIM Cards for our private cellular network deployment: USIM AND ISIM.

First, Opencells provides USIM cards used in private LTE/5G networks [12]. Their SIM cards often focus on interoperability, offering multiple form factors (mini, micro, nano) and compatibility with various hardware setups such as 5G routers, CPE, and mobile phones. SIM reconfiguration can include some parameters like IMSI (International Mobile Subscriber Identity), KI (secret key), and APN settings for specific data services, ensuring access to the correct network and data services.

Second, Osmocom provides ISIM cards designed for use in both data and IMS (IP Multimedia Subsystem)-based services over LTE/5G [13]. We utilized both, sysmoISIM-SJA2 and sysmoISIM-SJA5. The last one supports any configuration in 3GPP release 17. They supports secure authentication algorithms for 4G and 5G networks, such as KI, Opc (Operator Key), and ICCID (Integrated Circuit Card Identifier). The sysmoISIM-SJA2/SJA5 also allows customization for IMS services, enabling VoLTE (Voice over LTE) setup, which are necesary for video conferencing and voice services in rural areas.

Based on SIM card information benchmarck presented before, we selected Osmocom SIM Cards to provide data, SMS, phone calls, videoconference and IPTV services. Then we use the pysim software to write all variables for each user end. A programming command example to configure the sysmoISIM-SJA5 SIM with the values network name, acc, imsi, mcc, mnc, ki, opc, ims-hdomain, impi, msisdn, impu, pcscf, and iccid is the following:

```
python3 pySim-prog.py --pcsc-device=0 --type="sysmoISIM-SJA5" --name=Open5GS --pinadm=12345678 --acc=0002 --imsi=001010000010010 --mcc=001 --mnc=01 --ki=12345BDDF6789C0BFA1234B567890C1 --opc=1BA1234D56CC67890EF1CCE012345678 --msisdn=10010 --ims-hdomain=ims.mnc001.mcc001.3gppnetwork.org --impi=001010000010010@ims.mnc001.mcc001.3gppnetwork.org --impu=sip:001010000010010@ims.mnc001.mcc001.3gppnetwork.org --pcscf=pcscf.ims.mnc001.mcc001.3gppnetwork.org --iccid=000111200000223350
```

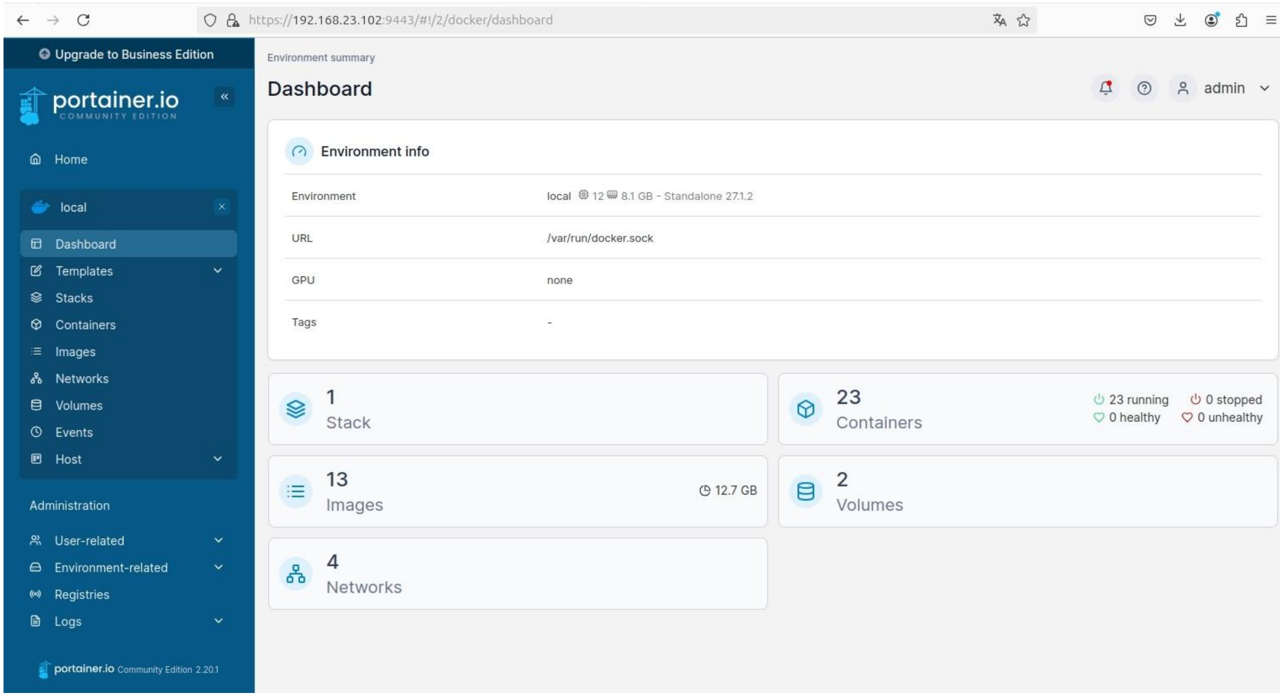
2.2. Software compilation and instalation

