

Universal access to education based on Software Defined Radio (SDR): The case of Mali

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Abstract—This study presents an innovative solution to improve access to education in Mali using a private 4G/5G mobile network based on software-defined radio (SDR) technology. Faced with the persistent challenges of the Malian education system, including insecurity, recurrent strikes, and lack of infrastructure, our approach integrates cutting-edge technologies to offer a resilient and flexible alternative. The proposed architecture combines 5G Non-Standalone (NSA), SDR, and an IP Multimedia Subsystem (IMS) to create a comprehensive educational ecosystem, including an online learning platform. Our experiments demonstrate the technical feasibility of this solution, with successful 5G connectivity and educational content streaming tests. The results show that this approach can effectively extend network coverage in underserved areas and provide educational services even in challenging conditions. While challenges remain in terms of scalability and security, this research opens new perspectives to reduce the digital divide in education in developing countries facing similar obstacles.

Index Terms—e-learning, SDR, 5G, distance education, Mali, universal access, software-defined radio

I. INTRODUCTION

Mali has been facing a deep crisis in its education system for several years. The lack of teachers and educational resources, poor management of financial and human resources, overcrowded classrooms, and the inaccessibility of schools due to terrorism and the sabotage of telecommunication infrastructures are some of the problems facing the Malian education system. Even more worrying, the closure of schools by armed groups, recurrent strikes by teachers and students, result in incomplete or even wasted academic years, contributing to an alarming decline in the level of students. This situation has serious consequences on the entire education system. Pass rates in national exams are declining, a large part of the territory does not have access to education, and many students take longer than necessary to complete their basic cycle due to frequent repetitions. More than 50% of 2nd-year students and nearly 90% of 5th-year students in the basic cycle do not have the expected skills in French and mathematics [1]. Faced with these challenges, the deployment of a next-generation private mobile network, based on Software-Defined

Radio (SDR) technology, represents a unique opportunity to transform the country's educational landscape. By combining innovative technologies such as 4G/5G with flexible and cost-effective SDR solutions, it becomes possible to extend high-performance connectivity even to the most remote regions, thus offering new possibilities for distance education and access to digital educational resources. This paper explores this innovative approach in detail. Section II presents the state of the art. Section III describes the tools and technologies used. Section IV details the proposed overall architecture. Finally, the experimental results and their discussion are presented in the last section.

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II. STATE OF THE ART

Access to information in rural areas of sub-Saharan Africa is hampered by geographical and linguistic barriers, leading to proposals for using embedded 5G mobile networks and Software-Defined Radio (SDR) infrastructures to broadcast content in local languages [2]. However, 5G deployment remains primarily concentrated in urban areas, as shown by studies conducted in Indonesia and Brazil, risking an increase in the digital divide [3], [4]. Beyond economic aspects, technical challenges emerge in specific applications such as connected and automated mobility in Europe or smart grid monitoring, requiring innovative solutions in dimensioning, edge computing, and radio spectrum management [5]–[8]. To address these challenges, innovative solutions are emerging, including spectrum sharing models and long-range 5G architectures [9], [10]. SDR technology proves particularly suitable for connectivity needs in rural and remote environments [11]–[13]. In the education sector, while digital transformation has promoted the development of online learning, the adoption of these new teaching models faces obstacles, particularly in higher education institutions located in rural areas [14]. These limitations emphasize the need to develop innovative

also operate as a 5G NSA (4G-5G) base station, thus offering an integrated solution for wireless communications.

B. 5G NSA

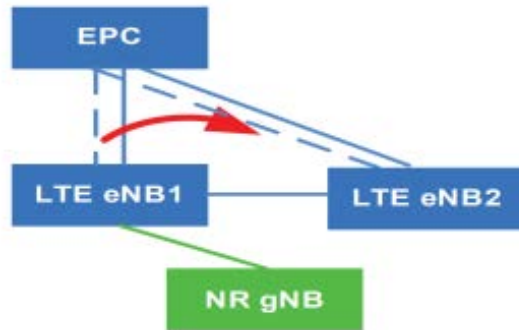


Fig. 2: 5G NSA Architecture

5G non-standalone (NSA) deployment utilizes dual connectivity, integrating 4G standard elements from Release 12. It operates through a 4G infrastructure where an eNodeB serves as the main base station, while 5G communication is handled by a secondary gNodeB station working with the 4G Evolved Packet Core (EPC) [15]. Research shows that NSA deployment enables rapid 5G service implementation at reduced costs compared to standalone solutions [16]. This approach is particularly beneficial for developing countries, as it helps bridge the digital divide while offering innovative solutions for rural areas and regions affected by terrorist activities.

