Evaluation of Open-Source Mobile Network Software Stacks: A Guide to Low-cost Deployment of 5G Testbeds

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***Abstract*—Wireless mobile networks are evolving towards supporting ubiquitous data exchange between interconnected systems and humans. Such interconnections will accelerate digital transformation in service sectors, e.g., healthcare, education, transport, and industrial automation. However, each service sector demands a diverse set of network performance requirements that must be met to achieve the optimal quality of service. Hence, network testbeds are necessary to evaluate the performance of target applications before their field implementations. Traditionally, network deployments relied on proprietary and vendor-specific hardware and software. As a result, network deployment was expensive and rigid. This paper presents a guide to configuring, deploying, operating, and evaluating open-source-based 4G and 5G mobile network testbeds. This design overcomes proprietary restrictions and achieves fast, cheaper, flexible, and permissionless private network deployment. Quality of service parameters, such as latency, throughput, and received signal strength, were evaluated against the theoretical specifications for 4G and 5G. Furthermore, comparative evaluations were done between the performance of the network testbeds and a commercial network, i.e., MTN South Africa. Evaluation results show that it is easy and cheaper to configure and operate open-source-based 4G and 5G network testbeds that meet the theoretical specifications and enable performance evaluation for test applications before their real-world implementation.**

***Index Terms*—Testbed, 4G, 5G NSA, 5G SA, Open-source, Software Defined Radio**

I. Introduction

The Third Generation Partnership Project (3GPP), the global telecommunications standards body, specifies that the fifth generation (5G) of mobile networks will bring a paradigm shift in mission-critical and non-mission-critical service delivery applications [1]. This is because 5G brings the new radio (NR) technology that supports ultra-high data rates, ultra-low latency, and massive interconnections of smart devices [2]. For instance, smart cities, telemedicine, and smart agriculture are among the expected key application areas of 5G in Africa. It is necessary to test and validate the performance of these applications on test networks before they can be implemented on commercial networks. Unfortunately, there is limited work on the realization of mobile network testbeds in Africa to accelerate the testing and deployment of the 5G use cases and applications [3]. Therefore, the development of the 4G/5G testbed presented in this paper forms among the first Africa-based 5G-enabled testbed for evaluation and validation of digital health and telemedicine solutions at the University of Cape Town, South Africa.

5G can be deployed in standalone (SA) or non-standalone (NSA) models [4]. While the SA architecture entails end-to-end 5G services and infrastructure, i.e., NR access and 5G core network, the 5G NSA leverages the existing 4G network infrastructure at the radio access and core network. Consequently, 5G NSA offers a cost-effective 5G deployment option for mobile network operators (MNOs). However, the full capabilities of 5G, e.g., ultra-low latency, ultra-high data rates, ultra-high reliability, and availability, are realized over the 5G SA model. Despite the desirable QoS metrics delivered by 5G SA, the commercial rollout of 5G, especially in low-income and developing countries, is slow. This is due to the expensive costs of acquiring proprietary vendor equipment and network software. Furthermore, the high cost of 5G capable user equipment limits the customer base, making it challenging for MNOs to invest in the 5G network infrastructure when the return on investment is not justifiable.

Network vendor-specific and proprietary infrastructures are expensive, rigid, and limit the flexibility to customize a network per use-case requirements [5]. However, the possibilities brought by the softwarization and virtualization of network functions, open-source network stacks, and the availability of commercial-off-the-shelf (COTS) equipment have changed the dynamics of building a private mobile network. As a result, researchers can easily and cheaply configure, customize, deploy, and experiment with 4G and 5G private mobile network testbeds using open-source software and COTS radio equipment [4].

Therefore, the 4G and 5G network testbeds presented in this paper adopt a COTS indoor 4G base station (eNodeB), software-defined radio (SDR) kit, and open-source core network and radio access software stacks such as srsRAN, open5GS, and Open Air Interface (OAI). Overall, this paper investigates and addresses the following research questions;

- How can private 4G and 5G networks be deployed flexibly and cost-effectively?
- How does the performance of open-source-based 4G and 5G network testbeds compare with theoretical specifications and commercial networks?

The rest of the paper is organized as follows; Section II outlines some of the related work in building mobile network testbeds. Section III describes the hardware and software prerequisites for the testbed deployment. Section IV presents the 4G testbed, while Section V and section VI present the 5G NSA and the 5G SA testbed implementation, respectively. Section VII discusses the metrics, results achieved, and the respective comparative evaluations. Finally, the conclusion follows in section VIII.

II. Related Works

Open-source frameworks and COTS equipment to build radio access networks (RAN) and the core network (CN) have made it easy and cheaper to configure, deploy and experiment with private mobile network testbeds. However, Africa seems to lag in developing modern network testbeds, as the most prominent 5G and beyond testbeds worldwide are in Europe and Asia.

Such testbeds include the 5GIC, Ericsson's 5G Testbed, 5TONIC, Mosaic5G, FOKUS Fraunhofer, 5GIIK, NITOS, 5G Test Network (5GTN) in Oolu university, and SK Telecom 5G Playground. For instance, the 5GIC testbed supports diverse application testing by researchers and organizations, encompassing 5G service domains, i.e., enhanced mobile broadband (eMBB), ultra-reliable low latency communications (uRLLC), massive machine type communications (mMTC/mIoT), and vehicle-to-everything (V2X) applications. Further details on the implementation status of these major testbeds, including descriptions of their deployment and comparative performance, have been reviewed in [3].