To begin the deployment of our private network infrastructure, we started by installing Docker, which serves as the containerization platform to buil images and ensure all network components are isolated and easily managed. Once Docker was set up, we installed Docker Compose to orchestrate the multiple containers required for this project. Docker Compose simplifies the management of complex deployments by using YAML files to define and run multi-container Docker applications from images. After that, we installed Wireshark, a tool for analyzing network traffic and ensuring that the packets between our core network elements are functioning as expected.

Following these prerequisites, we proceeded with the compilation and installation of Open5GS, the open-source 5G core network framework, as per the detailed steps provided in the GitHub repository [10,11]. Open5GS forms the backbone of our 4G/5G core network, enabling communication between various components like the User Equipment (UE) and Radio Access Network (RAN). We then installed Kamailio, an open-source server, to manage Session Initiation Protocol (SIP) traffic for IMS services. Then, we installed UERANSIM, a tool for simulating User Equipment and RAN interactions with the core network, allowing us to test endto-end communication without employing SDRs. These steps, all executed following the GitHub instructions, laid the groundwork for our private 4G/5G network deployment.

Finally, After completing the installation of the core components, we used Portainer, as depicted in **Figure 2**. Portainer is a lightweight management tool for Docker environments via the endpoint http://<DOCKER_HOST_IP>:9443. Portainer provides a centralized, user-friendly interface to manage our containers, images, networks, and volumes. This tool simplifies the oversight of the Docker infrastructure, allowing us to monitor the status of each container and troubleshoot more efficiently. With Portainer, we can easily manage containers lifecycle, making it an essential tool for throubleshooting all of them, use the terminal of each container, see services deployed for our private 4G/5G network, including Open5GS, Kamailio, and UERANSIM and more.

Figure 2. Portainer dashboard with all deployed containers.



2.3. Private cellular network configuration

After completing the software compilation and installation, we proceeded with the configuration of the private cellular network. The first step involved registering the SIM cards in the Open5GS core. To begin, we accessed the Open5GS dashboard via the endpoint http://<DOCKER_HOST_IP>:9999. This dashboard serves as the central interface for managing network subscribers, including the SIM card details. Within the dashboard, we input the necessary SIM card values, as we show in a table 1. At the dashboard also it is configured APNs for data and IMS services (internet and ims).

Table 1. SIM card values.

