MAQ5G: Deployment of a complete 5G Standalone network testbed for testing and development

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***Abstract*—This paper presents the culmination of a Final Degree Project undertaken to fulfill the requirements for the title of Electrical Engineer with a specialization in Telecommunications. The project revolves around the creation of a comprehensive 5G Standalone network testbed utilizing open-source resources, specifically leveraging the OpenAirInterface development framework integrated with real radio interfaces facilitated by Software Defined Radio (SDR) technology. The assembled testbed's functionality undergoes rigorous evaluation, encompassing behavioral analysis, capability measurements, and identification of both system and deployment limitations. Furthermore, an alternative scheduler software is developed and seamlessly integrated to demonstrate the system's versatility as a developmental environment. The outcomes of this project not only validate the system's efficacy for educational and research purposes but also establish its potential as an infrastructure platform for related systems.**

***Index Terms*—5G, OpenAirInterface, Scheduler, SDR, Testbed**

I. Introduction

Mobile networks are in a constant state of evolution to meet the growing demands for diverse services, which come with varying requirements in terms of traffic, quality of service, and energy efficiency [1], [2]. The deployment of fifth-generation networks (5G) is well underway, with rapid advancements leading toward widespread penetration and technological maturity. However, discussions surrounding future networks, such as Beyond 5G and 6G, are already gaining momentum, highlighting the continued importance of innovation in this dynamic field [3].

Engaging in research and technical discourse on these topics is intrinsic to the core mission of universities. It is vital to align these endeavors with the requirements of operators, regulators, and developers to propel the advancement of mobile networks. Our institute's ongoing research, encompassing radio resource scheduling, the integration of artificial intelligence to optimize resource allocation, and the convergence of optical networks with mobile networks, is strategically focused on addressing short and medium-term needs. These initiatives are driven by the escalating demand for research and development in mobile communications. In the midst of a landscape teeming with technical challenges and opportunities for innovation, the establishment of test environments where researchers can experiment with technologies under controlled conditions before their integration into commercial networks is paramount. Such environments facilitate the exploration of novel solutions and the validation of theoretical concepts, ensuring robustness and efficacy prior to deployment in real-world scenarios. In this context, simulators and testbeds play a pivotal role in providing a secure and flexible platform for experimenting with the capabilities and limitations of 5G networks. These environments enable researchers to validate algorithms and protocols, evaluate device and system performance, and simulate real-world scenarios.

This article presents the installation of a practical tool for current and future research endeavors: a 5G Standalone network testbed deployed in an open-source environment with operational radio interfaces (based on Software Define Radio (SDR) technology). The system's functionality is assessed, and its potential is validated through modifications, including the development of an alternative scheduler, demonstrating its efficacy as a development environment. The paper extensively details the implementation of a network utilizing the OpenAirInterface (OAI) system, covering configuration options, tested scenarios, and achieved results. Throughput tests, incorporating various configuration variations, have yielded promising outcomes, with transfer rates reaching 70 Mb/s in single-layer Time Division Duplex configurations with an 80 MHz bandwidth. Furthermore, commercial phones have seamlessly accessed the Internet over the network, evidenced by uninterrupted video calling services. The successful development of an alternative radio resource scheduler necessitated a thorough exploration of system architecture and has validated its utility as an effective development tool. In conclusion, the ongoing progression of this learning and deployment process, along with its utilization as both a research tool and teaching aid, represents immediate and essential steps forward.

Subsequent sections of this paper will delve into the design of the installed network testbed, evaluate its performance, and explore its potential for education and research purposes. Firstly, Section II delves into the intricacies of constructing and establishing the test environment. It details the methodologies, frameworks, and technologies employed in creating a robust infrastructure for experimentation. Following this, section III scrutinizes the testbed's functionality and effectiveness. Through rigorous analysis and measurement, this section assesses the testbed's capabilities, identifying strengths and potential areas for improvement. Next, section IV explores

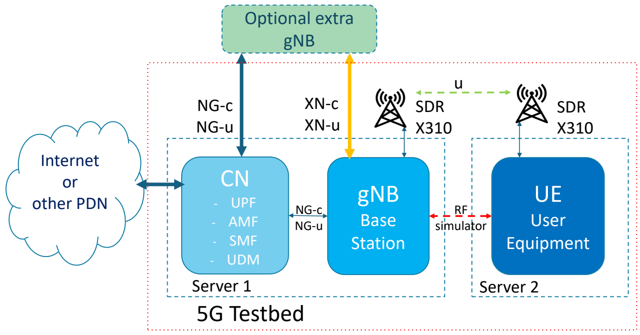

Fig. 1. Schematic Diagram of the Testbed: Illustrating Component Blocks and Interfaces.

the broader implications and applications of the testbed. It discusses how this platform serves as a valuable tool for both educational instruction and research exploration, unlocking new avenues for learning and discovery. Finally, the article concludes in section V.