Adopting open-source software stacks enables network flexibility and customisation of the network performance. The publication in [6] from the University of Washington, USA, present the development and deployment of enhanced OpenAirInterface[1] Enhanced Packet Core (EPC) to create a community LTE network (CoLTE). The CoLTE realizes a lightweight LTE network that offers community cellular networking services to its subscribers. The deployment of CoLTE is that EPC and the eNodeBs are decentralized and co-located in the field, unlike the popular centralized CN deployment in commercial networks. Furthermore, the design of CoLTE is improved compared to the traditional 4G networks in that function separation was done by isolating the network management system and tools for policy enforcement. Such flexible design and implementation enable the tailoring of the network to meet specific use-case requirements, unlike commercial network deployments, which are generic.

[1]https://openairinterface.org/

The shift from traditional hardware-based, vendor-specific network equipment to software-based and reconfigurable deployments has been made possible with software-defined radios (SDRs). SDRs implement radio signal processing in software, supports reconfigurability, and reprogramming. Hence, one SDR can be programmed to serve as an eNodeB and/or a 5G base station (gNB). This capability significantly cuts the costs of realizing network functions. Jussif et al. in [7] presented a 5G NSA testbed to evaluate voice-over-internet protocol (VoIP) services and internet connection. Their RAN setup comprised two user equipment (UEs) and Universal Software Radio Peripheral (USRP) B210 SDR model implementing the eNodeB and gNB. The CN was realized using the Open5GS[2], an open-source CN framework for 4G and 5G, running on a Linux-based host computer. Their evaluation investigated parameters such as jitter, throughput, and round trip time (RTT) between the UEs making a VoIP call 1 meter away from each other. However, their evaluation results were far from the 5G specifications of ultra-low latency and ultra-high throughput, as an average RTT of 150 ms and an approximate throughput of 375 Kbps were achieved.

Joaquim et al. in [8] presented an in-depth study of the open-source 5G CN software stacks available or under development to guide the selection process of the most suitable CN for network testbeds deployments. Their comparison evaluated three frameworks, i.e., Magma[3], Open5GS, and Free5GC[4]. Among the considerations is the stage of the current development roadmap, provided coverage, community support, ease of configuration, and deployment hardware requirements. The authors chose Magma due to the features offered, including an orchestrator that collects, processes, and stores network performance parameters. Furthermore, their choice was motivated by community engagement in the magma development and the good documentation offered for support. However, this work opts for Open5GS, a C-language open-source implementation for 5G Core and 4G EPC, due to its easy-to-deploy, lightweight nature and maturity in development, with the current update being the Release-16 of 5G.

The experimental setup presented in [9] from Eurecom, France, implements a 5G NSA whereby the RAN comprises an OAI eNodeB and a gNB running on general-purpose x86 servers and USRP SDR N310 software-defined radios. OAI 4G core network, the EPC, was used to realize the CN. All the CN functions were implemented as docker containers. Such isolation and optimization of CN functions are possible with function virtualization and softwarization. While this setup demonstrates the improved 5G NSA signalling, cell addition, user registration and traffic handling, compared to 4G, the analysis of end-to-end network performance and possible use cases was not fully considered.

[2]https://github.com/open5gs

[3]https://magmacore.org/

[4]https://www.free5gc.org/

Therefore, this work addresses some of the identified gaps through;

- Implementing among the first 5G-enabled university-based mobile network testbed in Africa
- Adopting lightweight open-source EPC and 5G CN for flexible and cheaper network deployment
- Using high-performance, re-configurable COTs SDR with 2x2 multiple-input-multiple-output (MIMO) capability for high data rates support and re-programmability
- Configuring, deploying, and operating the 4G and 5G mobile network testbed while evaluating the end-to-end KPI metrics such as throughput, end-to-end (e2e) latency, and the received signal strength (RSSI). The end-to-end network deployment supports real-world evaluation and validation of test applications
- Presenting comparative QoS results of the 4G and 5G testbed realized over different software stacks, i.e., srsRAN, Open5G, and OAI.

III. Prerequisites for the Testbed Implementation

A. *The eNodeB COTS Equipment*

Baicells^{TM} Neutrino 224[5] eNodeB, operating at band 40, with a channel bandwidth of 20 MHz, and a downlink absolute radio frequency channel number (EARFCN) of 38750 MHz was used. The configurations and management for the eNodeB, including defining the CN IP address for mobility management and connection, the public land mobile number (PLMN), and the Tracking Area code (TAC), operation mode (Time division duplex or Frequency division duplex) were done on a graphical user interface (GUI) accessed over an admin portal accessed at *http://192.168.150.1*.

B. *Software Defined Radio (SDR)*

An SDR implements flexible and re-configurable radio frequency signal processing based on programmable software which relies on digital signal processors and field programmable gate arrays (FPGAs). The USRP X300 2944 and the B210 SDRs developed by Ettus Research were used to realize the testbed eNodeB and gNB. The X300 implements 2x2 MIMO capability and enables the realization of increased network bandwidth over frequencies between 10 MHz and 6 GHz. This capability enables the achievement of higher capacity for multiple users simultaneously. Similarly, the B210 model offers an integrated radio platform supporting frequencies between 70 MHz and 6 GHz, with full duplex MIMO and up to 56 MHz of real-time bandwidth. The SDRs were operated from Ubuntu 18.04 computers with a low-latency kernel over an open-source Linux-based USRP hardware driver (UHD), which enables the exchange of control signals between the computer and SDRs.

