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Evaluating an Evolving OAI Testbed

Overview of Options, Building tips, and Current Performance

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***Abstract*—Mobile connectivity has become a must in both developed and developing countries. The ability to work with new technologies, and localise them requires appropriate testbeds. This work offers a brief overview of the field and describes a testbed being built at the Council for Scientific and Industrial Research (CSIR) in South Africa for experimental work on mobile networks. The testbed uses an Open Air Interface (OAI) Radio Access Network (RAN), Fraunhofer core network and a USRP X310 equivalent software defined radio. Some installation hints and current performance results (e.g. measured download/upload speed and latency between different parts of the system) are provided.**

Keywords—cellular, mobile network, OpenAirInterface, OAI, Long Term Evolution, LTE, 4G, 5G, testbed, test bed.

I. Introduction

Internet access has become an essential part of daily life for most of the global population. It has a substantial effect on employability and income [1], [2]. Some countries go as far as to refer to connectivity as a human right [3], [4]. With over 5 of 7 billion people using mobile phones and over 4.5 billion people being Internet users [5], mobile networking is currently the most widespread communications technology. It has been around for more than four decades and has evolved through five generations. The broadest installed base consists of fourth-generation mobile networks (4G; often termed LTE or Long Term Evolution) [6]. Fifth-generation networks (5G) are now being deployed. Beyond 5G (B5G) and the sixth-generation (6G) networks are now becoming a topic of active research [7].

The developments in the telecommunication technologies and convenience of mobile connectivity have translated into faster speeds and new applications. The ease of introducing and using online services and sharing and accessing information have supported the growth and further economic developments. The World Bank estimates that mobile broadband provides 2.5 to 4 additional jobs for each broadband job [1]. Ericson, GSMA and others [8]-[10] estimate that increasing broadband speed and penetration of mobile data render an increase in annual gross domestic product (GDP) growth of between 0.5% to 2.8% and that 5G will contribute over USD 10 billion to the world economy. Furthermore, the pandemic has made connectivity essential for providing education to children (76% of respondents in a survey [11]), staying in touch with family and friends (74% of respondents), being able to continue with business (67% of the respondents) and other essential daily tasks [11], [12]. In particular, access to education offers a cumulative effect on people's future income and contributions to the national economy [13].

All these factors contribute to exponentially growing demand for data services [14], [15], [6]. To provide services, the mobile broadband and fixed wireless access (FWA) networks (the latter particularly popular in rural areas) require radio frequency spectrum. Faster speeds demand proportionally more spectrum, access to spectrum has traditionally been a significant bottleneck. However, the ITU's WRC-19 has just allocated over 17 GHz of new spectrum to 5G [16], [17]. Access to new spectrum usually requires long and expensive national processes. The 5G design has enabled 5G to dynamically share the same frequency bands as 4G, helping to simplify the regulatory process and make the deployments much faster and cheaper.

In addition to dynamic spectrum sharing (DSS), the latest generations of mobile technologies also offer many other beneficial features. These include more flexible and faster services, softwarisation of the platforms to enable more flexibility and a broader range of manufacturers, and decoupling of the uplink and downlink frequencies that can double the range and make the latest cellular networks more affordable for deployment in rural areas. The ability to flexibly share mobile networks' equipment and software between several operators can significantly reduce capital and operational expenses. This reduction makes it cheaper to build and run mobile networks and provide mobile services, including broadband, to the remaining underserviced areas [18].

Many vendors and governments have recognised the importance of mobile networks and especially 5G for both economy and security. This recognition has led to various models to open up competition (e.g. Open RAN [19]-[21]), to secure international markets (e.g. the USA vs China), or protect national interests (e.g. Russia has recently declared that only locally-made equipment can be used in Russian 5G networks from 2024 [22], [23]).

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Developing nations also require access to cost-efficient 5G technologies. Such access is becoming possible with initiatives such as Open RAN (Radio Access Network), TIP (Telecom Infra Project) and O-RAN Alliance targeting low-cost, vendor-neutral and network-as-a-service architectures. The drive towards generic hardware, open software, the experience of China and the current Russian approach towards developing national capacity in 5G ([22], [23]) all indicate that the technological base for localised development of cellular technologies is becoming a reality. An essential component of this trend is developing national capacity and resources and establishing the appropriate testbeds (since the simulation tools are not yet able to model all scenarios correctly, e.g. [24]).