II. Design and Implementation of the Testbed

After evaluating several options for prototype development, the most promising turned out to be srsRAN and OpenAirInterface (OAI). The progress of 5G implementation is much greater in OAI as is its community. With these considerations, it was decided to implement this 5G prototype with OAI framework.

The testbed currently comprises three software applications: a Core Network (CN), a base station (gNB, in 5G nomenclature), and a User Equipment (UE). The CN assumes responsibility for user registration and authentication, IP assignment, tunneling for navigation, mobility management, security enforcement, policy implementation, accounting, and overall network management. Conversely, the gNB defines the radio access interface, facilitates user connections, dynamically assigns physical resources, and maintains control over the radio link assuring navigation capabilities for all connected users. As the linchpin of this work, the gNB's configurations represent the most critical decisions in each test scenario. Meanwhile, the UE acts as the user-side counterpart, operating under the control of the gNB.

Both the CN and the gNB are installed on the same physical machine, while the UE operates on a separate computer. Both computers are connected to an SDR X310 via a 10 Gb Ethernet interface (we also test the solution with USRP B210, a lower end SDR device). This setup allows the second computer to establish connections to external networks through CN gateways, utilizing its services and control, and using the radio interface between the gNB and the UE. The UE provides a virtual network interface to the host machine. This architectural configuration is depicted in figure 1. All three systems are implemented using the OAI 5G Core Network project and the 5G RAN project's software.

As depicted in figure 1, an alternative network connection between the UE and gNB facilitates the provision of the same service without relying on the radio interface. This interface, denoted by the red arrow, is realized through a client-server application called RF Simulator (RFsim), embedded within both modem software. Through the exchange of sample packets over IP and processing by a channel simulator, a simulated radio connection is established. This option proves invaluable for conducting controlled environment analyses of protocols or Layer 1 functions.

In the subsequent subsections, we outline the essential hardware components, delve into core network functionality, explore RAN deployment strategies, and discuss various building scenarios.

A. Hardware Essentials

In our current approach, we prioritize cost-effectiveness and replicability, selecting minimal standard hardware that guarantees all necessary functionalities. A comprehensive breakdown of these components is provided in Table I. Crucially, 10 Gb Ethernet interfaces are essential to enable the fronthaul connection of the USRP X310. Additionally, we employ additional USRP B210 units connected via USB 3.0. Commercial off-the-shelf (COTS) UE Samsung A33 devices, outfitted with Open Cells' writable SIM cards and a SIM writer, are also integrated into the setup. The hardware kit is rounded out by antennas, coaxial cables, and attenuators, ensuring a complete and versatile hardware setup.

TABLE I
Hardware Table

Item Quantity	Items description	
	Item	*Characteristics*
2	Computer	12th Gen Intel Core™ i7-12700 12 Cores; Frecuency 2.1-4.9 GHz Cache Size: 35 MB Threads: 20 16 GB DDR5, 512 GB SSD
2	Ubuntu 22.04.1 LTS	kernel 6.2.0-33-generic
2	USRP X310[a]	UBX 160 daughterboard[b]
3	USRP B210[a]	
2	10 Gb Network Card	
2	Samsung A33	Android 12 & 13

[a]A SDR from Ettus Research.
[b]One daughterboard per USRP.

B. Core Network functionality

The Core Network (CN) is conveniently available in Docker containers, offering a versatile solution for projects focused on the Radio Access Network (RAN). All principal functions, defined in TS 23.501 [4], are readily provided, as illustrated in figure 2. Each function is encapsulated within its independent container, allowing for streamlined management. With Docker Compose, it is possible to execute all CN functions with a single command. Moreover, configuring these functions is simplified through the use of a single file: docker-compose.yml.

