III. International Conference on Electrical, Computer and Energy Technologies (ICECET 2023)
16-17 November 2023, Cape Town-South Africa

OpenAir Interface for 4G Core Network and 4G/5G Base Stations

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2023 International Conference on Electrical, Computer and Energy Technologies (ICECET) | 979-8-3503-2781-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICECET58911.2023.10389282

***Abstract*—With the advent of the fourth industrial revolution (4IR), 5G networks are aiming to support a broad range of network services and applications. Network operators are looking to open-source implementations to expand on the flexibility and re-programmability of networks. This paper introduces an implementation including a 4G Core Network (using the OpenAir Interface (OAI) platform), OAI 4G and 5G Base Stations, and the 4G/5G User. This paper shows the steps followed to have a complete 4G/5G mobile network using OAI. We used Wireshark software for packet visualization when the two Base Stations connect/disconnect to the CN and when the phone is attached/detached from the network. Additionally, some installation pointers, current performance statistics, and video streaming (such as measured download/upload speed and latency between various system components) are included in this paper.**

Keywords—4G, 5G, Base Station, Core Network, mobile network, User Equipment,

I. INTRODUCTION

The fifth generation (5G) mobile network is expected to offer virtually ubiquitous, ultra-high bandwidth, and low latency connectivity to individuals and connected objects. Network operators are, however, facing challenges around the deployment of key 5G network components, such as the radio access network (RAN). A RAN is a crucial component of the telecommunication network located between the core network and the users equipment that facilitates connectivity through radio [1]. 5G is the latest in the series of standards produced by the International Telecommunication Union (ITU) and the third generation partnership project (3GPP) and was released with a new air interface called New Radio (NR) along with support for a wide range of services and future applications. 5G allows partial support for other access networks, such as the fourth generation (4G) Long Term Evolution (LTE). This enables continued use of existing 4G infrastructure and maintain support for legacy access technologies while improving network performance through the NR component.

Commercial 5G network equipment has made it possible for network operators to deploy their own 5G networks, but the reliance on a small number of vendors has been met with issues around network flexibility, cost, and security. Network operators looking for more control and flexibility in their networks have started to consider and adopt the Open RAN model for network deployments. Open RAN model is a non-proprietary version of the RAN system that allows interoperation between cellular network equipment provided by different vendors.

A. Radio Access Networks

RAN is a major part of mobile networks. It connects the user equipment (UE) to the core network [2]. In the early days, mobile network deployments were based on a monolithic approach, with the RAN composed of a physically integrated baseband processing unit and radio modules [3]. At that time, a small number of base stations (BSs) were sufficient to serve data-less cellular services, such as voice calls in the first-generation mobile network system (1G) and text messages in 2G to a small number of people [2]. Network requirements have since become complex, and mobile network systems have evolved to open the cellular network to more users. This led to subsequent generations of 3GPP-based mobile network systems adopting split architecture for their radio access nodes or base stations. The split architecture is between central and distributed units that allows coordination for performance features, load management, real-time performance optimization and enables adaptation to various use cases and the quality of service that needs to be supported (i.e. gaming, voice, video), which have variable latency tolerance. RAN disaggregation was introduced in 3G network systems, where RAN was split into a Radio Network Controller (RNC) and a base station (called NodeB) [3]. By deploying multiple base stations connected to the RNC, a wider network coverage could be achieved, but the architecture made the RNC a single point of failure, whose downtime affected cells of an entire geographical region. The fourth generation (4G) mobile networks adopted a direct connection between the base stations (eNodeBs) and the 4G Evolved Packet Core (EPC) network. In 4G, eNodeBs were split into Radio Remote Heads (RRHs) or Remote Units (RUs) and Base Band Units (BBUs) and placed within site proximity. The architecture is termed Distributed RAN (D-RAN) [3]. A BBU is responsible for processing operations like radio management, resource utilization/sharing, transmission error correction, etc. The RU uses transceiver antennas for transmission and reception.