1) Setup of the UHD: Figure 1 shows the connection between the SDR and the host computer over the peripheral component interconnect express (PCIe) board
Firstly, UHD was installed by executing the command;

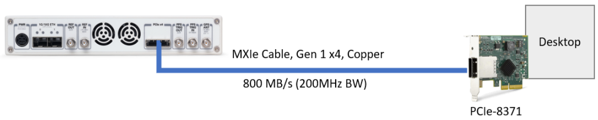


Figure 1: SDR-Host computer PCIe connection [10]

```
sudo apt install libuhd-dev libuhd003 uhd-host &&  sudo apt-get -y install uhd-host
```

Secondly, the FPGA image packages that enable the programmability of the SDR were downloaded by executing the UHD images downloader, i.e., `sudo uhd_images_downloader.py`. Thirdly, the drivers that enable interfacing of the USRP to the host computer were configured as described in the NI Linux drivers installation guide.

C. *Subscriber Identity Module (SIM) Provisioning*

SIM cards contain unique details to identify subscribers of a network. These details include the international mobile subscriber identity (IMSI), mobile country code (MCC) identifying a specific geographic region, and mobile network code (MNC) identifying the network operator. The combination of MCC and MNC forms the PLMN identifier. The sysmoISIM-SJA2, i.e., programmable Java SIM cards developed by the Osmocom project[6] for user authentication in private 2G, 3G, 4G, and 5G networks, were used. These SIM cards come with pre-provisioned subscriber details. However, to use different details from the pre-provisioned, SIM card reprogramming must be done using a card programmer supported by the *pcsc-lite*[7] software stack on Linux and Pysim[8]. For instance, SIM reprogramming was done to change the pre-provisioned PLMN of 90170 to 00101, which is recommended for testing in private networks.

D. *User Equipment (UE)*

A UE is used by the network subscribers to access services the mobile network offers. It can be a smartphone, laptop, tablet, or other device equipped with a mobile broadband adapter. The programmed SIM cards were used on the Samsung Galaxy A22 5G, Huawei P40 lite 5G, 4G/5G Waveshare Industrial router[9] and Waveshare 5G Pi Hat[10] equipped with SIM8200EA-M2 SIM card module. The Key Performance Indicators (KPI) metrics being throughput, latency, and RSSI, were monitored and measured.

E. *Software Radio System (SRS) Suite*

SrsRAN[11] comprises an open-source 4G and 5G software radio suite, including emulated 4G and 5G compatible UEs (srsue), a lightweight 4G CN (Evolved Packet core (EPC))

[5] https://na.baicells.com

[6] https://osmocom.org/
[7] https://tech.springcard.com/guides/pcsc-unix-with-pcsclite/
[8] https://github.com/osmocom/pysim
[9] https://www.waveshare.com/sim8200ea-m2-5g-router.htm
[10] https://www.waveshare.com/sim8200ea-m2-5g-hat.htm
[11] https://github.com/srsran/srsRAN

(srsepc), and eNodeB (srsenb) and gNB (srsgnb) for COTS SDR. srsRAN was installed as per the online installation guide.

F. *OpenAirInterface (OAI) RAN project*

OAI[12] implements both the RAN and the CN software stacks deployed and run from two different computers. Tutorials and instructions on installing and running the OAI CN and RAN components are provided in OAI guide. Furthermore, build and running instructions outlined in IV-C andV-B were referred to in the testbed implementation.

IV. 4G Testbed Implementation

Figure 2 shows the 4G end-to-end network architecture. Three deployment scenarios of the 4G testbed were carried out with the following eNodeB and EPC implementations, 1) with Baicells eNodeB and srsEPC, 2) SDR and srsEPC, and 3) with SDR and OAI EPC.

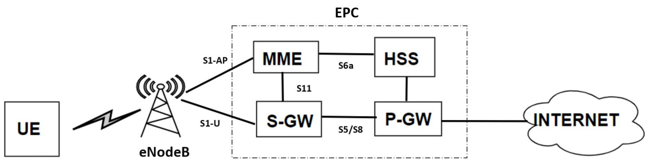


Figure 2: End-to-end 4G Network

A. *4G Network Testbed With Baicells eNodeB and srsEPC CN*

The RAN comprised the Samsung A22 5G-enabled mobile phone and the Baicells eNodeB. The eNodeB network configuration parameters were defined in Section III-A. The MME address points to the computer running the EPC functions. On the other hand, the CN functions were realized using the srsEPC, which implements main CN functions such as the home subscriber service (HSS), MME, service gateway (S-GW), and packet data network gateway (P-GW). The HSS database stores subscribers' information, which is used to authenticate and authorize users' access to the network. The MME provides the control and anchoring functions to the network while maintaining UE's connection to the network. The S-GW provides a tunnelling and gateway connection between the UEs and the P-GW, which then routes UE's traffic to external networks such as the Internet. EPC IP address and access point names were defined in the *epc.conf* to enable communication with eNodeB and the Internet.