The Council for Scientific and Industrial Research (CSIR) in South Africa has extensive wireless networking experience. This experience includes commercialising and deploying Wi-Fi mesh network technology in over 200 rural schools and many other initiatives to accelerate rural developments (e.g. [25]-[27]). The CSIR has also locally developed television white space (TVWS) technology, starting from basic research, with over 100 papers published (e.g. [29], [30]), to trials with global impact (e.g. [31]-[33]) and an internationally recognised Geolocation Spectrum Database (GLSD) used for offering and providing commercial services in several nations (e.g. [34], [35]). Several research groups in the CSIR are now collaboratively developing promising designs including two already operational testbeds based on a Nokia RAN and both Fraunhofer [36] and Cumucore [37] mobile network cores. Now, the team is working on launching a testbed based on Open Air Interface (OAI) [38], [39].

This paper introduces the current state of the development of this testbed, including the ability to attach and connect a phone to our mobile network, and accessing the Internet through the phone, as well as summarises the present performance results.

Section II overviews the software modules available around the world and considers samples of published testbeds. Our OAI testbed is introduced in Section III. Section IV overviews the methodology used for and results from the measurements, followed by a summary and planned work described in Section V.

II. Overview of Existing Technologies, Platforms and Testbeds

This section briefly overviews the most related mobile network technologies and existing technologies and platforms and provides a few examples of testbeds. We selected OAI based on these choices [40].

A. Related Technologies

The easy availability of handsets and popularity of the mobile networks will likely keep it as the dominant technology.

2G/3G: The second and third generations of mobile networks are on the decline in the developing world, but thanks to their lower cost, they are still actively used in many developing countries. Many examples of successful community cellular networks (CCN) exist. Examples include projects Rhizomatica 2G/GSM in Mexico [41], CoCoMoNets 2G/GSM in the Philippines [42], and Tucan3G (3G/UMTS) in Peru [43]. Some other examples are described in [44]-[47]. These projects typically serve communities of hundreds of people. A project in the Philippines [48], served thousands of customers and was accomplished through a partnership with a national operator.

While having the lowest handset cost and offering valuable voice and SMS services, the 2G/3G mobile networks have numerous limitations. These include interconnecting with carriers (e.g., with regards to phone numbers and interconnection agreements), usage of licensed bands, low-grade connectivity and limited Internet access speed. Also, as the older technologies, such as 2G and 3G occupy valuable spectrum, and are unable to use it efficiently, operators are terminating 2G and 3G around the world, with first switch-offs in Austria, Netherlands, Switzerland and Lichtenstein in 2018-2020 [49]-[50].

4G/5G/NR: 4G (whose sub-versions are commonly known as LTE, LTE-A/Advanced, and LTE-Advanced Pro) and 5G (which is also called "New Radio" or NR) specifications are contained in over 100 documents from 3GPP, e.g. [51]-[54]. The overall 5G requirements have been defined by the ITU Working Party 5D (WP 5D) - International Mobile Telecommunications (IMT) Systems [55] with the standard [56]. In extending on the mobile broadband already available with 4G, 5G offers the much faster enhanced Mobile Broadband (eMBB). Notably, 5G also introduces brand new communication profiles called the Ultra-Reliable Low-Latency Communications (URLLC) [57], and Massive Machine Type Communications (mMTC) enabling new industrial applications. More details may be found, for example, in [58] and [59].

A mobile network includes User Equipment (UE, often referred to as handsets or cellphones), a Radio Access Network (RAN) associated with multiple base stations and one or more core networks. Discussions on UE, core networks and backhaul networks connecting the core to the RAN are outside of this paper's scope.

There is a variety of choices for open-source 4G and 5G RANs, discussed below in brief.

B. Related Software Technologies

There are many software packages and experimental testbeds and networks taking advantage of this software, e.g. see a long list provided in [60]. This section compares some of the modern realisations.

Open Air Interface (OAI): The Open Air Interface (spelled as OpenAirInterface and hereinafter referred to as OAI) [61], [62] is an open-source initiative. The OAI promises to provide a 3GPP-compliant reference implementation of key elements of LTE and 5G Radio Access Network (RAN) and core network. OAI is driven by the OpenAir Software Alliance (OSA), a French non-profit organisation. It aims to make available a suite of open components for research and for product development in 5G networks, using standard general purpose x86 and ARM platforms running Linux and commercial off-the-shelf (COTS) Software-Defined Radio (SDR) platforms.

Unlike most other projects, the OAI's public license allows contributions from 3GPP member companies while at the same time allowing commercial exploitation of the code, which is not at all possible with other open-source projects [63] The usage of OAI code is free for non-commercial/ academic research purposes.

The first 3GPP implementation supported is Release 13. Currently, a subset of LTE for UE, eNB, MME, HSS, SGw and PGw (Release 10) is available. The objective is to eventually provide a reference implementation of 3GPP Release 13. Much of the activity is centred around EureCom (http://www.eurecom.fr/en), a French educational institution emphasising digital security, data science and communications systems. Other strategic members are Orange, Qualcomm, Fujitsu, Facebook, Platforms for Advanced Wireless Research and Interdigital. Associate members and partners number over 70, mostly research institutions. None of the major equipment vendors or network operators seem to be represented.