C. Kamailio-based IMS Server

The Session Initiation Protocol (SIP), used to provide multimedia services such as Voice over IP (VoIP), video over IP, and instant messaging (IM), is supported by the Kamailio open-source IP telephony server [t3]. The IP Multimedia Subsystem (IMS) standard is implemented via the Kamailio-specific platform, known as Kamailio-IMS, which supports the following functionalities:

- Call Session Control Function (S-CSCF): The main role in session control within the IMS network, responsible for call routing and user profile management.
- Proxy Call Session Control Function (P-CSCF): Acts as a gateway between the IMS network and the public Internet.
- Interrogating Call Session Control Function (I-CSCF): Queries the Home Subscriber Server (HSS) to obtain user-related information.
- Home Subscriber Server (HSS): The central database of the IMS network, where user information such as phone numbers, IP addresses, and service preferences are stored.

To provide multimedia services on 4G and 5G networks, the IP Multimedia Subsystem (IMS) plays a key role. It is a central network infrastructure that interconnects various types of networks, including cellular, Wi-Fi, and fixed, to offer uniform services. IMS is used in the latest generation of mobile networks to ensure high-quality IP telephony services as well as communication session management. This allows users to make and receive video calls on their mobile devices while moving between different types of networks. Through the integration of Kamailio-IMS, it is possible to efficiently build a central IMS network and leverage voice and other multimedia services on LTE [t4].

D. Optical Fiber Network

In Mali, optical fiber deployment continues nationwide through state and private operator collaboration [17], [18]. Integration with national infrastructure is achieved using air-Fiber AF60 LR antennas, providing 1.8 Gbps links over 12 km distances [19], facilitating rural connectivity and reducing the urban-rural digital divide.

IV. GENERAL ARCHITECTURE

A. Proposed Architecture

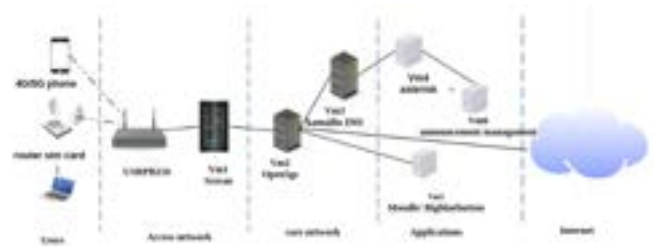


Fig. 3: Proposed architecture

The proposed architecture comprises four essential elements: end-users with SIM-equipped devices (phones, routers, dongles, tablets); an access network managing wireless communication through RF hardware and SDR software; a core network handling routing and service management with an IMS server for voice integration; and finally, an application layer including e-learning platforms and servers interconnected to the Internet for online resource access.

B. Physical Architecture

We have set up and evaluated our testbed on the premises of the École Centrale des Logiciels Libres et des Télécommunications de Dakar (EC2LT) in Senegal [https://www.ec2lt.sn]. Our configuration, illustrated in Figure 5, consists of carefully selected physical equipment. At the heart of our setup is a Dell laptop, used to execute the



Fig. 4: Test and validation system

necessary terminal commands. For the software-defined radio communications, we have integrated a USRP B210 (Universal Software Radio Peripheral) equipped with multiple antennas. The 4G connectivity is provided by a dedicated access point (AP). Finally, our configuration includes two smartphones, identified respectively as 4G and 5G user equipment (UE). The specific details of the communication process have been explained in the previous subsection, where we presented the communication diagram.

V. RESULTS AND DISCUSSION

A. Results



Fig. 5: Start of Access and Mobility Function (AMF)

Figure 5 demonstrates the successful initialization of the Access and Mobility Management Function (AMF) in logging mode, showing its capability to process Non-Access Stratum (NAS) messages between User Equipment (UE) and Core Network (CN) for data services, handover management, and network authentication.

Figure 6 illustrates the successful start-up of the User Plane Function (UPF) in logging mode to obtain more information. This figure shows the details regarding the UPF configuration file and log file, as well as the Packet Forwarding Control Protocol (PFCP) on port 8805 for the interface between the control plane and the data plane, and the GPRS Tunneling Protocol (GTP) on port 2152. Thanks to this start-up of the UPF, the interconnection between the Radio Access Network (RAN) and the Data Network (DN) is established.