The HSS in srsEPC is implemented as a comma-separated values file, i.e., the *user_db.csv*. The file was edited to input the subscriber information programmed to the SIM card, including IMSI, Operator code (OPc), UE's sequence number, QoS Class Identifier (QCI), and the IP allocation strategy at the S-GW, i.e., static or dynamic.

i. Enabling the UEs to access the internet

To enable UEs to access the Internet, it is necessary to perform IP masquerading. This is the source network address translation (SNAT) used to perform many-to-one IP address translations, making a computer in the network serve as an IP gateway. IP masquerading enables the Linux kernel to perform packet forwarding for traffic between the 4G and external networks. The masquerading was done by executing the *srsepc_if_masq.sh* script against the Wi-Fi or Ethernet interface that connects the computer running the EPC to the Internet, as follows.

- `sudo srsepc_if_masq <out_interface>`

Finally, the EPC functions were started using the command,

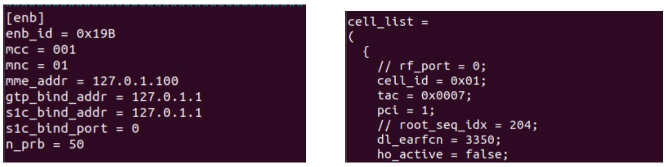
- `sudo srsepc`

Observation

The UE connects to the network, and the EPC execution logging shows the UE's registration, attachment, and ultimate access to the packet data network (PDN), the Internet.

B. *4G Network Testbed With SDR eNodeB and srsEPC CN*

SDR X300 2944 was flushed with the srsRAN eNodeB image, whose radio resource configurations include an EARFCN of 3350MHz, and 50 physical resource blocks (prbs) with uplink and downlink frequency channels at 2680 MHz and 2560 MHz, respectively. Prbs signify the number of subcarriers allocated by the scheduler at the base station. Some of the eNodeB and radio resource configurations are shown in Figure 3.



```
[enb]
enb_id = 0x19B
mcc = 001
mnc = 01
mme_addr = 127.0.1.100
gtp_bind_addr = 127.0.1.1
s1c_bind_addr = 127.0.1.1
s1c_bind_port = 0
n_prb = 50
```

(a) eNodeB

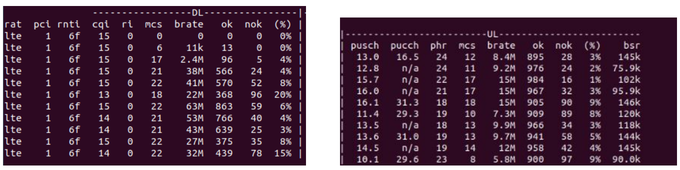
```
cell_list =
(
  {
    // rf_port = 0;
    cell_id = 0x01;
    tac = 0x0007;
    pci = 1;
    // root_seq_idx = 204;
    dl_earfcn = 3350;
    ho_active = false;
```

(b) 4G Radio Resource

Figure 3: 4G SDR-srsEPC Configurations Parameters

Observation

Upon initiating the EPC functions, enabling IP masquerading and forwarding, and flushing the SDR with the eNodeB image, the UE connected to the network and the Internet. The signal trace at the eNodeB terminal showing downlink and uplink data rates over LTE access is shown in Figure 4.



			DL						
rat	pci	rnti	cqi	ri	mcs	brate	ok	nok	(%)
lte	1	6f	15	0	0	0	0	0	0%
lte	1	6f	15	0	6	11k	13	0	0%
lte	1	6f	15	0	17	2.4M	96	5	4%
lte	1	6f	15	0	21	38M	566	24	4%
lte	1	6f	15	0	22	41M	570	52	8%
lte	1	6f	13	0	18	22M	368	96	20%
lte	1	6f	15	0	22	63M	863	59	6%
lte	1	6f	14	0	21	53M	766	40	4%
lte	1	6f	14	0	21	43M	639	25	3%
lte	1	6f	15	0	22	27M	375	35	8%
lte	1	6f	14	0	22	32M	439	78	15%

(a) Downlink Data Rates

				UL				
pusch	pucch	phr	mcs	brate	ok	nok	(%)	bsr
13.0	16.5	24	12	8.4M	895	28	3%	145k
12.8	n/a	24	11	9.2M	976	24	2%	75.9k
15.7	n/a	22	17	15M	984	16	1%	102k
16.0	n/a	21	17	15M	967	32	3%	95.9k
16.1	31.3	18	18	15M	905	90	9%	146k
11.4	29.3	19	10	7.3M	909	89	8%	120k
13.5	n/a	18	13	9.9M	966	34	3%	118k
13.6	31.0	19	13	9.7M	941	58	5%	144k
14.5	n/a	19	14	12M	958	42	4%	145k
10.1	29.6	23	8	5.8M	900	97	9%	90.0k

(b) Uplink Data Rates

Figure 4: 4G SDR-srsEPC Signal Trace at the eNodeB

C. *4G Network Testbed With SDR with OAI eNodeB and CN*

The OAI CN and eNodeB were run on two computers communicating over Ethernet. Figure 5 shows the 4G mobile network testbed connection. The OAI CN and eNodeB were set up per the instructions provided by the OAI guide.

[12]https://openairinterface.org/

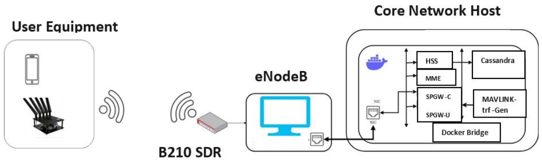


Figure 5: 4G OAI-Based Testbed

In the eNodeB configuration file, 50 prbs were specified, and the eNodeB connection to EPC was established by defining the EPC and MME IP addresses. The EPC functions were started by initialising the cassandra[13] database that implements the HSS, followed by running the rest of the Network functions in the docker-compose file. Finally, the eNodeB image was flushed to the SDR.