OAI has been used to implement LTE using the x86 environment [65].

Although 5G RAN support is not available at the time of writing (January 2021), indirect information indicates that 5G support is promised within the next few months.

In 2020, OAI also announced that it is implementing an experimental 5G Core Network [64].

Open LTE: OpenLTE [66] is a partial open-source 3GPP LTE implementation. It offered a variety of building blocks for LTE using GNU Radio. The Web pages on Sourceforge indicate no activity within the past year. No 5G implementation seems to be available.

O-RAN Alliance: The O-RAN Alliance [67] claims that 26 mobile network operators as members. They claim that these operators serve 2400 million subscribers. Prominent members include AT&T, Bell, BT, Orange, Singtel, Sprint, T-Mobile, Verizon and Vodafone. They are also associated with 190 suppliers and research associates, including semiconductor suppliers, handset makers, network equipment makers, computer companies and academic institutions. Their Open Software Reference Design claims three million lines of code from 15 contributing companies.

O-RAN appears to intend to expand existing and pending 3GPP standards, specifically those defining the RAN. Specific aspects of their focus revolve around disaggregation, automation and virtualisation of the RAN. Much of this effort revolves around distributing the front-end processors between Remote Radio Units (RRUs) and vBBUs (Virtual Baseband Units) to maintain adequate performance while limiting the required bandwidth in the fronthaul segment of the network.

Open Compute Project (OCP): The OCP [68] was initiated by Facebook, in an effort to address its computing needs in an energy-efficient and scalable manner. Their own efforts are claimed to have resulted in energy efficiency improvements of 38% and cost reductions of 24%. In 2011, Facebook revealed its designs to the public and with several partners, established OCP.

OCP aims to develop open hardware, allowing a wide variety of vendors to adopt more energy-efficient architectures worldwide. Its operating principles are very similar to those used in open-source software circles.

OCP now operates under the auspices of corporate Board members including Facebook, Goldman Sachs Microsoft and RackSpace. All these companies have widely implemented OCP hardware. However, excluding these companies, other members already implement hardware worth around $1200 million per annum (p.a.) in 2018. The corresponding number is expected to grow to $6000 million p.a. by 2023. Telecom network operators are regarded as perhaps the biggest single sector that can benefit from the principles and products of OCP. This estimate is central to the founding of TIP (see below) in 2016.

OCP's emphasis on innovative hardware may provide attractive platforms for implementing commercial 5G networks in due course. However, for the moment, they offer no software implementations and no hardware that provides functions that cannot be duplicated using generic computing platforms.

srsLTE: srsLTE [69], [70] is driven by Software Radio Systems (SRS), based in Ireland. It is a complete LTE implementation, including all components of the UE, RAN network and core network running on Ubuntu Linux. The free offering appears to be used as a vehicle for selling SRS's consulting services. They claim to be "trusted by" major vendors (Analog Devices, National Instruments, NEC, Nokia) and research organisations (Fraunhofer, MIT, Purdue University), although the nature of the relationship between them and these organisations is not clear.

Telecom Infra Project (TIP) 's OpenRAN [71]: TIP's stated aim is to accelerate the development and deployment of open, disaggregated standards-based technology solutions to deliver high-quality connectivity, now and in the future. The basic approach appears to be to provide maximum flexibility and minimum use of "black boxes" that limit the flexibility of a network deployment. With software-defined networks (SDN) and software-defined radio (SDR), network topology can be reconfigured as required, allowing full convergence of mobile and fixed networks.

Membership is claimed to include "hundreds of companies". Network operators on their membership list include Airtel, BT, T-Mobile, Facebook Connectivity, Intel, MTN, NTT, Orange, Sprint, Vodacom and Vodafone. Vodafone is involved in widespread trials using OpenRAN, including in South Africa and several neighbouring countries.

The TIP Exchange includes 45 products from 28 member companies. TIP adheres to O-RAN standards and cooperates with the O-RAN Alliance, GSMA and ONF.

With TIP's operator-centric orientation, its offering is perhaps less suited to the research environment than other choices like OAI. Although it uses and advocates open standards, it does not have a reference implementation suitable for building an experimental 5G RAN.

During the launch of TIP, Andre Fuetsch, senior VP of Architecture and Design of AT&T, stated that 75% of its network functions would be virtualised by 2020 [72]. Their intention is to increasingly use "sophisticated software running on commodity hardware". This assumption is reinforced that up to ninety 5G trial networks are already in operation worldwide, despite the fact that the IMT2020 specifications had not been finalised, with the final specifications only being approved in February 2021.

