An Experimental 5G Standalone Testbed for Rural Connectivity

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Abstract. Digital transformation in service sectors like agriculture, education and healthcare has to be accelerated specifically in African countries to achieve the Sustainable Development Goals (SDG) in 2030. 5G technology allowing flexibility and scalability in networks service deployment is among the technologies that can help this acceleration but its deployment is expensive with proprietary and vendor specific hardware and software. Therefore, open-source implementation allowing low-cost system design gains importance mainly for rural areas where the duration of a return on investment is long or even not guaranteed for operators, thus promoting private initiatives. Even though non standalone 5G networks (5G NSA) deployment approach is seen as an economic way for 5G migration, it is not suitable in contexts where 4G LTE is barely deployed or for private networks. This is the case for most Sub-Saharan countries where 4G LTE coverage is foreseen to be lower than 30% in 2025. We deployed a low cost standalone 5G network (5G SA) using the open source OpenAirInterface (OAI) and commercial-off-the-shelf (COTS) equipment to leverage 5G technology. This testbed helps to test and validate 5G services with private networks affordable to low budget laboratories for digital transformation in rural zones. Two types of experiments were conducted to validate the platform: (1) to assess enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low latency (URLLC) capabilities, (2) to assess common users needs by implementing and testing Voice over New Radio (VoNR).

Keywords: 5G · Standalone · OpenAirInterface · VoNR

1 Introduction

The question of the optimal deployment mode for the transition from 4G to 5G is widely addressed in the literature and cost is often put forward to choose the NSA

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mode. 5G NSA constitutes the majority of the first deployments and relies on the existing 4G infrastructure to benefit from low-band coverage and connection to the 4G network's evolved packet core (EPC) to which the functionalities required to support the new 5G standard are added for more reliable connectivity with enhanced mobile broadband. However, such a choice requires an existing global 4G coverage but this is not the case in many African countries where the level of 4G coverage is low with disparities between urban and rural areas. The resulting digital divide is an obstacle to economic, health care, very high attendance social activities. The question arises for operators whether to invest in 4G infrastructure and deployment or to make the leap from 3G to 5G and adopt standalone migration to 5G despite the cost of investment. Bridging the digital divide is an urgent need if we want to achieve the SDGs in 2030 and long-term strategies cannot prosper and this favours private initiatives.

Actually, use cases where ultra-low latency and much higher capacity are required will only be feasible with 5G SA. Consequently, a different migration scheme not relying on 4G LTE infrastructure and able to provide full benefits of a 5G network would be more appropriate and beneficial. As such, directly implementing 5G SA, without going through 5G NSA, may be an appropriate choice. Besides offering greater possibilities to exploite new network use cases, 5G SA also makes it possible to overcome spectral and technological constraints for those who have not deployed 4G [1]. Liu et al. [2] analysed and compared new radio (NR) 5G SA and 5G NSA in terms of coverage, network capacity, interworking between 4G and 5G, complexity, deployment cost and the latest developments in the sector. While 5G NSA NR appears to outperform in terms of interworking in the initial phase, 5G SA NR outperforms in terms of network capacity, device performance, energy efficiency, simplicity of network deployment and cost-effectiveness [3]. Another advantage of 5G-SA is network slicing which gives the possibility to divide the network according to utilisation needs and perform network resources sharing. In addition, 5G represents a major turning point for Internet access at much higher speeds than 4G, African countries must adopt this technology, particularly to bridge the SDGs. Deploying 5G networks can help reduce the digital divide by improving Internet accessibility in rural and remote areas where fixed infrastructure is limited. It also can enable the rural communities to access connectivity based services such as distance education and remote medical care. Low cost private networks capable to deliver customised solutions can help to bridge the digital divide and 5G SA are great opportunity to exploit.

However, the cost of deploying 5G can be expensive. It is thus important to set up testbeds to deploy 5G SA networks to study and test use cases, particularly in the absence of a 4G LTE network. Network simulators are often used to this end but they are not always sufficient and a rigorous evaluation of the actual operating mode is required [4]. The option of carrying out real-life evaluations on testbeds using commercial 5G equipment is a scenario with many restrictions related to the constraints on deployment and configuration flexibility inherent to proprietary solutions. This is why the market for open-source solutions is booming in the telecoms sector, particularly in mobile networks. The traditional RAN has, for example, evolved into an open, flexible and virtualised network known as Open-RAN [5] which enables multi-vendor deployment to use interchangeable hardware and software with open interfaces. Thus, thanks to open-source implementations and SDN (Software Defined Networking) and NFV (Network Functions Virtualisation) technologies, we can deploy a 5G network in real mode and at low cost.