Observation

The above execution prompted the SDR eNodeB to switch on and be on standby, waiting for UE attachment requests. Consequently, the HSS checks subscriber information for verification and sends the information to MME, which authorizes UE's resource requests.

V. 5G NSA Testbed Implementation

Figure 6 shows the 5G NSA architecture. The RAN comprises the gNB and eNodeB interconnected over the X2 interface, while mobility functions at the CN are implemented with EPC.

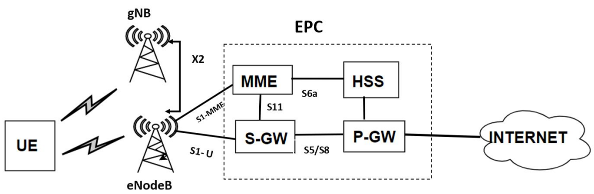


Figure 6: 5G NSA Network

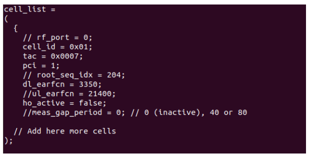
5G NSA testbed was realized in two models, i.e., firstly, with the srsRAN (eNodeB and gNB) and srsEPC, and secondly, with SDR and OAI.

A. 5G NSA Testbed With SDR, srsRAN, and srsEPC CN

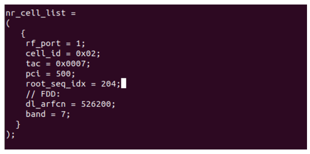
To achieve the 5G NSA RAN implementation, the SDR X300 2944 was flushed with the srsRAN eNodeB and gNB images simultaneously. This was done by specifying the NSA operation mode in the radio resource configuration file, *rr.conf*, as shown in Figure 7. A downlink and uplink EARFCN of 2680 MHz and 2560 MHz were configured for the 4G cell, whereas the NR cell operated at 3513 MHz and 3513.6 MHz, respectively. Additionally, in the *enb.conf* file, the respective MME-IP, MCC, MNC, TAC, and base station transmission mode (2), were updated.

On the other hand, the CN was implemented using srsEPC. The respective configurations to ensure the base stations

[13]https://cassandra.apache.org/_/index.html



(a) 4G cell radio resource



(b) 5G cell radio resource

Figure 7: Radio Resource Configuration for eNodeB and gNB

can reach the MME and other CN functions were done as described in section IV-A.

Observation

Upon initialising the EPC, eNodeB and gNB, two transmission channels opened, as shown in the base station signal trace in Figure 8. At the 5G UE settings, the access point name was configured such that the bearer, i.e., service technology that the UE searched for, was indicated as LTE and NR. The UE connects to the 5G NSA network and shows a 5G icon upon complete registration. The UE switches between the 5G NR and 4G connection, depending on which connection has a stronger signal strength.

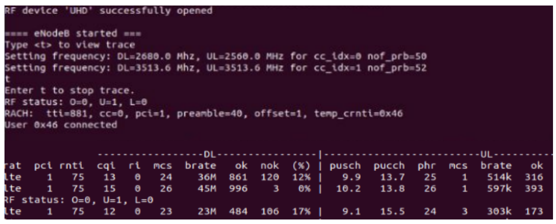


Figure 8: 5G NSA operation mode signal trace

B. 5G NSA Network Testbed With OAI

5G NSA over OAI was realized by implementing the OAI EPC, eNodeB and gNB. The base stations were run on separate SDRs, as shown in Figure 9. The configuration to connect the gNB and eNodeB was done by enabling X2 and setting up the communicating nodes' IP addresses. Further information on the configuration and deployment of the 5G NSA OAI CN and RAN components are provided in OAI guide.

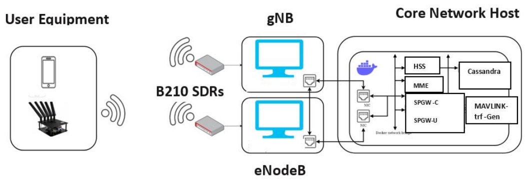


Figure 9: 5G NSA OAI Test-bed

Observation

The UE attaches to the 5G NSA mobile network via the 4G control plane, and if the user parameters show that it is 5G capable, then that connection is passed on to the gNB for NR access.

VI. 5G SA Testbed Implementation

Figure 10 shows simplified 5G SA architecture. The RAN comprises gNB and 5G capable UE, while the CN functions are implemented as micro-services, achieving a service-based architecture (SBA). SBA enables the interaction and exchange of information over open interfaces between the CN functions. Furthermore, 5G CN adopts techniques such as control/user plane separation (CUPS), network function virtualization (NFV), and software-defined networking (SDN). NFV achieves network flexibility by implementing network functions on virtual machines or containers [11]. The CUPS is achieved through SDN by decoupling the control plane (CP) from the user plane (UP) [12]. CUPS enables independent scaling of the network functions, allowing for easier per-use case dimensioning of the network [11].