Comparison of Platforms

The descriptions above reveal that only the following platforms provide any means of implementing a suitable RAN for experimental purposes:

· Open Air Interface (OAI)

· TIP's OpenRAN

The remainder of the platforms and organisations fall into other categories, e.g.:

- GNU Radio offers signal processing building blocks and a framework for tying them together, which could potentially be very useful in the long run. However, no high-level building blocks applicable to 5G networks are available, apart from a partial LTE implementation.
- OpenLTE provided a partial LTE implementation, but appears to have come to a natural end. No activity is evident on their public platforms for at least the last year.
- O-RAN Alliance is an alliance of network operators. They are establishing a series of standards that operate on top of 3GPP's recent releases, facilitating open interfaces for network operators. However, most of the implementations appear to be proprietary, and available from their members on a commercial basis. Their standards are important for future implementations and should become part of the arsenal in future.
- Open Compute Project (OCP) emphasises the development of innovative energy-efficient generic processing platforms. Their outputs may be useful for implementing real-life networks, but seem to offer little advantage over generic computing hardware for experimental or proof-of-concept purposes.

The main remaining task is, therefore, to inspect the two viable options as to their suitability for an experimental open RAN. The comparison is listed in Table I.

It, therefore, appears that OAI is the most viable choice for licence-free implementation on generic hardware. OpenRAN may prove to be a better solution once a potential operator has decided to implement a live network, especially where large volumes of hardware will be involved.

TABLE I. ARGUMENTS IN SELECTING THE PLATFORM.

Platform	Advantages	Disadvantages
OpenAirInterface (OSA)	• Free licence • Large development community with support via forums • Full 5G (IMT2020) implementation scheduled	• Limited documentation outside the development material • No support for full 5G implementation
OpenRAN (TIP)	• Portability to generic hardware • Widespread industry adoption • Commercial products to implement networks (via members) • Numerous trial installations • Implementations comply with IMT2020 (3GPP) and O-RAN standards	• Licence required for implementation

C. *Notes on the Core Network*

A number of open-source core networks are available, e.g. OpenAirInterface, srsLTE, Open5GS, OMEC, free5GC [75]. For our project, based on our prior experience and its relatively flexible licencing conditions, we selected the Fraunhofer core. We have used the Fraunhofer core [36] because it offers a good deal of flexibility and also because we have worked with this core before. It is, however, important for us to maximise the use of open-source resources. We have selected the OpenAirInterface, retaining the option of commercial exploitation. We selected the USRPs because they offer great flexibility and are compatible with the majority of the open-source projects. The next section details our implementation.

D. *Examples of known cellular testbeds and trials based on open-source projects*

The long term objectives in building a testbed include being able to do state-of-the-art experiments and field deployments. This section summarises some specifications and experiences found in the literature.

CoLTE community network with Satellite Backhaul: The papers [76] and [77] from the University of Washington, USA discuss a stabilised, extended, and enhanced OpenAirInterface Enhanced Packet Core (EPC) to create CoLTE, the Community LTE. The CoLTE is said to be an LTE EPC suitable for use in a live network with paying users and realising community networking, more specifically, Community Cellular Networking (CCN). The key differentiator of CoLTE, when compared to other existing LTE solutions, is said to be that "in CoLTE the EPC is designed to be located in the field and deployed alongside a small number of cellular radios (eNodeBs), as opposed to the centralised model seen in large-scale telecom networks."

The key contributions from [76] and [77] are claimed to be threefold:

- They contributed several improvements to the OpenAirInterface codebase and made some architectural choices to this effect.
- They built some locally-hosted Web services that allow for configuration of OpenAirInterface and user-based account management.
- They built an IP-based network manager called Haulage that interfaces with OpenAirInterface to provide user accounting and authorisation. All of their code is entirely free and open-source and is available at GitHub repositories listed in [76] and [77], especially [78]. It is essential to mention that CoLTE solutions must rely on over-the-top (OTT) IP-based services such as Skype and WhatsApp and does not support the network-native telecommunications typically provided by a cellular network, such as voice and SMS. They support this with a motivation that HD Voice VoLTE calls cost over 2000 times the median data price (in 2018 prices).

Furthermore, their system deviated from the traditional architecture by separating the network management system and tools (i.e. The PCRF and PCEF) from control and placing the RADIUS interface between them, enabling OAI to be deployed with or without an AAA server. A nano-scale CoLTE requires two computers (one laptop, one miniPC with a 1.6 GHz, 4-Core Intel Celeron processor, 8 GB RAM, and a 250 GB hard drive), a small USB software-defined radio (an Ettus B205), a commercial smartphone and the necessary cables/power adapters. A field deployment version of the CoLTE uses two 1-watt BaiCells 850 MHz Nova-233 eNodeBs (eNBs) with a basic unmanaged gigabit Ethernet switch. The cost of installation with one EPC, two eNBs, antennas, cables, SIM cards and other necessary parts is USD 9334. The monthly operational costs are said to be USD 391. The deployment and usage at a flat rate of USD 1.18c per megabyte showed a gross income of USD 1930 per month, implying sustainability.