Furthermore, to maximize data transmission efficiency and coordination of resources in 5G, part of the baseband processing was moved to a central hub, which constituted a centralized RAN (C-RAN) architecture. The split RAN architecture enabled virtualization and cloud deployments for centralized network processing [3]

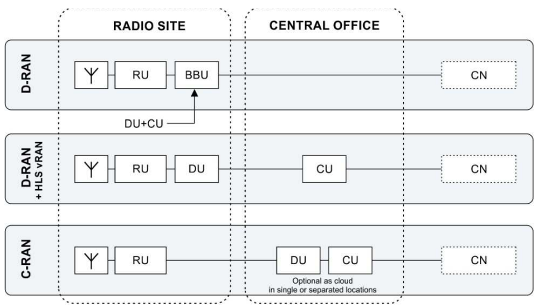

Fig. 1. Difference between D-RAN, partially cloudified D-RAN, and C-RAN [3]

In the early days, mobile network deployment was based on a monolithic approach in which baseband processing units and radio modules were placed near an antenna. These two main elements constitute which we commonly call RAN which is a principal part of mobile networks next to the core network, terminals and transport. In 4G/LTE, vendors started to deliver eNB nodes disaggregated into Radio Remote Heads (RRHs) and Baseband Units (BBUs), which are placed within close site proximity, which is commonly referred to as distributed RAN (D-RAN)-see Fig. 1.

B. *RAN softwarization and virtualization*

The monolithic and inflexible infrastructure of traditional cellular networks is limited in supporting the diverse services. Thus, more flexibility was introduced in 5G.

Industry and academia are in agreement on the adoption of new, agile, and open paradigms for network deployment, control, and management [4]. This is in part thanks to the open-source nature of programmable networks that facilitates network flexibility and makes software solutions more accessible to a broad community of researchers and developers [4]. Network operators adopting open and programmable network components do so to take advantage of their flexibility and fast reconfiguration [5], which can be owed to softwarization and virtualization.

Virtualization is the process of abstracting computing resources to enable multiple software applications to share a single hardware. Softwarization refers to the concept of running a specific functionality on a software platform instead of hardware [5]. Openness refers to reliance on the ability to use generic hardware and open standards for interfaces [6].

The success of softwarization and virtualization in cloud and edge computing, including network function virtualization (NFV), is encouraging the adoption of these technologies for 5G. Through these five concepts, networks can leverage features such as network slicing, energy efficiency, statistical multiplexing, mobile edge computing, and high-capacity handling [7]. Software Defined Networking (SDN) and NVF are enablers for cellular network softwarization and edge network deployments. 5G Network softwarization enables RAN dis-aggregation, where the RUs operate as basic transceivers, leaving all processing and control operations to be performed in software through open interfaces and Application Programming Interfaces (APIs) [4]. Some of the open-source RAN frameworks support many of these features. For our mobile network implementation, we used OpenAir Interface, srsRAN, OpenLTE, NextEPC, and LTE sidelink [5] [21] [22].

C. *RAN deployment challenges*

According to [6], there are three main challenges faced by mobile network operators when deploying network infrastructure. Firstly, the costs of deploying a RAN are high and can amount to 70% of the capital expenditure. Secondly, just three companies (Huawei, Nokia, and Ericsson) dominate the 5G RAN equipment market with a combined market share of approximately 80%. This offers them less incentive to sell equipment at low prices or drive innovation that will disrupt their market power. Thirdly, the 5G RAN sold by the suppliers has aggregated hardware and software, making them non-interchangeable.

Due to these factors, network operators often become reliant on a specific equipment supplier and are not afforded any flexibility in the deployment of network systems. Furthermore, in [8], the European Union expressed caution towards mobile network operators who rely on a single supplier for network equipment. According to the published report [8], relying on a single third-party supplier or having one supplier dominating across networks creates multiple points of failure and increases the severity of fault across the network. Following the concerns expressed by the US government, the EU also expressed concerns about the security risks posed by the reliance on foreign suppliers who have a strong link with their government and no legislative or democratic checks and balances in place. Last but not least, the radio spectrum is a limited resource that affects the ability of network operators to deploy mobile networks. According to [10], to fully enable 5G in South Africa, 80-100 MHz of spectrum in the mid-bands and 400 MHz to 1 GHz in the high bands are required. Spectrum acquisition is expensive, and it limits access for small players in the market. In March 2022, ICASA concluded a spectrum auction for 700/800/2600M/3500 MHz bands for 5G networks bands where network operators put up 14.4 billion of Rands to secure a part of the 5G spectrum [9].