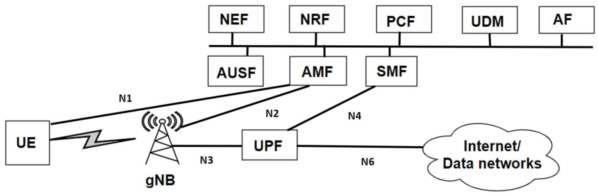


Figure 10: 5G SA Network

As of this writing, the srsRAN project has only implemented the gNB but supports third-party CN frameworks, with a recommendation for Open5GS. On the other hand, OAI 5G SA stack testbed implementation is under development.

A. 5G SA Testbed with SDR, SRSRAN gNB, and Open5GS

The SDR X300 SDR was flushed with the srsgnb image, while the Open5GS CN stack was deployed in a 4Gb RAM virtual machine as outlined in the installation guide. Configurations to enable the gNB to connect to the CN and accept connections from registered UEs were defined in the *enb.conf* file. These include the TAC (7), MCC(999), MNC(99), mobility management IP, transmission gain of 80 dB, and tunnelling IP addresses. Additionally, the current implementation of srsRAN supports using 50 prbs, a subcarrier spacing of 15 kHz, and a bandwidth of 10 MHz, frequency division duplex (FDD). FDD enables the simultaneous exchange of information between the transmitter and receiver by using two different frequencies for uplink and downlink communication channels. Furthermore, radio resource configurations for NR, such as EARFCN of 526200 MHz, and transmission band 7, were defined in *rr.conf*.

Additionally, an interface was created at the CN with IPV4 forwarding over the network address translation (NAT) network to tunnel UE traffic to the Internet, as follows;

```
sudo sysctl -w net.ipv4.ip_forward=1
sudo sysctl -w net.ipv6.conf.all. forwarding=1
sudo iptables -t nat -A POSTROUTING -s 10.45.0.0/16! -o ogstun -j MASQUERADE
```

Observation

The 5G UE connected to the network over the NR access technology and the trace logs at the gNB showing uplink and downlink data rates were shown in Figure 11.

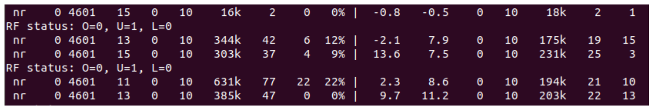

```
 nr    0 4601   15   0   10    16k    2    0   0% |  -0.8   -0.5    0   10    18k    2    1
RF status: O=0, U=1, L=0
 nr    0 4601   13   0   10   344k   42    6  12% |  -2.1    7.9    0   10   175k   19   15
 nr    0 4601   15   0   10   303k   37    4   9% |  13.6    7.5    0   10   231k   25    3
RF status: O=0, U=1, L=0
 nr    0 4601   11   0   10   631k   77   22  22% |   2.3    8.6    0   10   194k   21   10
 nr    0 4601   13   0   10   385k   47    0   0% |   9.7   11.2    0   10   203k   22   13
```

Figure 11: UE Registration at the gNB

VII. Testbed Evaluation Results and Discussion

The network key performance indicator (KPI) parameters of e2e latency, throughput, and received signal strength indicator (RSSI) were considered in evaluating the network testbed performance. E2e latency measures the delay between sending and processing radio signals between the base station and the UE. In contrast, throughput measures the rate of successful data transfer over a period sent over a specific network interface. Finally, the RSSI is the quality of the received signal at the UE, defined by signal power, noise, and synchronization. Network measurements tools, such as Iperf3, Netperf, and Speedtest.net, were used to evaluate throughput and latency, whereas RSSI was determined using the cellular-Z[14] mobile application installed in the UE.

A. 4G Testbed Evaluation Results

The KPIs for the three deployments of the 4G testbed were evaluated and summarised in Table I. The testbed latency and RSSI performance were significantly better than the theoretical and commercial MTN values. In addition to using the latency and throughput-optimized COTs eNodeB, the srsEPC framework implementation is lightweight compared to OAI. This makes it faster for the CN functions to process and route traffic from UEs to external networks. The RSSI performance is because the testbed deployment was indoor-based, minimizing the effects of interference and signal fading often caused by geographical features and weather conditions.

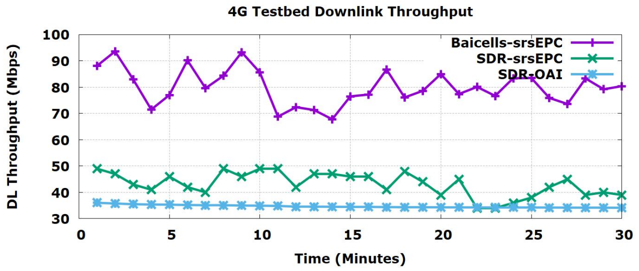
TABLE I: Comparison of 4G Theoretical Specifications, Commercial, and Testbed Results

KPI Metrics	Theoretical	MTN	Baicells, srsEPC	SDR, srsEPC	SDR, OAI
DL Throughput (Mbps)	100	40	80.02	43.1	34.66
UL Throughput (Mbps)	50	30	9.4	9.8	18.0
E2e latency (ms)	20	23	11.7	11.6	16
RSSI (dBm)	-80	-51 to -25	-48	-51	-43

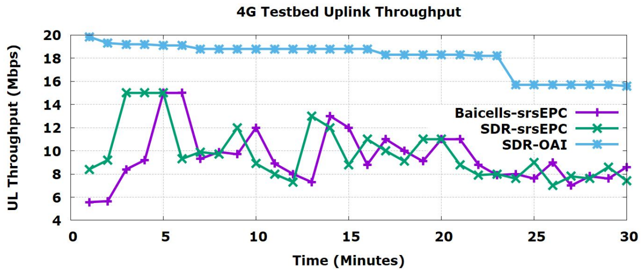
The graphical analysis of the variation in throughput for the srsEPC-based and the OAI-based 4G testbed implementation was shown in Figure 12.