The CN functions utilize a virtual network, facilitated by an interface assigned to the host machine, enabling the connection with the gNB. IP addresses and various traffic definitions, such as Mobile Country Codes (MCC), Mobile Network

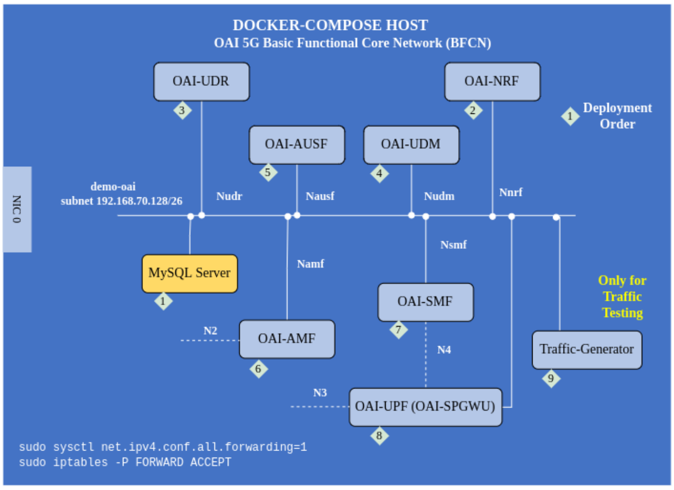

Fig. 2. CN functions and VN connection. Figure from OAI web page https://openairinterface.org.

Codes (MNC), Tracking Area Code (TAC), IP range for DHCP, and slice definitions, are configured within the docker-compose.yml file. Additionally, user data can be incorporated into the MySQL server either offline by editing the SQL file or online using SQL commands.

At the user plane level there are three implementation alternatives. The option selected in this work, SPGWU is an evolution of the user plane distributed between the Serving Gateway (SGW) and the Packet Data Network Gateway (PGW) of OAI's LTE solution. Although it constitutes the most basic function with the worst performance, it is also the most tested one with the longest evolution.

C. RAN deployment

The OAI RAN comprises four essential applications: a New Radio (NR) gNB, an LTE eNB, and two user equipment, NR-UE and LTE-UE. For optimal performance, it is advisable to install these applications directly on bare metal, avoiding virtual machines. This approach is preferred due to stringent real-time constraints inherent in these systems. The physical and link layers demand strict Transmission Time Interval (TTI) compliance, necessitating full calculations to be completed within each slot time.

In this setup, the gNB is installed on the same machine as the CN, albeit the only requirement is to establish an IP connection with the CN Docker interface. All gNB characteristics are meticulously defined through a manually crafted ASN-1 configuration file. The file encompasses a multitude of definitions, including TDD or FDD settings, carrier frequency, bandwidth, frame structure, System Synchronism Block (SSB) placement, bandwidth parts (BWP), and Subcarrier Spacings (SCS). Additionally, it delineates the connection parameters to the CN, the served network's parameters and its slices. Fully comprehending these configurations, their interrelations and associated parameters necessitates an in-depth study of related 3GPP TS documents. The file's coherence ultimately relies on the developer's expertise. It presents a steep learning curve, requiring extensive knowledge and the development of a valuable configurations library over time. While there are extensive templates and examples available to guide initial setup, they may not precisely align with specific expectations.

In contrast, configuring the UE requires less effort as it is controlled by the gNB. OAI UEs do not engage in tracking to find a gNB; instead, parameters such as frequency, bandwidth, and SSB location are set as command parameters at initialization. Network configurations can be included in an eSIM file or overridden by command parameters. COTS UEs with programmable SIM cards can also be employed within this network setup.

1) The carrier frequency example: Frequency band selection is the first step in the model design. Available band, or coaxial connection, or a Faraday cage are the possible solution to avoid licensed band interference. Once defined the carrier frequency, the bandwidth, and the exact location of the SSB in the frequency domain should be configured. The step-by-step configuration file filling process will be shown for this topic, as an example.

This configuration lines are located in the configuration file at gNBs/servingCellConfigCommon part.

- dl_frequencyBand = 78; //Selected TDD band.
- dl_absoluteFrequencyPointA = 640008;// The absolute radio-frequency channel number (ARFCN) of the first subcarrier possible of any of the defined BWP: 3600.120 MHz.
- dl_offstToCarrier = 0; // Distance in Hz between uplink and downlink carriers. It is 0 for TDD.
- dl_subcarrierSpacing = 1;// 0=15 kHz, 1=30 kHz, 2=60 kHz, 3=120 kHz
- dl_carrierBandwidth = 106; // Bandwith in PRB. $106RB \times 12\frac{RE}{RB} \times 30\frac{kHz}{RB} = 38.16\,MHz$. Adding guards, it is a 40 MHz channel.
- absoluteFrequencySSB = 641280; // ARFCN of the SSB central frequency. The first SSB subcarrier should be equal to or greater than the first primary BWP subcarrier. Similarly, the last SSB subcarrier should be equal to or less than the last primary BWP subcarrier. The central SSB frequency must be a Global Synchronisation Channel Number (GSCN), because the UE Sync raster only look up for those channels. This is the 7929 GSCN, 3619.200 MHz.