D. *5G New Radio*

The International Mobile Telecommunications (IMT) for 2020 refers to the vision for future mobile networking systems, as outlined by the ITU, to promote new ICT markets, bridge the digital divide, develop new ways of communication, promote energy efficiency, and facilitate digital social spaces. IMT-2020 covers the objectives and framework guiding the development of the 5G network systems. As such, each mobile technology that satisfies IMT-2020 is labelled as 5G. 5G New Radio (5G NR) or 3GPP Release 15 [11] was the first standard for 5G with novel designs and technologies that meet ITU-R requirements under the IMT-2020 umbrella [12]. The NR is the latest in 3GPP standards, following GSM, UMTS, and LTE. It is a wireless interface between the UE (user equipment) and the gNB (base station). The first technology released in December 2017 was limited to non-standalone (NSA) NR, which uses the existing 4G LTE core network infrastructure for access and mobility. The 5G standalone (SA) architecture was introduced in June 2018 and uses an end-to-end 5G network [13] [14].

The main objective of our current research is to implement a customized 4G/5G radio access network for experimental work. This paper shares some of the learnings.

The paper is organized as follows. Section II provides an approach used to develop the testbed and highlights the contributions, Section III presents a comprehensive discussion of the results from implementation, key components descriptions, configuration steps, and system integration. Section IV provides the general architecture of the Vertical Handover Algorithm use case, and Section V concludes the paper and provides future directions.

II. TESTBED IMPLEMENTATION AND REQUIREMENTS

The following components/elements are included into the testbed:

- The OpenAir Interface 4G/5G RAN architecture to be implemented will largely depend on the OAI 4G Core Network (CN). The OAI core network (Release 13), which consists of the Evolved Packet Core (EPC), Mobility Management Entity (MME), Home Subscriber Server (HSS), Packet Data Network Gateway (P-GW), and Serving Gateway (SGW), is operated on a server within the organization associated with the organizational LAN (local area network) thus providing access to the Internet.

- The eNodeB/gNodeB BS (Base Stations) machines run Ubuntu Linux version 20.04 and use the OpenAirInterface (version 2.0) on a Dell Precision 3630 with an Intel i9-9900 8-core processor with 16 MB of cache and a 3,1 GHz clock speed. It gets connected to the Core server by gigabit Ethernet and serves as the S1 interface between the Core and eNB/gNB.

- The software defined radio (SDR: NI USRP-2944R, equivalent of Ettus X310, PCIe card, capable of operating in the frequency range of 10 to 6000 MHz with simultaneous bandwidth of 160 MHz) is connected to the eNodeB/gNodeB BSs computer servers through the MXI Express interface.

- Two Poynting OMNI-280 antennas—one for transmission and the other for reception—are mounted to the USRP-2944R.
- The user equipment (UE) is represented by a dual connection Huawei P40 Pro ELS-NX9 with a SIM card that has been carefully customized.

The system is divided into subsystems individually developed or configured to meet the system requirements [15] [19]. The subsystems identified are:

- Open-source RAN software (OAI),
- Network transport,
- Host machines, and
- User equipment.

Each sub-system has a role to play in satisfying user and network requirements, making it a 5G system that supports key ITU requirements. According to 3GPP standards, some of the key performance metrics include the utilisation of radio resources, throughput, and packet delay [14]. This work will also focus on the network performance to the physical layer, of which throughput is a key performance indicator. The objectives of this paper are thus:

- Satisfaction of user requirements.
- Network throughput performance.
- Satisfaction of 3GPP standards.

At the physical layer, hardware capabilities and settings, as well as software and processor constraints are considered. This paper considers the physical implementation of an OAI 4G/5G RAN. As such, according to [16], performance analysis should focus on the physical layer to gain insight into system improvement analysis. Most studies on open-source cellular network implementations focus on the throughput performance of a system without considering or going into detail about how each physical configuration affects the system as a whole. Similarly to [16], for a successful implementation, parameters that will be considered (those that have an effect on the system at the physical layer) include resource utilization in time and frequency, modulation and coding scheme, and transmission and receive gains at the RF front end. These parameters can be explored in practical tests. The integration of the OAI 4G/5G RAN with an OAI core network is a significant objective of this work, but one that depends on the successful implementation of the OAI 4G/5G RAN and considerations of its service requirements. The integration part includes sub-system integration and interfacing with the core network.