The Baicells-srsEPC had the highest downlink throughput, with an average of 80 Mbps and a peak of 96 Mbps. In contrast, the SDR-based implementations had a throughput of approximately 45 Mbps and 35 Mbps for srsEPC and

[14]https://m.apkpure.com/cellular-z/make.more.r2d2.cellular_z



(a) Downlink Throughput



(b) Uplink Throughput

Figure 12: 4G Testbed Throughput Analysis

OAI stacks, respectively. This observation is attributed to Baicells eNobeB being optimized and ready to deploy for indoor coverage, with omnidirectional antennas radiating at 5 dBi. On the other hand, with the SDR implementations, directional antennas were used. These antennas were manually configured and positioned to achieve optimal performance. The three 4G testbed setups performed better than MTN, while the Baicells-based implementation had close to the theoretical downlink throughput for 4G.

The uplink throughput for srsEPC implementations had a peak of $\simeq$ 15 Mbps, while OAI had a peak of $\simeq$ 20 Mbps. The uplink throughput was approximately half the downlink values. This is largely due to the modulation schemes, i.e., in 4G, the downlink modulation scheme employed is Orthogonal Frequency Division Multiple Access (OFDMA), allowing more sub-carriers to fit within a given bandwidth. However, in the uplink transmission, single carrier-orthogonal frequency division multiple access (SC-OFDMA) is used to achieve a lower Peak-to-average-power ratio (PAPR) than OFDMA. However, this comes at the cost of throughput. The testbed, however, showed lower uplink throughputs compared to the theoretical and MTN specifications. However, an advantage of SDR-based deployments is that the number of prbs can be increased to achieve higher downlink and uplink throughput. This is particularly important for use cases like video streaming applications, such as over-video medical examinations and consultations.

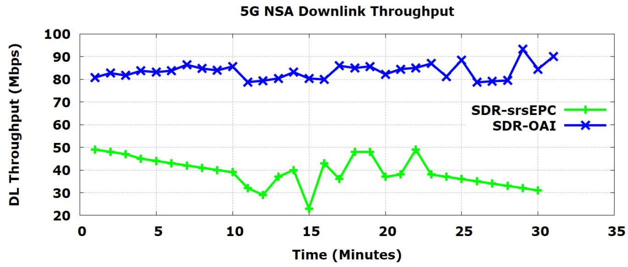
B. 5G NSA Testbed Evaluation Results

Similar KPI evaluations for the 4G testbed were done for the 5G NSA implementation. The comparative results are summarised in Table II.

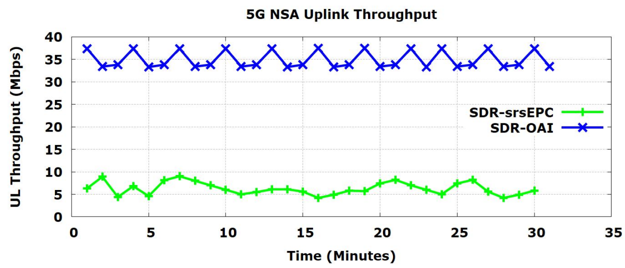
TABLE II: Comparison of 5G NSA Theoretical Specifications, Commercial, and Testbed Results

KPI Metrics	Theoretical	MTN	SDR, srsEPC	SDR, OAI
DL Throughput (Mbps)	1000	252	38.5	84.5
UL Throughput (Mbps)	500	30	9.8	34.9
E2e latency (ms)	10	10	11.8	5
RSSI (dBm)	-75	-51 to -25	-57	-51 to -25

Throughput evaluations for the 5G NSA testbed were conducted over 30 minutes, and the graphical representation of the results is shown in Figure 13.



(a) Downlink Throughput



(b) Uplink Throughput

Figure 13: 5G NSA Testbed Throughput Analysis

While the testbed performance for downlink and uplink throughput was lower than both the theoretical and the commercial MTN values, the SDR-OAI-based implementation had a desirable average of $\simeq$ 85 Mbps in the downlink and $\simeq$ 35 Mbps in the uplink. The current implementation of the OAI framework supports using 106 prbs, and the srsEPC only works with 50 prbs and 10 MHz bandwidth for the NR cell parameters in 5G NSA and SA deployments. Consequently, the srsEPC implementation had an average performance of $\simeq$ 39 Mbps in the downlink and $\simeq$ 10 Mbps.

Furthermore, latency performance for the srsEPC-based testbed was comparable with the theoretical and commercial MTN values. However, the OAI implementation achieved the goals of ultra-low latency specifications, i.e., $\simeq$ 5 ms latency.

C. 5G SA Testbed Evaluation Results

The evaluation results of the 5G testbed implemented over srsRAN gNB and Open5GS CN were as shown in Table III.