F. John et al. [6] and Y. Gao et al. [7] addressed OAI-based deployment of 5G SA networks and several others like F. M Tufeano et al. [8] used software-based deployment. A minimal deployment is presented in [6] while a minimal and basic deployments using virtual machines (VM) were considered in [7] and a comparison between the performance of minimal and basic deployments with the gnbsim software was established in [8]. Tufeano's results in [8] are based on simulations while emulation of real-mode operation is desirable with real equipment, particularly for 5G-SA. The VM used Gao in [7] are known to use far more resources than docker containers [8,9] and require powerful machines and constitute a major limitation for low budget designs considered in this work. Furthermore, although the unified data management (UDM) function is used in [7], as compared to [6], the authentication server function (AUSF) server and the unified data repository (UDR) are not included whereas AUSF is a complementary function to UDM necessary to provide a secure and consistent user experience in a 5G network [10].

The main contributions of this paper include (1) building a low cost 5G SA testbed with open-source solution, limited energy consumption and applicable in challenging environments and rural areas in the absence of 4G Telecommunication infrastructure preventing NSA migration. (2) Developing a testbed with eMBB, mMTC, and URLLC capabilities to enhance connectivity and digital services opportunities in rural zone to bridge the digital divide and promote 5G education, heath and intelligent agriculture uses cases to leverage 5G technology to achieve SDG. (3) Validating the testbed capability to cover users' common needs and support VoNR implementation.

This paper addresses the implementation and tests of an affordable basic 5G SA testbed using OAI open-source solutions, docker containers, Universal Software Radio Peripherals (USRP B210) and COST equipment. The affordable testbed is intended to build privates networks to set up 5G use cases to reduce the digital divide in rural and remote areas. The rest of the paper is organised as follows. Section 2 is devoted to the presentation of the 5G SA testbed. Section 3 gives the results of the assessment tests of the testbed along with experimental results on VoNR tests to validate the deployment. Section 4 draws concluding remarks and outline ongoing work.

2 The 5G SA Testbed

Our testbed is based on the open source OpenAirInterface (OAI) implementation [11] which enables to set up future open-source cellular networks by offering both core (5GC) and radio access (5G RAN) deployment possibilities with Docker containers to virtually create all the components and enhance resource usage. The OAI 5G RAN stack supports and emulates [12] the gNodeB and the user equipment (UE) and manages the interactions between them. The UE can be either a 5G phone or an OAI-UE. The OAI-5GC provides a 3GPP-compliant implementation and is easily adaptable to different 5G use cases [13]. The system is deployed on computers with the following specifications: Operating System: Linux Lowlatency kernel Ubuntu 20.04 LTS; Processors: Intel(R) Core (TM) i5-10210U CPU @ 1.60GHz 2.11 GHz; RAM: 8 GB; UHD Driver. Two USRP B210 SDRs are used in the setup, one acting as a radio access point at the gNB level and the other emulating a UE. We also used an Oppo 5G phone equipped with an Open cells SIM card. Each USRP is linked to a machine via an Universal Serial Bus (USB) 3.0 interface. The experimentation was performed in the n78 band (3300 MHz–3800 MHz) at a 3.6 GHz frequency and a 40 MHz bandwidth (106 PRB). The key physical layer parameters are gathered in Table 1. The architecture of the basic 5G SA with the network functions (NF) deployed are shown in Fig. 1.

Table 1. Key parameters of the physical layer.

Parameter	FR1
Access scheme	DL: CP-OFDM, UL: CP-OFDM 14 Symbols: DL (6), UL (4) flexible (4)
carrier aggregation	1 carrier: 3.6 GHz
Bandwidth per carrier	40 MHz (106 PRB)
Subcarrier spacing	30 kHz
Number of subcarriers	1272
Modulation scheme	QPSK, 64 QAM
MIMO scheme	1x1
Duplex mode	TDD

The IP addresses of all the subsystems and NFs are grouped in Table 2. The NFs in the 5GC and the IMS are deployed in a docker container in the same computer as the gNB to reduce the latency.

The AMF (access and mobility function), UPF (user plane function), SMF, AUSF, UDM, UDR and NRF functions are deployed in the 5GC. The experimental platform is shown in Fig. 2, it features four subsystems: 1) the 5GC (core network), 2) the 5G-RAN (access network), 3) the OAI UE and 4) the oppo 5G phone.

2.1 OAI 5GC and 5G RAN Configurations

The OAI provides the image of each network core component in a Docker containers. After extraction, the $docker - compose.yaml$ file must be mod-

Table 2. IP addresses.