A. Design Overview

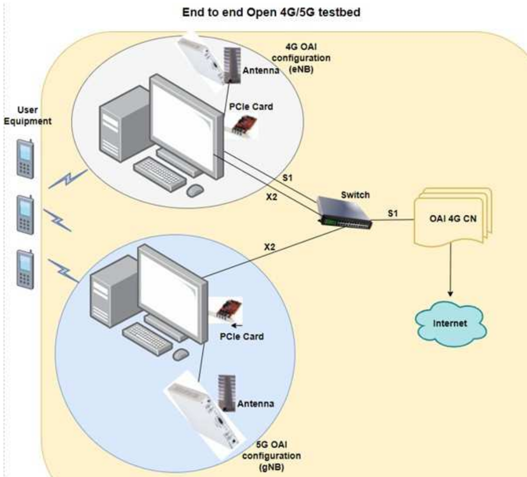

Fig. 2. High-Level system design

Our non-standalone architecture is shown in Fig. 2, with associated interfaces between nodes. The eNB/eNodeB and gNB/gNodeB are the master and secondary nodes, respectively. It may be noted that eNB and gNB may sometimes be referred to as eNodeB and gNodeB, respectively. Hereinafter, these terms associate with 4G/5G OAI base stations. The UE establishes dual connectivity by connecting to the master and secondary nodes at the same time.

The master node, which in this case is the eNB, has control and data plane connections with the core network through the S1-MME and the S1-U, respectively. From the core network, the S1-U interface transports user plane data and can be terminated at the eNB or the gNB. The OAI 4G CN is incompatible with the New Radio (NR) protocol; therefore, the control plane S1-MME only terminates at the eNB node. The two base stations are connected by the X2 interface, which is responsible for mobility and flow control for split bearer in an NSA operation. The UE sends control and user plane data over the air through radio connectivity.

III. SETUP AND PERFORMANCE RESULTS

The setup was done at the CSIR Lab and depicted in Fig. 3,. There, the eNodeB host machine (on the left) and the gNodeB host machine (on the right) are shown together with the 5G-capable smart phone Huawei P40 Pro (model ELS-NX9) used for 5G connectivity tests. The following steps were followed to have a complete 4G/5G mobile network testbed.

Fig. 3. Indoor system setup

Firstly, one server hosting the core network was implemented by installing the required packages and drivers on Ubuntu Linux 20.04. The server was connected to the Wide Area Network (WAN) to distribute network packets to the two base stations for the UE to have access to the Internet, as shown in Fig. 3. Below are the steps followed.

1. **Machine 1** with the OAI 4G CN code was cloned directly on the latest release tag.

- git clone –branch v1.2.0
- cd openair-epc-fed
- git checkout -f v1.2.0
- ./scripts/syncComponents.sh

The last part of implementing the OAI 4G CN was to **build** four major components, which are the Home Subscriber Server (HSS), Control Plane of the Packet Data Network Gateway (SPGW-C), User Plane of the Packet Data Network Gateway (SPGW-U), and Mobility Management Entity (MME). The building part of these components was not covered in this paper, because building them is a separate process. The Mobile Country Code (MCC), Tracking Area Code (TAC), and Mobile Network Code (MNC) were also configured to accommodate the configuration illustrated in Fig. 5. Although the installation of the core network was a success, some challenges were faced in the process. In the process of installing OAI 4G CN, the core network could not start when some commands were executed. The error was caused by the wrong formatting in the mme part of the core network. By fixing the format of the mme using Visual Studio (VS) code, the core network was successfully implemented, and the core started successfully.

Secondly, it was necessary to prepare a second Ubuntu Linux 20.04 server to run a master base station (eNB). The eNB in this setup was prepared to allow a 4G/5G UE toconnect after the eNB establishes a connection to the CN.The steps followed for this environment were:

2. **Machine 2** clones the OAI git repository into a desired folder. For this project, the code is cloned into the home directory.