The 5G SA testbed uplink and downlink measurements were below the theoretical and commercial MTN values,

TABLE III: Comparison of 5G SA Theoretical Specifications, Commercial, and Testbed Results

KPI Metrics	**Theoretical**	**MTN**	**SDR, srsRAN, Open5GS**
DL Throughput (Mbps)	10000	252	29.04
UL Throughput (Mbps)	1000	30	5.04
E2e latency (ms)	≤ 5	10	12
RSSI (dBm)	≥ -88	-51 to -25	-71

having an average of $\simeq$ 30 Mbps and $\simeq$ 5 Mbps in the downlink and uplink, respectively. The analysis of throughput is shown in Figure 14. In addition to the limitation of the current srsRAN gNB implementation supporting only 10 MHz bandwidth in 5G SA mode, the manual tuning and finding optimal placement for the base station antennas are possible contributors to low throughput. The e2e latency was comparable to the MTN, whereas the RSSI performance was better than the theoretical specification. This is due to the indoor deployment and testing of the testbed network, minimizing the exposure of signals to interference and fading.

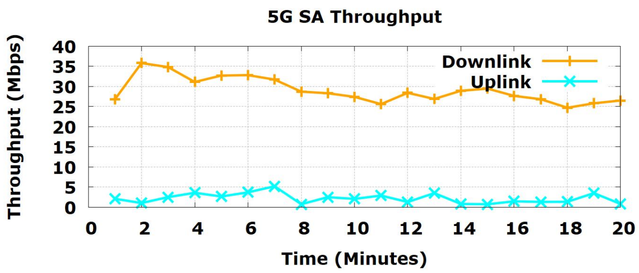


Figure 14: 5G SA Testbed Throughput Analysis

VIII. Conclusion

This work presented 4G and 5G testbed designs that achieved a flexible, permissionless, high-performance, low-cost network deployment. Throughput, e2e latency, and RSSI evaluations were done against the theoretical specifications and commercial MTN South Africa network. Furthermore, comparative performances were done for the used software stacks, i.e., srsRAN (srsEPC, srsENB, and srsgNB), Open5GS, and OpenAirInterface. The 4G performance was close to the theoretical specifications and can be used to evaluate applications with requirements of $\geq$ 50 Mbps throughput and $\leq$ 13 ms latency. On the other hand, the 5G NSA over OAI had a good latency performance of 5 ms. Hence, this testbed would be ideal for evaluating latency-stringent low-throughput applications. Despite the bandwidth limitations of srsRAN for 5G SA deployment, NR access technology connection over COTS UE was achieved. However, further optimization of software stacks and tuning the antennas and network parameters are necessary to achieve stable and close to or comparable performance to the theoretical specifications.

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References

[1] A. A. Ateya, A. Muthanna, M. Makolkina, and A. Koucheryavy, "Study of 5g services standardization: Specifications and requirements," in *2018 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, 2018, pp. 1–6.

[2] J. Navarro-Ortiz, P. Romero-Diaz, S. Sendra, P. Ameigeiras, J. J. Ramos-Munoz, and J. M. Lopez-Soler, "A survey on 5g usage scenarios and traffic models," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 2, pp. 905–929, 2020.

[3] A. Esmaeily and K. Kralevska, "Small-scale 5g testbeds for network slicing deployment: A systematic review," *Wireless Communications and Mobile Computing*, vol. 2021, 2021.

[4] L. Ndiaye, S. Diouf, K. Gueye, and S. Ouya, "Proposal for a deployment of a non-standalone 5g mobile network architecture for developing countries: Case of senegal," in *Interactive Mobile Communication, Technologies and Learning*. Springer, 2022, pp. 342–360.

[5] F. Kaltenberger, R. Knopp, N. Nikaein, D. Nussbaum, L. Gauthier, and C. Bonnet, "Openairinterface: Open-source software radio solution for 5g," in *European Conference on Networks and Communications (EUCNC), Paris, France*, 2015.

[6] S. Sevilla, M. Johnson, P. Kosakanchit, J. Liang, and K. Heimerl, "Experiences: Design, implementation, and deployment of colte, a community lte solution," in *The 25th Annual International Conference on Mobile Computing and Networking*, 2019, pp. 1–16.

[7] J. J. Abularach Arnez, W. Medeiros Silva, R. K. Gomes Do Reis, L. A. Da Silva, and M. G. Lima Damasceno, "Sdr 5g nsa mobile network and an ims core to provide voice over ip lte service," in *2022 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, 2022, pp. 071–076.

[8] F. J. De Souza Neto, E. Amatucci, N. A. Nassif, and P. A. Marques Farias, "Analysis for comparison of framework for 5g core implementation," in *2021 International Conference on Information Science and Communications Technologies (ICISCT)*, 2021, pp. 1–5.

[9] 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. IEEE, 2021, pp. 818–827.

[10] "NI Solutions overview of the ni usrp rio software defined radio," https://www.ni.com/en-za/shop/wireless-design-test/what-is-a-usrp-software-defined-radio/overview-of-the-ni-usrp-rio-software-defined-radio.html, accessed: 2022-10-05.

[11] L. Ma, X. Wen, L. Wang, Z. Lu, and R. Knopp, "An sdn/nfv based framework for management and deployment of service based 5g core network," *China Communications*, vol. 15, no. 10, pp. 86–98, 2018.

[12] K. Antonakoglou, X. Xu, E. Steinbach, T. Mahmoodi, and M. Dohler, "Toward haptic communications over the 5g tactile internet," *IEEE Communications Surveys Tutorials*, vol. 20, no. 4, pp. 3034–3059, 2018.