VALUE	SIM1	SIM2
IMSI	001010000010001	001010000010002

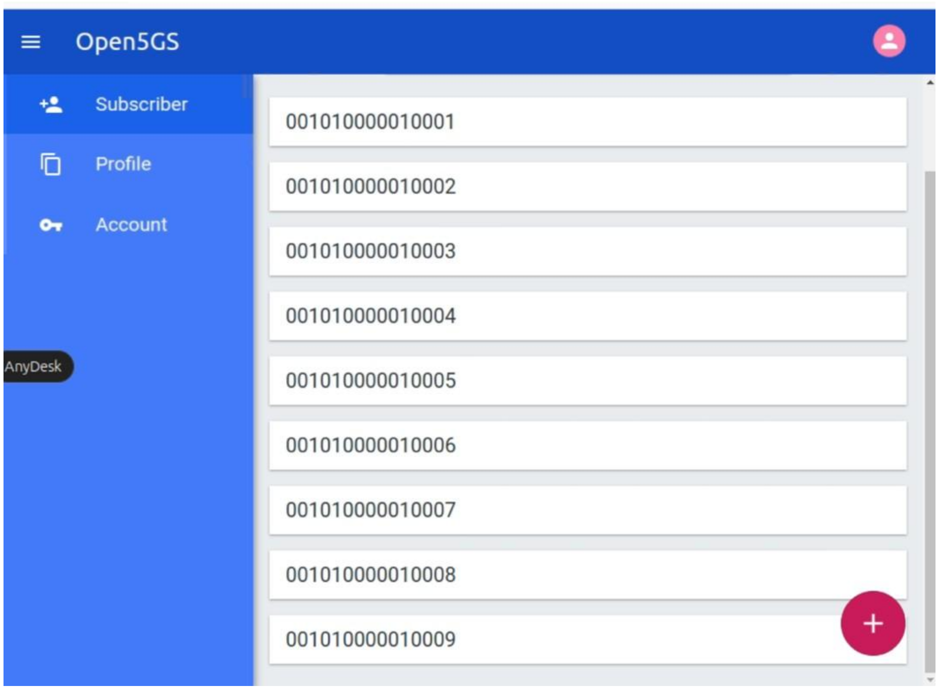
MSISDN	10001	10002
MCC	001	001
MNC	01	01
ADM1	XXXXXXXX	YYYYYYYY
ICCID	8988211000000543515	8988211000000543523
Ki	5BAD8598D1F631E3ED76F9333B8AA26F	DA4EDB6503743D404DA2F91A4446C26F
OPc	BA5205DDC6FCA1DF6B83A1CC69859514	1CFA68FDE88DCA322C1BF33D0F2709A0
ICCID	8988211000000543515	8988211000000543523
IMS DOMAIN	ims.mnc001.mcc001.3gppnetwork.org	ims.mnc001.mcc001.3gppnetwork.org
IMPI	001010000010001@ims.mnc001.mcc001.3gppnetwork.org	001010000010002@ims.mnc001.mcc001.3gppnetwork.org
IMPU	sip:001010000010001@ims.mnc001.mcc001.3gppnetwork.org tel:10001 sip:10001@ims.mnc001.mcc001.3gppnetwork.org	sip:001010000010002@ims.mnc001.mcc001.3gppnetwork.org tel:10002 sip:10002@ims.mnc001.mcc001.3gppnetwork.org

PCSCF	pcscf.ims.mnc001.mcc001.3gppnetwork.org	pcscf.ims.mnc001.mcc001.3gppnetwork.org
KIC1	CD9DB47453E5691B48971F86DFB408CE	056C8B738C1BCECA4F3A9C722E65562B
KID1	35132A622B39BFCCA25B84FE61C088BF	3F1D9A5FCEBB175644FDFDCBDE6B0E7C
KIK1	3381C956F30710A607061D5414F5F040	4054195F4984B8DA0ABF5B62393F0435

Source: https://xxxxxx

We include information from Table 1 iinto the Open5GS and OsmoHLR as shown in Figure 3.

Figure 3. Adding subscribers to the Open5GS core.



2.4. Register the IMSI and MSISDN with OsmoHLR

Please login to the osmohlr container using Portainer dashboard. Open the terminal of osmohlr and execute: telnet localhost 4258. Then execute: enable. Then subscriber imsi 001010000010001 create, then execute: subscriber imsi 001010000010001 update msisdn 10001. **Figure 4** depicts 10 registered subscribers in OsmoHLR.