- cd /
- git clone the oai/openairinterface5g.git.
- cd openairinterface5g.
- Checkout develop branch. The 5G Release 15 codeis being maintained in the OAI develop branch.
- git checkout develop.
- **OAI Build** source OAI environment variables.
- cd openairinterface5g source oaienv.
- Build the lte-softmodem and PHY simulators.
- Build the eNb, gNB, -I -w SIMU.
- --I installs the required software libraries for OAI.

- --w SIMU installs an RF board simulator.
- –eNB and –gNB builds libraries for LTE and NR, respectively. The lte-softmodem and nr-softmodem executables will be created and saved in /home/openairin- terface5g/cmake targets/ranbuild/build/

After the source files, a single build command was used by calling the build script. This process gets the binaries supporting all the OAI softmodem use cases (UE, eNodeB, and gNodeB). Any OAI softmodem executable can be built separately, depending on the OAI usage. After completion of the build, the binaries were available in the cmake targets/ranbuild/build directory, as shown in Fig. 4 below. They appear in green.

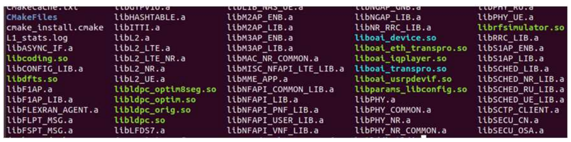

Fig. 4. Binaries processed after running the build commands.

3. **For configuration** to make OAI RAN work, the configuration files were adapted to the OAI 4G CN used. The main parameters configured in the eNB/gNB config files are Mobile Country Code (MCC), Tracking Area Code (TAC), and Mobile Network Code (MNC). The values used for these parameters are shown in Fig. 5 TAC = 1, MCC = 809 and MNC = 90. Physical parameters such as maximum gains, physical resource blocks, band frequencies, and a number of antennas were configured. The Mobility Management Entity (MME) parameters were also configured.

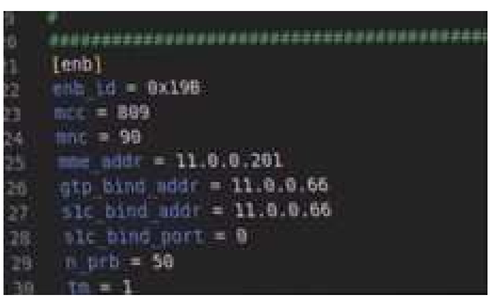

Fig. 5. Main parameters that were configured in the eNB script file using Visual Studio Code

Thirdly, to prepare another Ubuntu Linux 20.04 server to host the second base station (gNB), which acts as a slave to this mobile network testbed. This server was implemented in preparation for the vertical handover algorithm in OAI.

4. **Machine 3** steps followed in Machine 2 were used by cloning the OAI git repository, checkout the develop branch then running the build commands.

Fourthly, A programmable Subscriber Identity Module (SIM card) from sysmocom (a sample is shown in Fig. 6) was programmed and inserted into the Huawei P40 Pro ELS-NX9 phone as shown in Fig. 7.

Fig. 6. SysmoUSIM SJS1, which was used for the 4G/5G network.

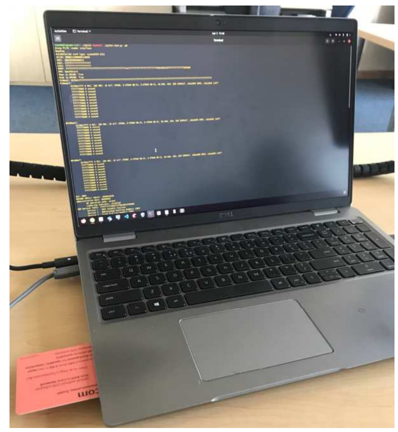

Fig. 7. Shows the setup when the SIM card was inserted into a Dell Latitute5521 laptop.

The SIM card was programmed using a Dell Latitude 5521 laptop running Ubuntu Linux 20.04. The SIM card programmed using the pySIM software, which is the application used for programming SIM cards. There was no limitation in using this software since there are software tools that can be used to program the SIM card, such as sysmo-usim-tool.