Since the OAI UE does not perform the sync raster, both the carrier frequency and the SSB position must be specified as start command parameters: ./nr-uesoftmodem –numerology 1 –band 78 -C 3619200000 –ssb 516 –sa where the carrier frequency is:

$$C = f_{PointA} + \frac{BW}{2}$$

then

$$C = 3600.120MHz + \frac{38.16MHz}{2} = 3619.200MHz.$$

SSB and carrier are equal in this example, but it is not mandatory. The SSB offset parameter show the subcarrier distance between the Point A (first subcarrier) and the first subcarrier of the SSB.

$$SSB_{offset} = \frac{f_{SSB} - f_{PointA} - \dfrac{SSB}{2}}{SCS}$$

where

$$\frac{SSB}{2} = (\frac{20RB}{2} \times 12(RE/RB) \times 30(kHz/RE))$$

then,

$$\frac{SSB}{2} = 3600kHz$$

$$SSB_{offset} = 516.$$

This example shows the deep comprehension and detailed process required just for one simple aspect of the entire configuration file preparation.

2) Radio link: Following the configuration process, a radio link adjustment is necessary to complete the startup procedure. This adjustment involves modifying parameters such as programmable attenuators in both directions and maximizing reception gain on both ends. The optimal conditions for these adjustments depend on various factors, including the radiating system, antenna type, SDR model, spatial dimensions, and propagation conditions.

Additionally, the dynamic variation of transmitted power, influenced by fluctuating traffic demands, necessitates ongoing adjustments to optimize throughput. This adjustment-testing process is iterative, ensuring that the radio link operates efficiently under changing conditions.

D. Building scenarios

Three blocks have been described: CN, gNB, and UE. Several testing configurations may be deployed using them as building blocks. The main basic initial scenario (figure 1) allows to show most of basic functionalities, protocols, and procedures. The mentioned RF simulator tool enables to analyze protocols, procedures, or new development in an isolated environment without RF issues. Multiples UEs may be added using RF Simulator from several computers or using network namespaces in the same hardware. In standard configurations, with RF links, a SDR per UE is required. Those scenarios with multiple UE are useful for scheduling testing.

III. Performance evaluation

The performance evaluation of the testbed aims to gauge the capabilities of this network implementation across three dimensions. Firstly, it involves protocol analysis and measures, along with Key Performance Indicator (KPI) monitoring. Secondly, it assesses traffic throughput. Lastly, it examines the utilization of computer hardware and software stability.

A. Protocols and measurements

NGAP (Next Generation Application Protocol) is a protocol used in the implementation of the CN to communicate with the RAN. NGAP is employed for message exchange between the gNB and the CN, managing aspects such as session establishment, user mobility, connection setup, and data delivery. In this context, the N group interfaces, the user interface and the internal network between CN functions are open and are used to analyze traffic using Wireshark. Also, the logs of each software function show all the traffic exchange. The gNB software has several logs levels, and most of the internal variables may be inspected using it. But its uses is hard, due to the enormous amount of data generated. A GUI, capable of handle the information and save it as databases for post processing, or showing graphic measures online may be a great improve for the test bed future use.

B. Traffic throughput

These performance tests are focused on determining the maximum throughput of a connection through a core connected to a gNB and one or two simultaneous UEs. With this objective, two sets of tests are defined using the iperf3 client-server scheme. The tests were divided into different implementations, including the gNB and UEs through the x310 SDRs radio frequency air link by antennas and also with the same SDRs connected in a wired link by coaxials and RFsim by 10 Gbps Ethenet.

There is a limitation, the X310 SDRs support a maximum of 217 PRBs, that is, 80 MHz. All configurations used are single carrier (1 CC), single antenna port (SISO), and with a bandwith part equal to the total bandwidth of the cell. The system used is TDD, with a cycle of 10 slots. 7 DL slots, 2 UL slots and one hybrid slot are assigned with 6 DL symbols, 4 separation symbols and 4 UL symbols.

In figure 3, the throughput is shown discriminated by medium: air or coaxial, bandwidth according to the number of PRBs (24, 106 or 217) and in the direction of communication (UL or DL). They are also contrasted with the theoretical maximums of each category, based on the TS 38.306 specification [5].

