Bringing 4G LTE closer to students: A low-cost testbed for practical teaching and experimentation

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ABSTRACT

Cellular technologies are widely used in the ICT domain, that paving the way towards new opportunities for education and practical experimentation. It also tackles software-related engineering areas, from Digital Processing (DSP) to Software Defined Networks and Network Virtualization applications. Due to the various constraints such as limited access to hardware components, high costs of such equipment, and spectrum regulations that must not be violated, practical education in telecommunications, electrical engineering, and electronics usually lacks the opportunity to pursue experimentation on the realistic cellular deployments. Therefore, in this paper we present a network testbed that allows students to experiment with a fully functional 4G LTE system with no radio. This testbed system mimics the realistic 4G LTE deployment, supporting students towards acquiring valuable knowledge in the field of cellular networks. It is low-cost due the fact there is no need for radio components or Software Defined Radio (SDR) devices, with no limitation on frequency utilization and regulations. The testbed provides seamless scalability for education classes as it can be deployed on top of any machine with general-purpose processor, installing the whole system within two networked PCs or in a fully virtualized environment. We present the testbed framework, as well as the hands-on practices on incorporating such low-cost realistic testbed into the education within various engineering fields.

CCS CONCEPTS

• **Applied computing** → **Telecommunications**; **Interactive learning environments**;

KEYWORDS

Education, 4G LTE, 3GPP, Cellular Networks, Telecommunications

1 INTRODUCTION

Among various constraints in practical engineering education, one that highly affects the exploitation of educational testbeds is the prohibitive cost. Due to the high costs, 4G and 5G cellular networks impose significant challenges for the use of commercial facilities for education, training, and testing. Therefore in the education domain, practical experimentation related to the cellular technology is usually performed using simulation-based environments like Matlab[1] with LTE TOOLBOX [1], ns3, etc. But, low-cost testbed environments are available as Free or Open-Source Software (FOSS) projects like srsLTE [2], and OpenAirInterface™ Software Alliance [3], using Commercial Off-The-Shelf (COTS) PCs and Software Defined Radio (SDR) devices. These projects enable all interested parties outside the telecommunications industry (e.g. academia and research) to enter into this research space, and to experiment with advanced ideas, significantly accelerating innovation [4], but it also opens an opportunity to a more practical and hands-on approach for education and training like ours.

Thus, our testbed is a cost-efficient educational tool, that enables students to acquire valuable practical knowledge and skills in the field of cellular technology. Thereafter, we can use it to teach, train, and test cellular networks in a fully isolated, stable, simple, fast, and complete 4G LTE educational testbed, without radio and the need for a frequency license. As illustrated on the bottom of the Figure 1, the educational testbed is a system consisting of user equipment (UE) - a station acting as a cellular phone, an Evolved Node Base Station (eNodeB), and the Evolved Packet Core (EPC) which provides management and control. Such a complete experimentation environment enables students to test the dynamics between different 4G LTE entities (i.e., UE, eNodeB, and EPC), and to learn how each of these entities works. We emphasize that this system is not aimed to study radio properties, and it rather focuses on the system functionalities.

Miladinovic et al. [5], report that industry partners are constantly complaining about insufficient practical skills of the graduates of engineering studies. Moreover, they report that telecommunications related study programs frequently do not follow the trends that have shaped the industry, still maintains a significant number of credits from the European Credit System (ECTS) in electronic and hardware related courses. To this end, the proposed testbed significantly enriches the telecommunications' courses for bringing LTE 4G systems closer to students, filling in the gaps in their practical knowledge, and providing them with a valuable skill set for the future work in the industry.

2 RELATED WORK

Our educational testbed has features not available in the virtualized testbed for remote online telecommunications education presented by Marquez-Barja et al. [6]. The first feature is the fact that the introductory hands-on classes can be presented in laboratories with physical PCs, after it can be presented in virtualized remote testbeds or virtual machines. We consider that the introductory classes provide a more comfortable initial hands-on contact for all novice students than virtualized testbeds, especially remote ones. As a second feature, the experimentation environment illustrated

[1] https://www.mathworks.com/help/releases/R2019b/

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2020. ACM ISBN 978-x-xxxx-xxxx-x/YY/MM…$15.00
https://doi.org/10.1145/nnnnnnn.nnnnnnn