The procedures followed to program, attach, and set Access Point Name (APN) on the UE are:

- Ensure that the SIM card is inserted into the UE.
- Ensure that mobile data is enabled.
- The APN name can be changed to internet/oai.ipv4.

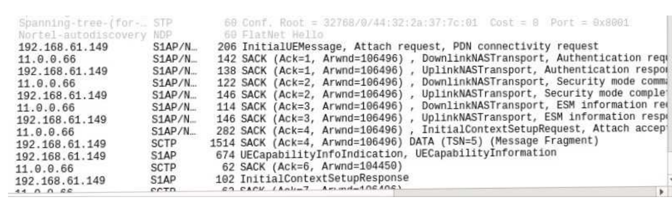

Fig. 8. Samples from the Wireshark simulator when the OAI 4G CN, eNB, and UE were communicating.

After the above steps, the carrier information was enabled to search for our network. The network visibility for the testbed was 80990. It was selected, and we were able to connect to the network. Fig. 8 shows packets from the Wireshark tool telling about the communication from the three devices. OAI RAN and the UE are providing a live packet. Following is an explanation of Internet Protocol (IP) addresses: The OAI core IP is 192.168.61.149, and the OAI RAN address is 11.0.0.66, and UE capability information is the message when the UE was accepted by the OAI RAN and OAI Core. When the UE was successfully attached to the network and the communication could be observed, the following were probed: the ability to browse the Internet and the YouTube website playing a high-quality video as depicted in Fig. 9. The network performance test was also done by enabling Wi-Fi Access Point on the Huawei P40 Pro ELS-NX9 to connect a Getac laptop to the network. The Getac laptop had TeamViewer, Zoom, and Microsoft Teams applications installed for joining meetings, as depicted in Fig. 10.

Fig. 9. Live streaming a Soccer World Cup match between Spain and Portugal, on UE

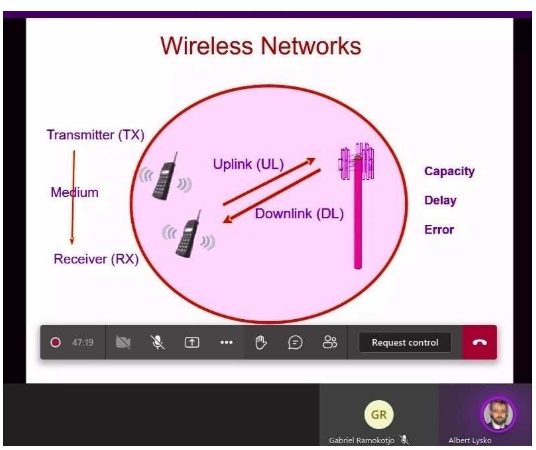

Fig. 10. Print screen of a random slide that was taken when the Getac laptop was connected to the Huawei P40 Pro ELS-NX9 phone.

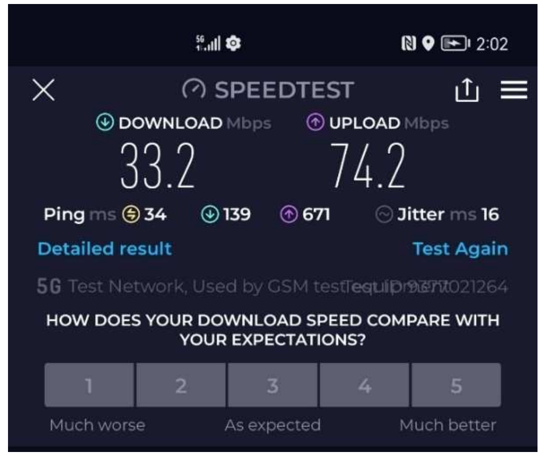

Fig. 11. A section of a print screen from a Huawei P40 Pro ELS-NX9 phone demonstrates the functionality of the connection on our 4G/5G network and the ability to use the Speedtest application.

TABLE II. RESULT ANALYSIS OF MEASURED DATA

Strategy testing	Measured throughput, (DL | UP) and standard deviation, Mbps	Measured ping delay, ms
Speedtest on a commercial network	45.1 | 29.7 ±2.6	20.5 ±0.8
Speedtest on a 5G OAI UE	31.32 | 25.98 ±1.3	27 ±6.5

These are the notations: The "UE" represents user equipment (a smartphone); "UL" means uplink from UE, and "DL" means downlink to UE. The UE app was utilized for the speedtest. In relation to the eNB/gNB antenna, they were repeated for a number of distinct UE positions around the space. We took five additional speed readings at each location to estimate means and standard deviations.