In links with antennas, a high number of retransmissions and an MCS (Modulation and Coding Scheme) that remains at intermediate values as a consequence of errors, are observed. Therefore, the modulation index Q_m and the coding rate R are lower than the maximum values taken in the theoretical calculation, which together with the retransmissions explains the difference. The measurements for the connection by antennas were made in a closed indoor environment, with a high impact of fading due to multiple paths. On the other hand, in the coaxial connection the parameters are maintained stable but without reaching the maximum MCS and with some retransmissions.

It should be noted that the channel balance is an iterative process that seems more like trial and error, since it does not include direct objective measurements. The useful range is limited and its values vary with the bandwidth and working

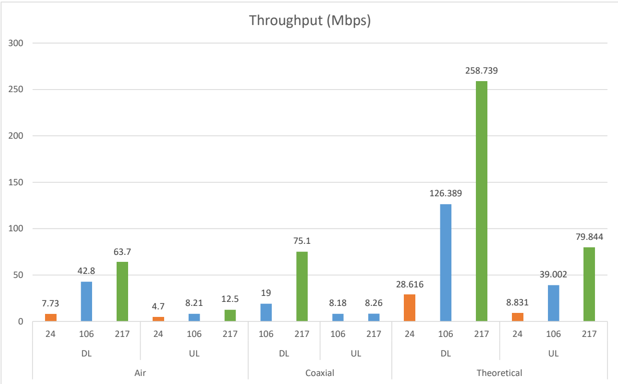

Fig. 3. Throughput according to medium and number of PRB; data obtained from air transmission, coaxial and the theoretical maximums are compared.

Fig. 5. CPU performance in gNB when two UE are connected and trafficking.

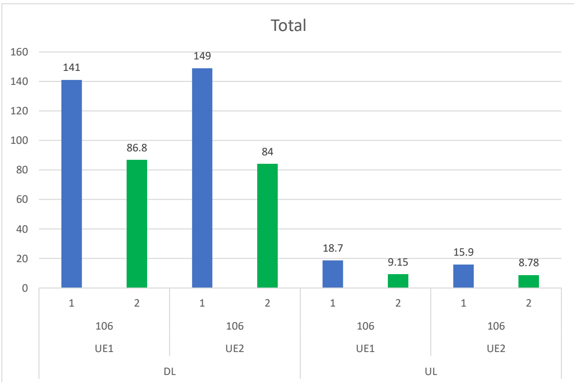

Fig. 4. Throughput (Mbps) RFsim 2 UE, transmitting alone (blue color) and simultaneously (green color).

frequency. The result of this adjustment is decisive in the performance of the tests, and imposes very different adjustment values for a link with antennas than for a coaxial link.

Another aspect that concerns the evaluation of performance is to compare the performance of the model in RFsim with two UEs generating traffic at the same time and separately. In the figure 4, the performance of the system is compared when the UEs are transmitted separately and when both are transmitted at the same time. All cases are referred to 106 PRB in band n78. The performance peak occurs in DL for UE2 at 149 Mbps transmitting separately, exceeding the theoretical maximum due to the use of the RFsim model with 10 Gbps Ethernet. But the most important aspect is to visualize the operation of the protocol with both UEs transmitting, the bandwidth is distributed approximately equally. This behavior tending to maintain the same level of bandwidth in both UEs is explained because by default the scheduling algorithm is Proportional Faire (PF).

The performance tests conducted demonstrate the functionality and utility of this testbed. Potential future enhancements could involve implementing a fixed radiating system to ensure test repeatability. Additionally, incorporating SDR hardware would enable MIMO configurations, thereby increasing traffic throughput. Integrating a synchronization system would improve stability and facilitate handover and multi-site testing.

C. The use of computer hardware and software stability

Under normal operating conditions, both computers operate with enough memory usage and sufficient processing power. As traffic demand increases, processor usage increases to very high values, but without reaching 100% (figure 5).

When traffic demand greatly exceeds the system's capacity, abnormal operations occur. If iperf tests are carried out, in UDP without speed limit, the resulting throughput is significantly lower than if the iperf transfer speed is adjusted to the maximum expected value. In these conditions the result is maximized. When this test is repeated over a radio link in poor condition, it often happens that multiple Service Data Unit (SDU) unavailable messages appear. A message indicating that a Transmission Time Interval (TTI) is interrupted because processing is not completed within the maximum time. When this condition is repetitive, the link is not reestablished and the IP connection is lost, even after canceling the test in course. To get out of this situation it is necessary to restart the UE. The descripted situation occurs with the OAI UE software. Using a COTS UE, if the link is improved, the traffic normalizes.