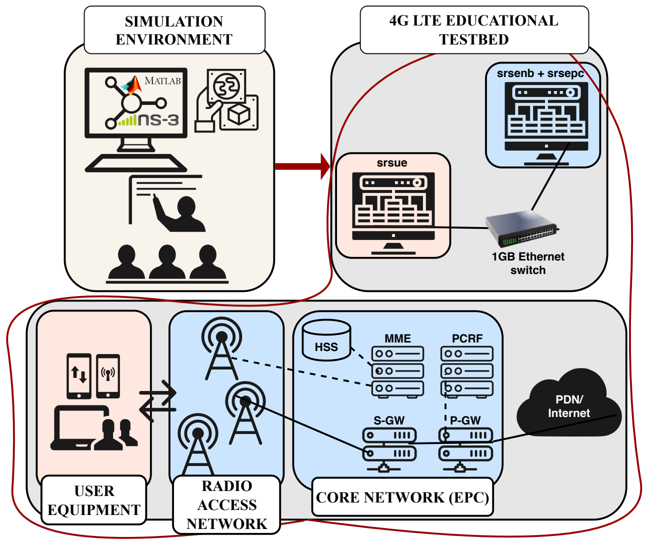

Figure 1: The LTE 4G Educational Testbed with perspective of real 4G LTE network deployment.

on the right side of the Figure 1, allows students to have their own educational testbed installed on their PCs, in the form of self-contained virtual machines. Thus, such an educational testbed is a personal "mobile" education environment, which can be used at home or any other place suitable for students to gain practical skills.

The third feature, which does not exist in remote virtualized testbeds, highlights the low-cost feature of our environment, as aforementioned, there is no need for radio or SDR devices, our testbed costs less than virtual testbeds which need energy, equipment, CAPEX and OPEX. In May 2020, depending on the deployed SDR device, each SDR can cost around $ 830 US Dollars, as in the case of one ETTUS B210mini[2] board. Another work, from Stewart et al. [7] has the goal of "teaching of DSP and communications theory, principles, and applications" deploys low-cost SDR (less than $ 20 US Dollars) added to DSP and Communications System Toolboxes (around $ 100 US Dollars), in the topic of radio signals, communication theory, and DSP. As a result of their educational-related research for modern wireless system education, González-Rodríguez et al. [8] present a low-cost SDR based testbed where the 4G LTE Physical Downlink Synchronization Channel (PDSC) and Primary Synchronization Signal (PSS) can be accessed by students. This work is suitable only for teaching radio system design as its main goal is to "build an optimized transmitter and receiver following the LTE standard guidelines". This work can be an advanced topic after our testbed usage shows students a complete 4G LTE system in action.

Another approach for students to learn by inquiry, i.e., through designing, simulating, and validating an LTE receiver is presented by Solar et al. [9]. However, this work solely tackles the LTE receiver, not focusing on the remaining LTE entities and the important dynamics that occur between them. Therefore, our educational testbed brings a plethora of benefits to practical education, by delivering the opportunity to approach hands-on practices in the field of cellular technologies. It allows students to enrich their theoretical knowledge with practical experience in working with fundamental LTE entities needed to establish an LTE connection.

3 BASIC COMPONENTS

The basic components of our 4G LTE testbed, as shown in Figure 1 are the UE, the eNodeB, and the EPC, explained as follows:

(1) UE: The user equipment acts as the 4G mobile device, it is a cellular phone, depicted in the bottom left in pink, it connects to the eNodeB using the radio channel
(2) eNodeB: The Evolved Node Base Station acts as the 4G LTE base station with its antenna, depicted at the bottom center in blue, it connects the UE to the EPC
(3) EPC: The Evolved Packet Core acts as part of a cellular operator infrastructure, depicted in the bottom right in blue, it runs in the same host together with the eNodeB in our testbed

The no-radio characteristic allows the educational testbed to explore the cooperation among the UE, eNodeB, and 4G LTE EPC entities seamlessly anywhere, with no issues on radiated power, spectrum utilization, and other radio requesting limitations. Moreover, the time and cost consuming activity of requesting a government RF license or permission is a big issue, not only for academia but especially for other types of teaching entities. The same applies to RF radiated power. Our present work focus on the cooperation among all 4G LTE entities, therefore all functionalities can be learned, tested, monitored, and tweaked.