IV. BUILDUP TOWARDS VERTICAL HANDOVER FOR RPAS UE WITH TVWS

There are two types of handovers, vertical and horizontal [17]. Horizontal handover occurs when a device moves within one type of network technology under one operator. For example, a mobile phone user that moves within their provider's network must switch cellular towers as they move into and out of the range of different towers. Vertical Handover (VH) is defined as the exchange of connections between different access points with switching to another network, which can be in Television White Space (TVWS) Wi-Fi, 4G LTE, or 5G. Television white spaces (TVWS) refers to vacant channels in the ultra-high frequency (UHF) band between 470 and 694 MHz assigned for television broadcast and TVWS can be used opportunistically for secondary users (SUs) [18]. Remote Piloted Aircraft Systems (RPAS) can be used as a use case for VH, where we can have a CN, 4G/5G mini base stations, and a Television White Space (TVWS) base station, which will be located on the ground. As illustrated in Fig. 12, the RPAS will be attached to a 4G/5G module to communicate with three base stations on the ground from different technologies. The idea is that it will move and hover over and between different base stations to validate the Vertical Handover Algorithm (VHA).

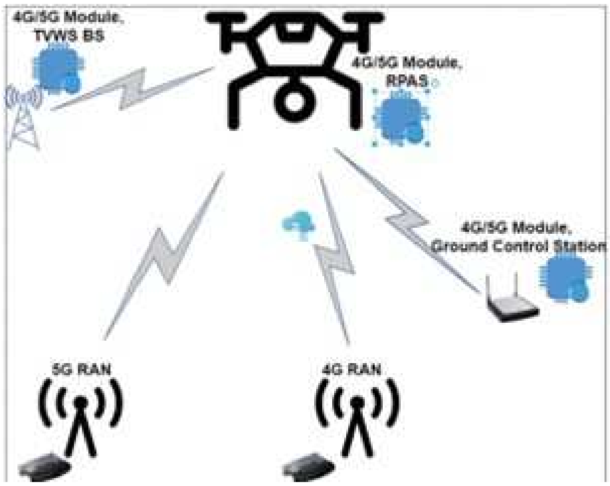

Fig. 12. Architecture of the Vertical Handover Algorithm using Remote Piloted Aircraft System as a use case.

V. SUMMARY AND FUTURE WORK

The paper details the setup and tips for solving several practical challenges. We used mainly the OAI 4G/5G RAN and a Huawei P40 Pro ELS-NX9 5G user terminal and a Getac laptop. After fixing several problems, successful Internet connection and usage of online applications such as Microsoft Teams, TeamViewer, Zoom and Latex Overleaf were achieved. Future work will use this testbed to develop a Vertical Handover Algorithm and the application of Remote Piloted Aircraft Systems as a use case.

ACKNOWLEDGMENT

The authors acknowledge the Council for Scientific and Industrial Research in the Next Generation Enterprises and Institution Cluster and the Tshwane University of Technology in the Department of Electrical Engineering for financial, material, and laboratory facilities support in this research work.

REFERENCES

[1] J.-C. Plantin, "The geopolitical hijacking of open networking: the case of open RAN," European *Journal of Communication*, vol. 36, no. 4, pp. 404–417, 2021. [Online]. Available: https://doi.org/10.1177/02673231211028375

[2] S. Singh, R. Singh, and B. Kumbhani, "The evolution of radio access network towards open-ran: Challenges and opportunities," 04 2020, pp. 1–6.

[3] D. Wypio´r, M. Klinkowski, and I. Michalski, "Open ran—radio access network evolution, benefits and market trends," *Applied Sciences*, vol. 12, pp. 1–18, 01 2022.

[4] L. Bonati, M. Polese, S. d'oro, S. Basagni, and T. Melodia, "Open, programmable, and virtualized 5G networks: State-of-the-art and the road ahead," Computer Networks, vol. 182, p. 107516, 08 2020.