The paper [77] states that "each eNodeB supports 255 connected users and 150 Mbps of throughput", and that the measurements showed daily traffic per user of between 100 MB and 200 MB. The real potential of the system, expressed by, e.g. "Loopback Throughput 14 Gbps", "Ethernet Throughput 956 Mbps" was limited by the hardware "USB-Ethernet Throughput 96 Mbps" and the VSAT satellite backhaul of 3 Mbps with a 10:1 contention. The paper also highlights a high total network overhead of 44.5% dominated by the control plane (39%).

LTE with Satellite Backhaul: The work [79] from Bundeswehr University and Fraunhofer Institute, Germany discusses a terrestrial network deployment with 4G mobile cell connectivity using a bandwidth limited satellite backhaul. Virtual nodes are exploited to distribute core network components to the edge of the cell co-located with the radio base stations. It considers the problem of how a moving platform such as a van with a Satcom-on-the-Move (SOTM) antenna can be integrated into an LTE network architecture using a bandwidth-limited satellite backhaul.

They selected the LTE Release 8 EPC solution *Ridux* from blackned GmbH [80] for the core network in the testbed. The EPC components ran on virtual workstations as edge nodes. The Nokia Flexi Multiradio 10 Base Station [80] solution was deployed as the hardware platform for the eNBs.

LTE-A testbed versus Simulation: Munich University of Applied Sciences, Germany, uses a small-scale completely shielded (shielding attenuation at least 80 dB) cellular testbed based on OpenAirInterface [125]. The packet delay and inter-arrival time are measured in several low and high load scenarios. The following equipment was used for UE: Huawei Mobile Broadband E3372h; for eNB: Ettus USRP B210, connected to a computer with Intel i7 6x 3.7 GHz, 16 GB RAM and using OpenAirInterface (OAI-RAN); and for EPC: OpenAirInterface (OAI-CN). The paper also attempts to validate the tool SimuLTE [82]. Identical scenarios are modelled in SimuLTE, comparing the results. The authors find that SimuLTE can model only low-load systems.

We consider this finding important since it says that *presently the simulation tools are unable to model even an LTE system-level network correctly and experimental validation is essential*.

LTE (OAI) v GPRS (OpenBTS): The work [83] from Universitas Indonesia, Indonesia compares the performance of GPRS and LTE cellular networks built using OpenBTS and OAI as well as software-defined radio (SDR) USRP B210.

The authors used two computers with a 64-bit operating system and 8 GB of RAM. The first computer with an i7-8750H CPU (2.20GHz × 12), Ubuntu 14.04.6 64-bit LTS, and OpenBTS version 5.0, was used to test the GPRS. The second computer with i5-4460 (3.20GHz × 4) and Ubuntu 16.04.06 64-bit LTS and OpenAirInterface, was used to test the LTE.

The paper states that evaluation includes throughput, delay, jitter, and percentage of packet loss. OpenBTS yields throughput, delay, jitter and packet loss of 62 kB/s, 1 s, 433 ms, and 5.20%, respectively. On the other hand, OAI yields 2.2 MB/s, 54 ms, 12.5 ms, and 3.12%, respectively. These visualise that "The use of OpenBTS does not support current services such as video access and search."

OpenAirInterface 5G NSA demo: In the demo setup [84] from Eurecom, France, the RAN comprises an OpenAirInterface (OAI) eNB and a gNB, both running on general-purpose x86 servers and USRP N310 software-defined radios. Further, they use the OAI EPC comprising home subscriber server (HSS), mobility management entity (MME), serving and packet data network gateway (S-PGW), which are all deployed in Docker containers. The demo demonstrates initial connection and user registration on the 4G cell, secondary cell addition, initial connection on the 5G cell, and some initial traffic on the 5G cell.

Summarising: In summary, the projects reviewed above indicate the viability of realising an operational cellular testbed with a large variety of options.

III. TESTBED SET UP OVERVIEW

Fig. 1 depicts an overall setup of an LTE mobile network:

- The Fraunhofer core network (Release 3), i.e. the Evolved Packet Core (EPC) including the Packet Data Network Gateway (P-GW), the Serving Gateway (S-GW), the Mobility Management Entity (MME) and the Home Subscriber Server (HSS) are run on an in-house server connected to the organizational local area network (LAN) and thus to the Internet.