As depicted in Figure 1, UE, eNodeB, EPC (with the functionalities MME, HSS, P-GW, and S-GW) modules, are made available as testbed applications. More technical components as the PHYSICAL, MAC, Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), Radio Resource Control (RRC), Non-Access Stratum (NAS),

[2] https://www.ettus.com/all-products/usrp-b200mini/

S1AP and Gateway (GW) layers are made available as common libraries.

4 4G LTE EDUCATIONAL TESTBED

In this section, we present more details on our 4G LTE educational testbed, carefully designed to address the gaps in students' knowledge, and their practical experience with cellular technologies. Our educational testbed is easy to scale and highly configurable as it can be deployed on the physical machines (e.g., PCs, laptops, bare metal, Raspberry Pis, etc.), but also within a virtualized environment (e.g., virtual machines, containers, etc.). As presented in the previous section, our testbed comprises three entities, i.e., UE, eNodeB, and EPC. All of these can be installed on separate machines/hosts, isolating the functionalities of different LTE entities. In Figure 2 we present the testbed setup, and as it can be seen, it comprises two COTS PCs, with srsLTE software installed, and connected to Ethernet switch via a network interface. With such setup, one machine mimics UE, with srsue application installed, while the other one hosts srsepc and srsenb applications, mimicking the eNodeB and EPC jointly.

The hardware and software configuration of particular 4G LTE entities that we implemented is shown in Table 1. To establish network connectivity between testbed entities we used network switch and Ethernet interfaces with the throughput of 1Gbit/s. Also, all machines have Linux Ubuntu 18.04 version installed, with low latency kernel.

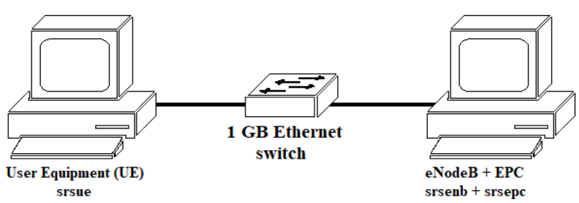

Figure 2: 4G LTE educational testbed - two networked PCs

Since our testbed is representing a 4G LTE environment for experimentation, but with no radio channel, we needed to install Zeromq as a package that mimics the Radio Frequency (RF) driver. This driver sends I/Q signals using Inter Process Communication (IPC) over a LAN. Thus, I/Q signals are representing the RF-modulated signals that are usually sent in the LTE system. In particular, Zeromq is a high-performance asynchronous messaging library, aimed at use in distributed or concurrent applications. It provides a message queue, but unlike the message-oriented middleware, a Zeromq system can run without a dedicated message broker. As shown in Figure 2, one instance of Zeromq runs at the srsue and another at the srsenb application, to establish communication between UE and base station.

All the three 4G LTE entities instances, namely the UE, eNodeB, and EPC, are started from separated Linux terminal screens. Each entity's screen displays default messages about the starting, running, and stopping operations with four levels of debugging. It is a useful feature to follow each entity's start and normal functioning.

4.1 Essential Features for 4G LTE Education

The educational testbed offers four essential features for 4G LTE education as follows: i) a debug report, ii) configuration files in the text format, iii) the C++ source code, and iv) hands-on operation as presented in the following sections. These features make it a well suited educational platform to ask many questions as exercises, enhanced with hands-on learning. The questions can be solved at the same time the students understand and change the algorithms, interactions, and configurations. The students can see screens while dynamically running the exercises, and capture the execution results/reports in a 4G LTE functional platform.

4.1.1 Debug Report: Follow Events, Troubleshoot and Learning. Students are able to observe and follow events, only based on the available debug reports, to track what happened for troubleshooting and learning. In all 4G LTE modules, associated layers, and protocols, much information can be extracted and some can be shown in real-time. Such information is available from the debug report options, listed below:

(1) Radio Frequency Layer (RF), when using radio devices
(2) Physical Layer (PHY)
(3) MAC Layer (MAC)
(4) Radio Link Control (RLC)
(5) Packet Data Convergence Protocol (PDCP)
(6) Radio Resource Control (RRC)
(7) Non-Access Stratum (NAS)
(8) GPRS Tunneling Protocol User Plane (GTPU)
(9) Gateway (Linux TUN Layer)
(10) Service and Packet Gateway (SPGW)
(11) Mobility Management Entity GTPC (MME_GTPC)
(12) S1 Interface Application Protocol (S1AP)
(13) Universal Subscriber Identity Module (USIM)

Moreover, the debug report offers four levels of logging: debug, info, warning, and error. They are useful to see and follow the events, at the same time allowing easy troubleshooting. It is a valuable tool for learning and following all 4G LTE system activities. Students can change parameter values, source code, monitor the actions, and follow the results via the debug report options.