[5] S. Iqbal and J. M. Hamamreh, "A comprehensive tutorial on how to practically build and deploy 5G networks using open-source software and general-purpose, off-the-shelf hardware," vol. 2, 12 2021.

[6] J.-C. Plantin, "The geopolitical hijacking of open networking: the case of open ran," European *Journal of Communication*, vol. 36, no. 4, pp. 404–417, 2021. [Online]. Available: https://doi.org/10.1177/02673231211028375

[7] D. Pliatsios, P. Sarigiannidis, S. Goudos, and G. Karagiannidis, "Realizing 5G vision through cloud ran: technologies, challenges, and trends," *EURASIP Journal on Wireless Communications and Networking*, vol. 2018, 05 2018.

[8] M. Rogalski, "Security assessment of suppliers of telecommunications infrastructure for the provision of services in 5g technology," *Computer Law Security Review*, vol. 41, p. 105556,2021.[Online].Available:https://www.sciencedirect.com/science/article/pii/S0267364921000297

[9] ICASA, "https://www.icasa.org.za /news/2022/icasa-concludes-successful-spectrum-auction-and-collects-more-than-r14-4-billion-proceeds," vol. 2023, 01 2023

[10] P. Lin, J. Hou, and X. Xu, "Research on 5g sa mobility management," in *2021 International Wireless Communications and Mobile Computing (IWCMC)*, 2021, pp. 503–507.

[11] M. Vilakazi, C. R. Burger, L. Mboweni, L. Mamushiane, and A. A. Lysko, "Evaluating an evolving OAI Testbed: Overview of options, building tips, and current performance," in *2021 7th International Conference on Advanced Computing and Communication Systems (ICACCS)*, vol. 1, 2021, pp. 818–827.

[12] ITUR,"https://www.itu.int/en/itud/regionalpresence/europe/pages/centresofe cellence/2022/centersofexcellence2022.

[13] B. Bertenyi, S. Nagata, H. Kooropaty, X. Zhou, W. Chen, Y. Kim, X. Dai, and X. Xu, "5G NR radio interface," *Journal of ICT Standardization*, vol. 6, pp. 31–58, 01 2018.

[14] 3GPP, "https://www.google.com/search?q=tsgr.+ts+138+300+-+v16.3.0+-+5g 3b+nr..69i57.784j0j4sourceid=chromeie=utf-8," vol. 2023, 02 2020.

[15] G. Dludla, M. Vilakazi, C. R. Burger, A. A. Lysko, L. Ngcama, L. Mboweni, M. Masonta, H. Kobo, and L. Mamushiane, "Testing performance for several use cases with an indoor OpenAirInterface USRP-based base station," in *2022 5th International Conference on Multimedia, Signal Processing and Communication Technologies (IMPACT)*, 2022, pp. 1–5.

[16] S. B. Sai Shruthi Nakkina and C. R. Murthy, "performance benchmarking of the 5G NR PHY on the OAI codebase and USRP hardware, 25th international itg workshop on smart antennas, eurecom, french riviera, France, Nov. 2021." vol. 2023, 11 2021.

[17] J. Santhi and K. Prabha, "Qos aware vertical handover process in heterogeneous wireless network," Measurement: Sensors, vol. 26,p.100710,2023.[Online].Available:https://www.sciencedirect.com/science/article/pii/S2665917423000466

[18] M. Masonta, L. Kola, A. Lysko, L. Pieterse, and M. Velempini, "Network performance analysis of the limpopo tv white space (tvws) trial network," 09 2021.

[19] F. Kaltenberger, A. P. Silva, A. Gosain, L. Wang, and T. T. Nguyen. Openairinterface: Democratizing innovation in the 5g era. Computer Networks, 176, 7 2020.

[20] Software Radio Systems/srsLTE. [Online] https://www.srslte.com. Last accessed 16 November 2020.

[21] I. Gomez-Miguelez et al., "srsLTE: an open-source platform for LTE evolution and experimentation," WiNTECH '16: Proc. of the Tenth ACM International Workshop on Wireless Network Testbeds, Experimental Evaluation, and Characterization, October 2016,pp.25– 32. [Online] https://doi.org/10.1145/2980159.2980163