If the traffic capacity is not pushed to the limit, no unexpected software interruptions are observed. A link has been kept running for periods of several hours without problems. Futures hardware enhancement or operating system tuning may reduce those kind or stress impacts and help with the throughput performance.

IV. Unlocking Educational and Research Potential through the Testbed

It is easy to imagine the wide uses' possibilities of a 5G testbed in a learning process. From a basic in dockers full implementation, in a single machine, used as a personal laboratory for students practice on protocol analyze or basic configurations, to a campus deployment, with coverage measurement, link budget or handover management possibilities to be used as laboratory works. Also, for research it enable a deployment framework where new ideas may be tested in an scenario less predictable than an emulator. At this section, we prefer emphasize in our experience as students using it in a project methodology.

A. The configuration challenges

The configurations necessary for the operation of the testbed are directly based on the 3GPP standards. It is necessary a deep understanding of this technology to comprehend and apply them to a specific configuration. This challenge involves iterative cycles where knowledge is fed back into the technology, standards, and configurations on the testbed, defining what is necessary for the progress of the work. These iterative cycles are crucial for advancing the work, as they allow for the refinement and adjustment of the testbed based on the progress and insights gained.

B. Diving into the code

We have made some modification into the code, building an alternative gNB scheduler. This functionality, effectively integrated into the software suite, proves the feasibility of use the testbed as a development framework. This challenge entailed achieving a deep understanding of the utilized system architecture and the details of the addressed functionality. The considerations mentioned earlier regarding iterating in a continuous learning cycle also apply in this case, extending the focus to software development. Diving into the code involves meticulously exploring the complexities of technical implementation. This process allows identifying possible improvements and adding functionalities, always ensuring coherence with established standards. The implementation details of the scheduler and its performance evaluation can be found in our Bachelor's thesis [6].

C. From the tech basics to the research lab; a fast track way

A Final Degree Project requires acquiring abilities and knowledge across various areas relevant to the project's main topic within a limited timeframe (approximately a year). From grasping technological fundamentals and the basics of system deployment to gaining a deep understanding of MAC layer and scheduling processes, and their implementation in a real-time environment, our journey has been demanding at every step. This process has provided us with a solid understanding of the related technologies. More importantly, it has equipped us with a wide range of resources, from methods of search and learning from 3GPP standards to reverse engineering to decipher how and why the studied processes are managed in the original system. These abilities enable us to explore new approaches or introduce additional functionalities not yet included.

The project methodology not only completes our academic journey but also furnishes us with the skills to embark on careers as researchers. We envision our work as a significant building block in the establishment of a telecommunications research laboratory capable of evolving through new projects. Our experience is reproducible, with a focus on other aspects, and iterative in its construction and improvement.

This laboratory represents a convergence point where the accumulated experience in the research and development of new functionalities and improvements, already existing in our academic environment, materializes into concrete projects. Initiatives like this laboratory could start with a testbed, like the one we have developed and be nourished by components that arise from other end-of-degree projects, thus contributing to staying at the cutting edge and enriching the knowledge available to the scientific community. Additionally, the laboratory plays an important role in the training of engineers and researchers, providing a conducive environment for practical learning and seamless interaction with the industry. In this dynamic environment, collaboration between academia and the business sector drives innovation and technological advancement.

V. Conclusions

Throughout this work, we have successfully selected, installed, and tested a comprehensive 5G system. Users can seamlessly exchange data with one another and connect to external networks, enabling Internet browsing utilizing the access provided by the network.

The creation of this testbed has been driving by the goal of furnishing a versatile testing tool for research groups. It provides an environment akin to a real network, allowing these groups to test their developments effectively. Moreover, it serves as a valuable learning laboratory, facilitating hands-on exploration and understanding of 5G technologies.

We have characterized the operation of the testbed in environments such as radio frequency in air, coaxial with attenuators and in a simulated environment with RF Simulator. Although the results in terms of throughput are far from those established in theory, they serve as a framework for future studies regarding the diversity of usable hardware.

The complete project shows the potential of this system, as learning lab tool, as a development framework or as a research testbed. And shows its own capability of self-improvement through several projects like this in the next years. Finally, and on the beginning again, a rich learning process has changed us through this project and pushing to continue in this path. All configuration files and examples are available in the repository [7].

Acknowledgment

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