4.1.2 Configurations Text Files. The 4G LTE testbed has some parameters and options changed just by modifying configuration text files, an easy way to see, comment, and understand approach, as in the above mentioned debug report options. It avoids the time-consuming rebuild of binary code and provides a faster way of testing and fine-tuning the intended modifications, although in some cases one or more entities must be stopped and restarted after the modification. As an example, we can turn on packet capture logging at the eNodeB just by editing a configuration file. Some configuration files available are: enb.conf (eNodeB), sib.conf (System Information Base), epc.conf (EPC), and ue.conf (UE).

4.1.3 Source Code. The availability of srsLTE C++ source code[3] in developer's social collaborative GitHub [10], shows the deployed algorithms and programming techniques. Students can follow the source code to learn how the activities are done. Exercises can address some interesting algorithms or interactions. We can change

[3]https://www.github.com/srsLTE/srsLTE

Table 1: 4G LTE entities hardware and software configuration

4G Entities	srsLTE v19.12.0 Components	Capabilities			Operating System
		RAM	CPU	Storage	
UE	srsue	8 GB	Intel Core™ i5-3330 CPU @ 3.00 GHz	500 GB	UBUNTU 18.04
eNodeB + EPC	srsenb + srsepc	8 GB	Intel Core™ i5-3330 CPU @ 3.00 GHz	500 GB	UBUNTU 18.04

virtually all functioning modules and entities, sometimes just to display some messages or values. As an example, we can study and change the 3GPP encryption algorithm deployed for security. Keeping the importance of security concerns in mind, it is important enabling students to identify the security issues in 4G LTE. Using our testbed, they can benchmark different security algorithms, and perform experimentation for the practical work of their

4.1.4 Hands-on testing of a cellular network in action. It is a time-consuming activity for students to understand a 4G LTE cellular network with its complexities based only on text, figures, and abstractions, which lacks the motivation provided by a hands-on testing approach in a real cellular network. The 4G LTE educational testbed has the distinctive feature of being able to isolate many working components and to concentrate on a topic or interesting procedure for teaching. As the testbed behaves like a real cellular network in action, the hands-on approach is a motivation factor that must be considered as one of its major educational features. This factor provides practical knowledge for students and professionals as they activate, deactivate, and modify all the 4G LTE components.

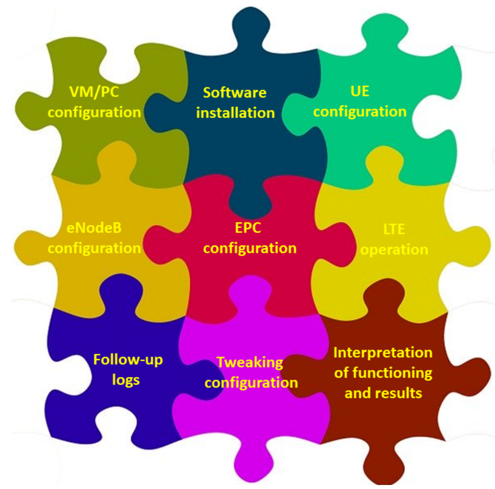

Figure 3: Teaching Modules

5 TEACHING MODULES

The ACM report "Computer Engineering Curricula 2016" [11] shows a knowledge area entitled Computer Networks - tagged as CE-NWK, divided into core knowledge units. Our educational testbed can be deployed in the "Wireless and mobile networks" (CE-NWK-5) core knowledge unit as it can provide some of the following proposed learning outcomes as shown in Table 2. We highlight the outcomes numbered 1, 2, 4, 5, 6, and 7 encompassing wireless, mobile IP, cellular networks, and typical wireless MAC protocols.