- The eNB BS (Base Station) server runs on a Dell Precision 3630 with Intel i9-9900 8-core, 16 MB cache, 3,1 GHz, 2x SDD, with Ubuntu Linux version 16.04) and uses the OpenAirInterface (version 2.0). It is connected via gigabit Ethernet to the Core server, used for the S1 interface between the core and eNB.

- The eNB BS server machine is connected to the software-defined radio (SDR: NI USRP-2944R, equivalent of Ettus X310, PCIe card, able to operate in 10 to 6000 MHz with simultaneous bandwidth of 160 MHz), using the MXI Express interface.

- USRP-2944R was attached to two Poynting OMNI-280 antennas: one antenna for transmitting signals and the other for receiving signals.

- A Samsung Galaxy J5 with a specially programmed SIM card is used to represent the user equipment (UE).
    - Five different phones representing all popular operating systems and different manufacturers are on order. The team is also investigating the feasibility of EU emulation in software, using a similar server/SDR combination as that used for the eNB.

The installation and configuration required some planning and debugging. EureCom's ExpressMIMO2 PCIe card requires a PC with a free 8/16-way PCIe slot. With an adaptor, the card can function in a 1-way PCIe slot or ExpressCard slot laptop slot. For the BS server to detect the PCIe card, the NI RIO kernel drivers had to be installed together with the appropriate Linux headers.

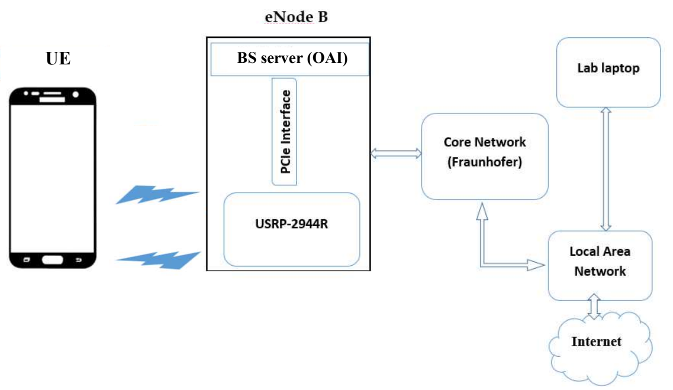


Fig. 1. The connections in our OAI 4G network. Some of the notations: UE refers to the user equipment (smartphone); Base Station (BS) server with OAI; USRP is the software defined radio connected to the BS (eNB) server and antennas (not shown).

A low latency Linux kernel is preferred. The USRP hardware drivers (UHD) are recommended because they provide interaction between the two components when running OAI scripts to form an eNB. Communication with the Fraunhofer core was performed using S1 interface where we configured the eNB and core to communicate through a network cable.

The UE needs to be able to connect to the eNB. To allow that, the eNB seeks authorisation from the core. Thus, the eNB was configured first to connect to the core network. Main parameters that were configured on the test devices are: Tracking Area Code (TAC), Mobile Country Code (MCC) and Mobile Network Code (MNC). TAC identifies a tracking area within a particular network. MCC is used in wireless telephone networks (GSM, CDMA, UMTS, etc.) in order to identify the country in which a mobile subscriber belongs. In order to uniquely identify a mobile subscriber's network, the MCC (identifies the geographic region of the SIM card) is combined with an MNC (identifies the operator). The combination of MCC and MNC is called Home network identity (HNI) and is the combination of both in one string (e.g. MCC= 100 and MNC = 10 results in an HNI of 10010). If one combines the HNI with the MSIN (Mobile Subscriber Identification Number) the result is the so-called Integrated Mobile Subscriber Identity (IMSI). The IMSI used to configure the SIM card. It uniquely identifies the user to all cellular networks. The overall format is: MCC + MNC + frnot standard. They were chosen for our private network to avoid any interference with other network operators: TAC=17, MCC=100, MNC=10, and HNI=10010.

Fig. 2 presents a picture of a part of our open mobile network in our laboratory. The UE device successfully connects to the 4G LTE network provided by the eNB and is able to access the Internet.

During our testing, we were not limited to OAI software only. srsLTE was successfully installed and run on our platform by a visiting student from the University of Cape Town.

IV. Performance Measurements: Methodology and Results

The following steps and approaches were used to test the functioning of the mobile network.

First, in order to ensure that the smartphone used as the User equipment (UE) is sufficiently fast, we tested the throughput achievable by this smartphone on a live commercial mobile network, using www.speedtest.net. The test was done at the location with the latitude -25.75614º, and longitude 28.2789º at around 10:30 in the morning. The measured values are shown in Table II and can be used as a reference in refining our setup.

Preparation of SIM cards: We started with the laboratory tests using our experimental testbed and prepared the SIM cards to be used in the UE. pySim software running on Ubuntu Linux 16.04 was used.