Figure 4. Registered subscribers in OsmoHLR.

```
Welcome to the OsmoHLR VTY interface

Copyright (C) 2016-2023 by Harald Welte, sysmocom s.f.m.c. GmbH
License AGPLv3+: GNU AGPL version 3 or later <http://gnu.org/licenses/agpl-3.0.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.
OsmoHLR> enable
OsmoHLR#  show subscribers all
ID     MSISDN        IMSI              IMEI              NAM
-----  ------------  ----------------  ----------------  -----
1      10001         001010000010001    -------------    CSPS
2      10002         001010000010002    -------------    CSPS
3      10003         001010000010003    -------------    CSPS
4      10004         001010000010004    -------------    CSPS
5      10005         001010000010005    -------------    CSPS
6      10006         001010000010006    -------------    CSPS
7      10007         001010000010007    -------------    CSPS
8      10008         001010000010008    -------------    CSPS
9      10009         001010000010009    -------------    CSPS
10     10010         001010000010010    -------------    CSPS
 Subscribers Shown: 10
OsmoHLR#
```

2.5. Registration of APN, AUC, subscribers and ims_subscribers

At the endpoint http://<DOCKER_HOST_IP>:8080/docs/ we find the API configuration as shown in **Figure 5 and Table 2**. This task is important if the private cellular network wants to have IMS services. The values to configure are apn, auc, subscriber, and ims_subscriber.

Figure 5. API endpoint to configure APNs, AUCs, subscribers and IMS subscribers.

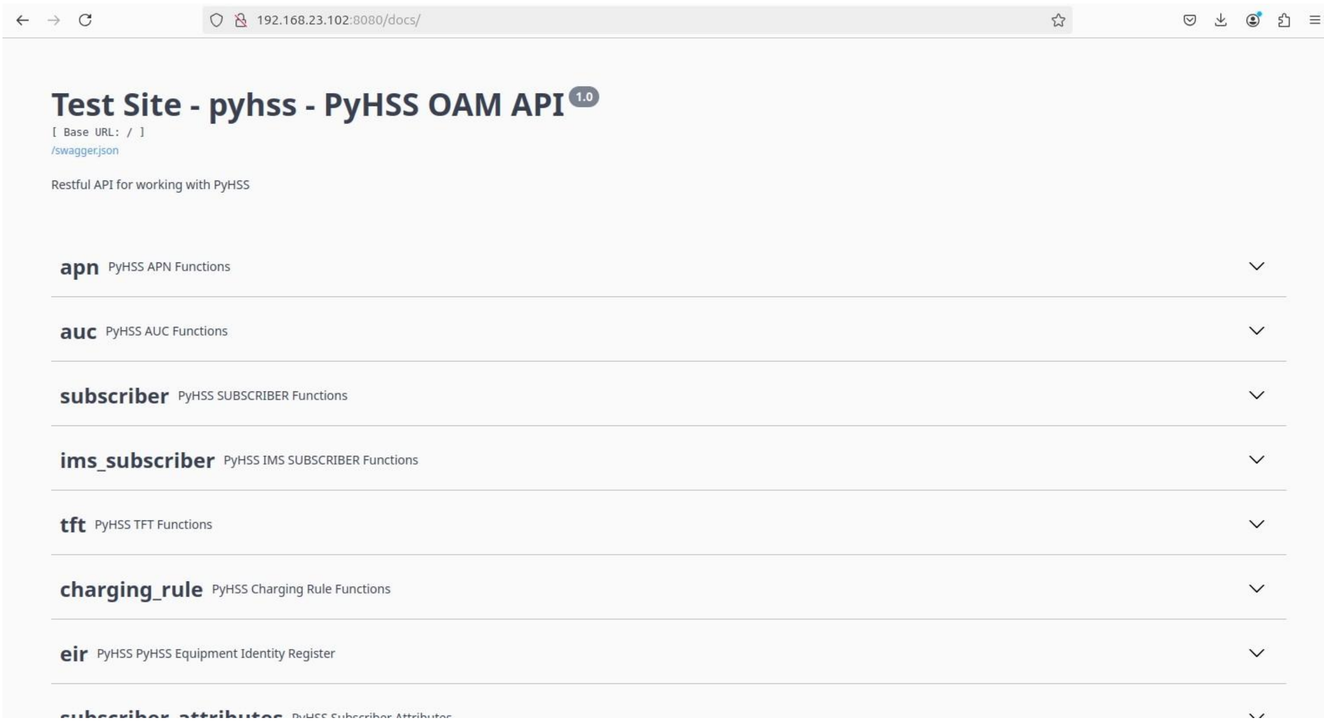


Table 2. APN configuration.