Next, we present the teaching modules that can easily make use of our practical 4G LTE testbed, as shown in Figure 3. To teach some components of the proposed educational testbed, more modules can be added or optionally excluded. As there are many possibilities for adding new modules and new topics, the present work shows only some of the examples.

5.1 VM/PC Platform configuration

The first condition to have the educational testbed is to make the platform available. A module teaches how to configure the host machines using ordinary physical COTS PCs or Virtual Machines can exist as a basic introduction to the underlying hardware, network, operating system, and application support, or to teach virtualization technologies [12]. As a topic example, we can show to configure a low-latency Linux kernel and ask students to explain why to use it.

5.2 Software installation

An exercise in the practice of srsLTE software installation can be useful as the proposed testbed doesn't deploy radio devices, but it can install SDR with its driver dependencies when needed. After understanding 4G LTE with no-radio, students can be directed to use and experiment with radio devices.

5.3 UE

The role and functioning of the mobile UE connected to a cellular network can be taught in this module, with all detailed protocol procedures from connection establishment to disconnection. UE authentication, energy-saving procedures, and configuration can be taught as examples. The Downlink channels and signals from the eNodeB to the UE are present: PSS, SSS, PBCH, PCFICH, PHICH, PDCCH, and PDSCH. The same applies to the Uplink channels and signals from the UE to the eNodeB: PRACH, PUSCH, PUCCH, and SRS. These Downlink and Uplink elements can have activities and events reported/logged, it provides a good understanding of how these signals and channels relate to each other.

An interesting feature is the capacity of "seeing" the active modulation. After the UE synchronization with the eNodeB, the constellations of the control channel (PDCCH) and the shared downlink channel (PDSCH) can be plotted on a graphic screen.

5.4 eNodeB

The eNodeB is the entity between the UE and the EPC as shown in Figure 2, some protocols layers, procedures, and parameters can be taught and modified as exercises related to UE and EPC end-to-end connections. Depending on the focused topic, as an example, the UE required TCP/IP connections establishment can be taught with student able to check the associated network interfaces, links, and acquired TCP/IP addresses.

Table 2: Official ACM/IEEE Guideline for Computer Engineering

Knowledge Area	Computer Networks (CE-NWK)
Core Knowledge Unit	Wireless and Mobile Networks (CE-NWK-5)
Learning Outcomes	
1 - Explain the source of changes in the wireless and mobile industry from the viewpoint of new service models such as the mobile ecosystem (e.g. Apple and Android ecosystems)	
2 - Describe the fundamental components that tend to be unchanged for long periods such as mobile IP, Wi-Fi, and cellular	
3 - Explain the potential issues in wireless media access such as the hidden terminal problem and the exposed terminal problems	
4 - Explain the basics of a Wi-Fi network such as protocol stack and frame structure as well as its development such as IEEE 802.11 a/b/g/n series standards	
5 - Contrast the basic concepts in cellular networks such network architecture, framework, and LTE	
6 - Describe the main characteristics of mobile IP and explain how it differs from standard IP regarding mobility management and location management; illustrate how traffic is routed using mobile IP	
7 - Describe features of typical wireless MAC protocols	

5.5 EPC

The EPC performs many functions like user data storage and retrieval, mobile management, packet filtering, routing, etc. These functionalities can be taught except for some functions like handover. After the student acquires the knowledge of this module, functionalities can be migrated to NFV, virtual containers and other technologies to be learned. Session management, UE registration and authentication, QoS features, and packet routing to external services over the Internet, are some of the available functionalities.

5.6 LTE operation

The LTE operation can be shown in an initial outlook to the students as an example of all entities in use when a UE connects, interacts with the LTE platform, and disconnects. In this case, some tests using iperf3[4] , and ping[5] tools can be done to show the performance of a particular protocol as the Stream Control Transmission Protocol (SCTP) [13].

5.7 Follow-up logs

To troubleshoot, events, and protocol interactions, follow-up logs could be an initial tool to consolidate student‘s understanding of the 4G LTE functions. The logs can be collected according to some defined parameters focusing on a specific topic like the usage of the Physical Random Access Channel showing how the UE connects to an eNodeB. Errors could be left to be located and solved by students.