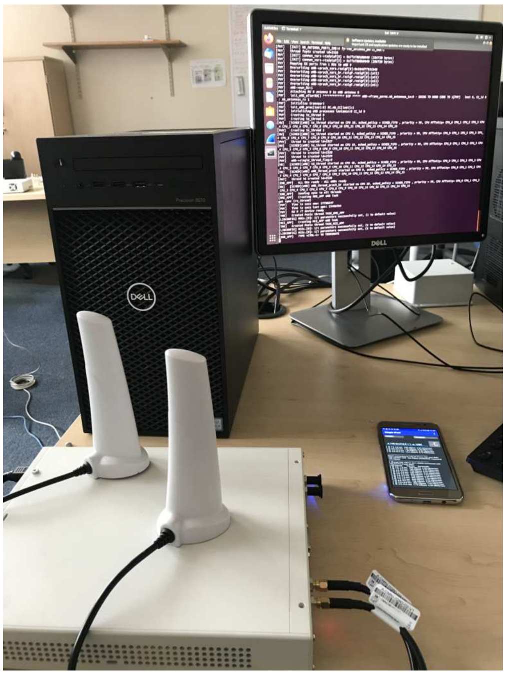
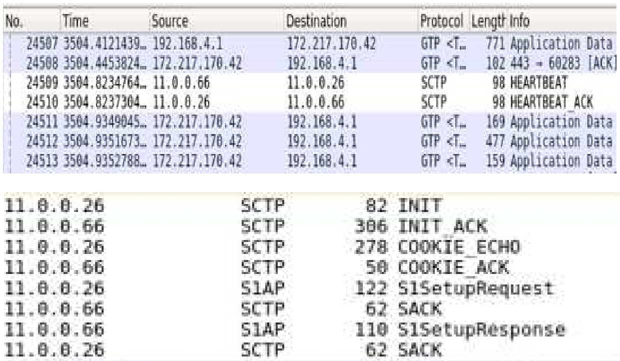


Fig. 2. Picture of the key portions of our hardware setup, depicting the antennas connected to the SDR, one of the servers and the UE.



a)

No.	Time	Source	Destination	Protocol	Length	Info
24507	3504.4121439…	192.168.4.1	172.217.170.42	GTP <T…	771	Application Data
24508	3504.4453824…	172.217.170.42	192.168.4.1	GTP <T…	102	443 → 60283 [ACK]
24509	3504.8234764…	11.0.0.66	11.0.0.26	SCTP	98	HEARTBEAT
24510	3504.8237304…	11.0.0.26	11.0.0.66	SCTP	98	HEARTBEAT_ACK
24511	3504.9349045…	172.217.170.42	192.168.4.1	GTP <T…	169	Application Data
24512	3504.9351673…	172.217.170.42	192.168.4.1	GTP <T…	477	Application Data
24513	3504.9352788…	172.217.170.42	192.168.4.1	GTP <T…	159	Application Data

b)

11.0.0.26	SCTP	82	INIT
11.0.0.66	SCTP	306	INIT_ACK
11.0.0.26	SCTP	278	COOKIE_ECHO
11.0.0.66	SCTP	50	COOKIE_ACK
11.0.0.26	S1AP	122	S1SetupRequest
11.0.0.66	SCTP	62	SACK
11.0.0.66	S1AP	110	S1SetupResponse
11.0.0.26	SCTP	62	SACK

Fig. 3. A Wireshark [85] screenshot for the Fraunhofer core's output, with handset connected to the eNB. a) samples of core network, eNB and UE communications, b) sample communications between core network and eNB via S1 interface.

Attaching UE to our mobile network: We then connected the user equipment (UE) with the programmed SIM card to the network. A sample of the activity is presented in a screen shot shown in Fig. 3. Fig. 3 depicts a print-screen taken from the Wireshark's graphic user interface which shows live packet from the eNode B and the UE. The IP addresses are explained as follows: 11.0.0.26 is the address of the eNB, 11.0.0.66 is the address for the Fraunhofer core, and 192.168.4.1 is the address for the UE.

Testing basic functionality: When the phone was attached to our mobile network, we tested the ability to browse the Internet pages from the phone on several randomly selected Websites and used the *www.speedtest.net* to measure the connection speed. This approach was then replaced by downloading and using the Speedtest app on the phone. A sample of a typical result is shown in Fig. 4.

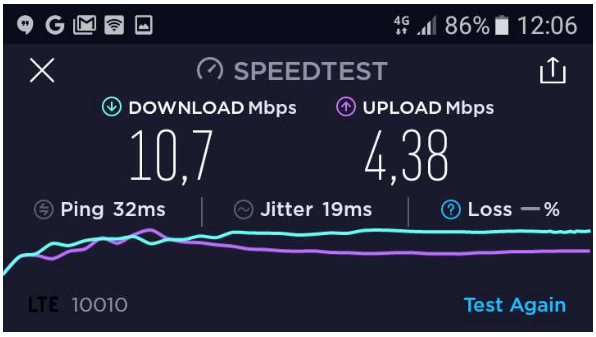


Fig. 4. A part of a print-screen taken from a Galaxy J5 phone showing that the connection on our 4G network is working and we were able to run the *Speedtest* app on the phone. Our current network ID ("10010") can be seen in the left bottom corner.