APN	Type	QCI	ARP	Capability	Vulnerability	MBR DL/UL (Kbps)	GBR DL/UL (Kbps)
Internet	IPV4	9	8	Disabled	Disabled	unlimited/unlimited	
ims	IPV4	5	1	Disabled	Disabled	3850/1530	
		1	2	Enabled	Enabled	128/128	128/128
		2	4	Enabled	Enabled	812/812	812/812

Source: https://xxxxx

2.6. Private cellular network and LoRaWAN integration

The LoRaWAN gateway interfaces with IoT sensors and the network server to enable data analytics. This includes both basic methodologies and advanced artificial intelligence techniques to analyze sensor data and optimize crop growth. However, the focus of this article is on the network infrastructure, not on the specific data analytics methodologies.

Our work centers on creating private networks using the 2.5 GHz band in Time Division Duplex (TDD) mode. The LoRaWAN gateway's modem, a Quectel EC25AUX, does not support the B41 band in the 2.5 GHz spectrum. Instead, it operates on the B40 band in TDD mode within the 2.4 GHz range, which is incompatible with our project's requirements. To resolve this issue, we implemented a solution using a Customer Premises Equipment (CPE) device that supports the B41 band. This CPE interacts with a Baicells Nova 227 eNodeB (eNB) operating on the 2.5 GHz band.

Figure 6. Our infrastructure for cellular networks.

The Baicells CPE provides Ethernet connectivity to the LoRaWAN gateway, creating an integrated Fixed Wireless Access (FWA) network. Acting as an Ethernet router, the CPE can also be configured to distribute internet access through Wi-Fi router if necessary, particularly in proximity to the deployment site. This enables rural users to sell products online, optimize resource management, and interact with clients via social networks.

Figure 6 illustrates the infrastructure of our implementation, which comprises servers, computers, a Baicells Nova 227 eNB, a Baicells CPE, a Milesight UG67 LoRaWAN gateway, a USRP B210, a 5G Huawei CPE, routers, and switches.

By leveraging these technologies, the system aims to improve agricultural productivity while supporting informed decision-making in rural areas. Our proposal involves using FWA to provide internet connectivity to the IoT network through the LoRaWAN gateway. This allows a private cellular network to interface with the cellular CPE, delivering LAN connectivity for IoT sensors. Moreover, we extend the capabilities of the 4G private cellular network to include IMS services, such as Voice over LTE (VoLTE), video conferencing over LTE, IPTV, and data services.

3. Conclusions

The implementation of private cellular networks with open-source software and SDR technologies offers a financially viable method to address connectivity issues in Colombia's rural areas. This approach reduces implementation costs by utilizing affordable, generalpurpose hardware and open-source tools, making it feasible to deploy advanced communication infrastructure at a lower expense.

By establishing Fixed Wireless Access (FWA) networks in rural areas, farmers will gain access to real-time data and digital tools that are critical for optimizing agricultural practices. Improved connectivity will enable farmers to manage resources more efficiently, access market information, and enhance their productivity, ultimately leading to more sustainable farming practices.

The proposed solution will bridge the gap between rural farmers and urban markets by providing reliable internet access. This connectivity will facilitate better market integration, allowing farmers to reach urban consumers more effectively and secure fair prices for their products, thus improving their economic opportunities.

The deployment of private 4G networks using open-source technologies aligns with the Colombian government's objective of connecting 85% of the population by 2026. This approach supports the achievement of national connectivity targets by providing scalable and adaptable solutions that can be extended to underserved rural regions.

The proposal addresses the broader goal of fostering sustainable development in rural areas. By improving digital infrastructure and enabling better access to information and markets, the initiative not only enhances agricultural productivity but also stimulates economic growth and development in Colombia’s rural communities. One example is the improvement of the gini index that is a statistical measure of how much income, wealth, or consumption within a nation or social group deviates from an equal distribution.

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