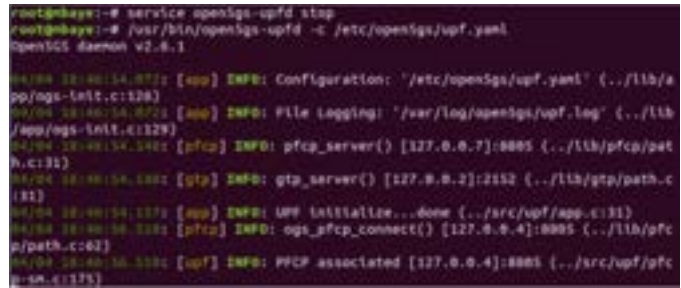


Fig. 6: Start of User Plane Function (UPF)

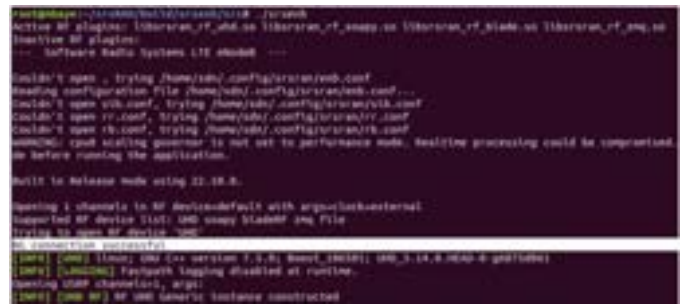


Fig. 7: Radio Frequency (RF) antenna startup

Figure 7 shows the start-up of srsran, which activates the RF plugins built in release mode with the srsRAN version 22.10.0. This figure also illustrates the opening of a channel on an RF device with default equipment and args=clock=external. The list of supported RF devices includes: UHD, soapy, bladeRF, zmq, and file.

Since the Radio Frequency (RF) equipment is connected to the 5G core network, we can now connect the mobile equipment (user equipment) after its configuration, even if the equipment is 4G, thanks to the hybrid network configuration that supports both 5G and 4G.



Fig. 8: The Web access from the 5G network

Figure 8 shows a screenshot of a smartphone connected to the private 5G network Labo RTN 5G. The user has selected this network in the operator selection settings. The image also shows that the Labo RTN 5G network is active, as indicated by the 5G icon.

Figure 9 shows the virtual classroom with students from the



Fig. 9: E-learning platform

Telecommunications and DevOps Master's program at the University of Bamako. This figure illustrates that, thanks to the connection to the 4G/5G network in the laboratory, the students can attend online courses through a Moodle e-learning platform and a BigBlueButton virtual classroom.



Fig. 10: Choosing the group and importing the audio message

As part of our development of this platform, we have designed an intuitive process illustrated in Figure 10. This process allows us to select a specific group of subscribers, for example those sharing the same level of education. We have also implemented a functionality to import pre-recorded audio messages. Once we have imported the audio message, we can initiate the call to the selected group using the Call button we have created. This approach that we have developed optimizes the efficiency of targeted communication.



Fig. 11: Call reception

Figure 11 shows the reception of a call broadcasting a study message about Professor OUYA's online course, demonstrating

successful call connection. The calls are initiated from our platform and received by phones through configured Asterisk clients, enabling efficient student information dissemination via a robust telephony infrastructure.

B. Discussion

Our study demonstrates the feasibility of a 4G/5G private mobile network using SDR technology for improving educational access in Mali. The successful integration of our e-learning platform aligns with [12]'s findings on rural online teaching solutions, while extending beyond by providing an end-to-end solution. Service continuity tests during outage simulations address network reliability concerns raised by [11], with SDR technology offering enhanced adaptability over traditional solutions. While our preliminary cost estimates suggest lower deployment costs than conventional approaches, supporting [5]'s observations on innovative 5G business models for developing countries, we acknowledge limitations. Unlike [20]'s work on spectrum sharing, we did not deeply explore regulatory implications, and our energy consumption analysis, highlighted as crucial by [10], requires further investigation. Nevertheless, our integrated approach combining 5G NSA, SDR, e-learning, and announcement management in Mali's context represents a novel contribution, demonstrating how advanced telecommunications can address educational challenges in complex environments. Future work should examine large-scale deployment, data security, and long-term economic viability to strengthen our approach's relevance for developing countries.

CONCLUSION

This study demonstrates 5G networks based on SDR technology's potential to revolutionize telecommunication access and education in complex contexts like Mali. Our integrated approach combining 5G NSA, SDR, voice messaging, and e-learning platforms provides a resilient solution to educational challenges. Experimental results validate the solution's technical feasibility in providing connectivity and educational services in underserved areas, with an architecture notable for its flexibility in vulnerable environments. While challenges persist in scalability, security, and energy optimization, this research establishes strategies for reducing the digital divide and could serve as a model for other developing countries. Future work should address large-scale evaluation, educational integration, and long-term economic viability, marking a significant advancement in applying telecommunications technology to education in challenging contexts.

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