Identifying the best location: These tests (like most of the tests mentioned below) were repeated for several different UE locations in the room, relative to the eNB antenna. At each location, we repeated the speed measurements five times and estimated the averages and standard deviations. Based on these results, we selected the best location (which was next to the BS and gave the highest speed) in the room for subsequent tests.

A summary of all the final results the measurements is provided in Table II (also applies to the steps that follow). The following tools were used:

iperf tests: We then did a throughput measurement using the utility *iperf* in the form of the "Magic iPerf" app downloaded from Google App Store. In order to get a glance at the influence of the base station, we measured the throughput between the different parts of our setup.

ping tests: We then used the "Ping Tools" application downloaded onto the phone from Google App Store to do a *ping* latency/delay measurement. To establish the delay introduced by our experimental mobile network, like before, we measured the latency between the different parts of our setup.

The results shown in Table II show that our current configuration offers uplink and downlink speeds up to about 30 Mbps and 28 Mbps, respectively, and has about 14 ms of latency (although iperf indicates that 32 Mbps should be achievable).

Finer analysis provided additional insights, e.g.

- The results of the speedtest run from the Core server and two iperf measurements between the base station and core servers and between the core server and a laptop on the organisational local area network (LAN) are all very stable (i.e. have low fluctuation) and yet limited to under 100 Mbps, despite the gigabit links and gigabit LAN (e.g. speedtest from the lab laptop showed 300-600 Mbps performance). This bottleneck needs to be investigated (e.g. it could potentially be attributed to the settings of the link).

- The very high latency observed for UE measurements in “UL” case as well as the also deserve a further investigation.

TABLE II. SUMMARY OF MEASURED RESULTS*.

Test method	Connection route / where the packets are sent from		Measured throughput, Mbps		Measured ping delay, ms	
	From	**To**	**UL**	**DL**	**UL**	**DL**
speedtest *on a commercial network*	UE	-	30 ±1.3	28.3 ±5	26.2 ±6.5	
Test via our OAI testbed platform:						
speedtest	UE	-	27.6 ±5	29.6 ±4	13.8±0.8	
speedtest	Core	-	93.8 ±0.6	80.7 ±5	20.2±1	
speedtest	Lab Laptop	-	573 ±42	306 ±8	19.2±0.8	
iperf	UE	BS server	28.2 ±8	34 ±7	-	
iperf	UE	Core	27.7 ±4	32.2 ±6	-	
iperf	UE	Lab Laptop	32.4 ±7	30.6 ±6	-	
iperf	BS server	Core	91.2 ±0.5	90.4 ±1	-	
iperf	Core	Lab Laptop	95.1 ±2	90.2 ±2	-	
ping	UE	BS server	-	-	75.1 ±20	13.4 ±2
ping	UE	Core	-	-	57.8 ±24	1.4 ±0.6
ping	UE	Lab Laptop	-	-	85.1 ±16	12.3 ±3
ping	Core	Lab Laptop	-	-	2.1 ±0.4	2.4 ±0.9

* *The notations are as follows: the “UE” refers to the user terminal (smartphone); “BS server” refers to “eNB server”, “Core” refers to the Fraunhofer core network server, “Laptop” refers to the “Lab laptop”. The “UL” stands for uplink (from UE; for iperf this corresponds to the default/forward direction), and “DL” for downlink (to UE; for iperf this corresponds to the reverse direction obtained with the use of “-r” command line option). The speedtest used an app on UE. The iperf and ping used both the apps and command line tools on UE and servers/laptop, respectively.*

V. SUMMARY AND NEXT STEPS

The paper overviews an experimental mobile network testbed based on the Open Air Interface for radio access network (RAN) and Fraunhofer core. The testbed has been tested in 4G mode and showed measured downlink and uplink throughput of 30 Mbps and 28 Mbps, respectively and Internet access latency of around 14 ms.

As the next steps, we plan to test UE handover between two identical eNBs, optimise the system and achieve performances closer to the theoretical limits of LTE. We also need to identify the source(s) of the bottleneck and substantial latency being experienced.

As the OAI software releases supporting 5G become available, we shall look into a non-standalone (NSA) configuration supporting both 4G and 5G. We plan to pay special attention to the above-mentioned features important for rural deployments, such as uplink/downlink decoupling [87].

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