5.8 Tweaking Configuration

Advanced students and researchers with a deeper knowledge of the 4G LTE environment can alter some parameters to try different responses from the cellular network. They can be some minor parameter variations just to teach how the educational testbed can have its behavior changes. In the worst case, the testbed will not work or will freeze, but the software can be restarted and continue the experimentation/education session with no further delay.

[4]https://github.com/esnet/iperf
[5]https://www.ietf.org/rfc/rfc777.txt

5.9 Interpretation of events and results

In all modules, the interpretation of events and results can be done according to the teaching goals. This module can be done by students already used to the educational testbed.

6 DISCUSSION

In this section, we discuss the available features and main benefits of our proposal for practical teaching and experimentation.

6.1 Low-cost

Being low-cost is a remarkable feature, as the educational testbed is all software configurable and can be deployed in a full virtualized environment. Our solution provides a satisfactory network response time, technically explained, the measured Round Trip Time (RTT) from the UE to the eNodeB reached 49 ms as its maximum and 39 ms mean value (using the Linux ping application), negligible network latency for hands-on learning of 4G LTE functionalities, as depicted in Figure 2. Moreover, there is no need for expensive PCs which emphasizes the low-cost feature of our testbed, no new hardware is needed. In a low-cost Intrinsic Motivation (IM) course conversion project, the authors make decisions to promote students' sense of purpose, autonomy, relatedness, and competence for learning the material [14]. Our educational testbed promotes these IM as students can have their testbed to act, with no added cost.

To illustrate the real costs of deploying a base station, and LTE environment, we refer to Nokia's paper published by the European Commission [15]. As stated in [15], the network CAPEX ranges from 40,000 to 400,000 EUR per base station site depending on the configuration. It is a high cost for evolving technology, not mentioning its maintenance costs for education purposes only.

6.2 Nomadic Hands-on Learning and Testing

The 24/7 availability feature, together with the ability to employ it in different places, provides students with the play where you want and play when you want flexibility. In our case, the testbed can be installed in a student notebook fully virtualized. This nomadic hands-on turns easier the process of learning and testing compared with fixed laboratory time and localization. As an example, a glimpse of an idea can be quickly implemented at home, school, work, or even when students are traveling. After installation, no Internet connection is required, unless in specific cases when the User Equipment requires Internet access. In these cases, the UE, like a common cellular phone, can run browsers for web navigation, run local applications that interact with cloud applications, and even run simultaneously other internet applications like email.

6.3 Experiments "inside" working entities

As the major features, our educational testbed makes students enter "inside" each working entity and experiment on the entity's configuration. Therefore, students handle application instances that behave like the components of a real cellular network in action. The cognitive process is better developed with experimentation. Experiments allow the material to govern the experimental and the target systems. This is unlike simulations, which need an abstract correspondence between the simulating and simulated system, as stated by Guala [16].

6.4 Teaching strategies

This work's main proposal is to bring 4G LTE close to students trough a low-cost testbed for teaching and experimentation, we left the teaching strategies open for the context and goals of each course. We presented some teaching modules as examples, but there are many possibilities for new modules. We understand that the presented work is a comprehensive 4G LTE testbed delivering many functionalities and topics for education, the better approach for teaching is now left for the education stakeholders.

7 CONCLUSION

We present in this paper a 4G LTE educational testbed with no radio where students can easily follow actions, events, and the functionalities like a real cellular network in action. The testbed makes available debug reports, easy to change configuration and source code, and hands-on testing of a real cellular network in action. We presented nine teaching modules to be used as examples of our testbed educational capabilities. System level functionalities are available in the testbed, with no legal limitations for licensed radio frequencies utilization, and no legal radio frequencies power limits. It is an ideal environment for learning while testing standard 4G LTE functionalities; it is low-cost without the inherent wireless impairments that can be deployed virtually anywhere and anytime.

Our educational testbed teaching modules are aligned with the Wireless and Mobile Networks core knowledge unit for Computer Engineering as the Official ACM/IEEE guidelines CE2016 [11]. Our 4G LTE educational testbed is a useful tool to deploy in undergraduate courses, but it also can be deployed in tests and research activities. Moreover, it can be deployed in many areas as the training of technicians, engineers, and other cellular network professionals. As future work, we intend to make the educational testbed image publicly available and to test the feasibility of a 5G environment with the same mechanism of Zeromq applied, aiming to have the same advantages of the 4G LTE educational testbed into 5G.

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