Subsystem/NF	IP address	Subsystem/NF	IP address
5GC	192.168.70.0/24	OAI-EXT-DN	192.168.70.135
gNB	192.168.70.129	UDM	192.168.70.137
NRF	192.168.70.130	UDR	192.168.70.136
AMF	192.168.70.132	AUSF	192.168.70.138
SMF	192.168.70.133	IMS	192.168.70.139
UPF	192.168.70.134	UE	12.1.1.128/25

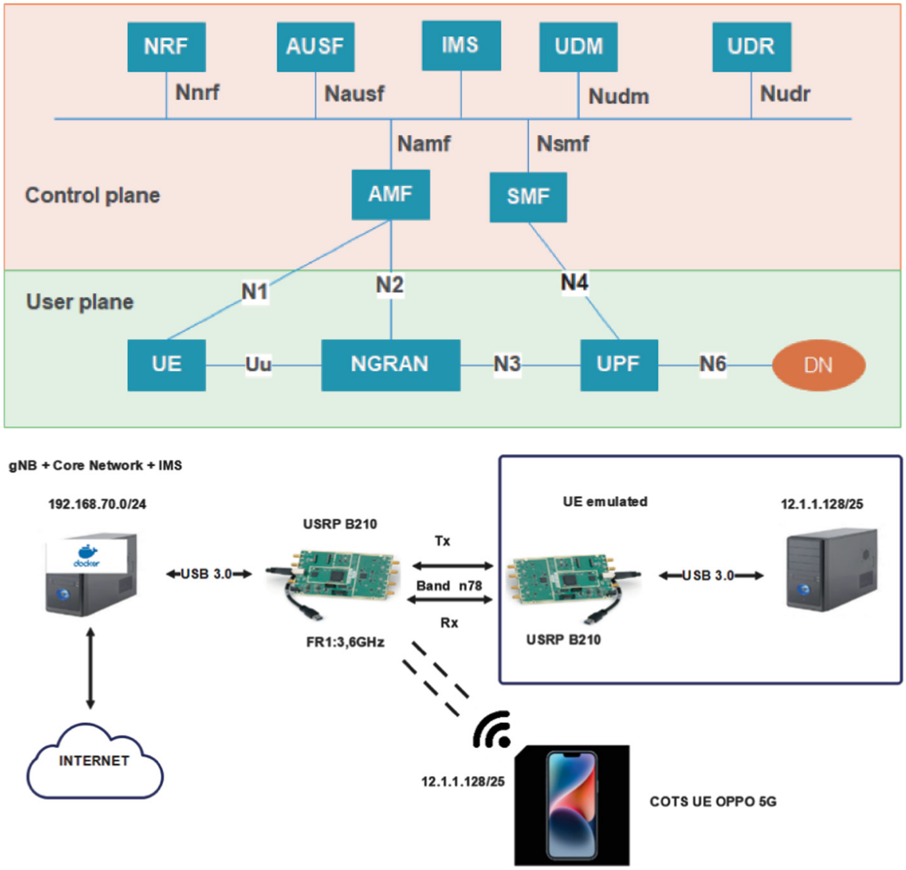


Fig. 1. The deployed basic 5G SA architecture with all the necessary NFs and used subsystems along with their IP addresses.

ified to achieve successful and stable communication between all components. As Docker container traffic is not forwarded to the outside world by default, IP forwarding must be enabled using the following Linux commands:

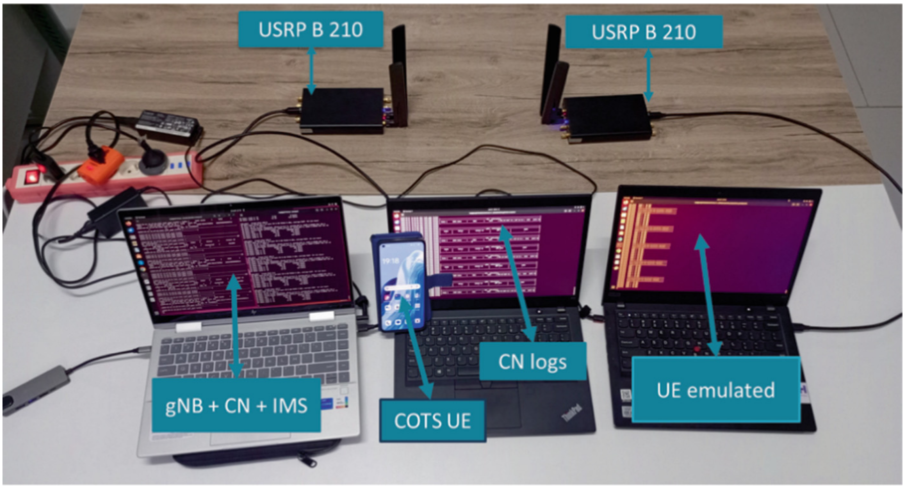
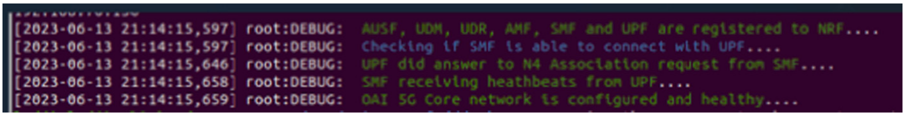


Fig. 2. The experimental 5G SA testbed.

$sudo\, sysctl\, net.ipv4.conf.all.forwarding = 1$ and $sudoiptables - PFORWARD\ ACCEPT$. Once the packet forwarding rules are defined, the Subscriber Identity Module (SIM) details for the OAI UE are added to the $oai\_db.sql2file$. The information added includes the user Identity (IMSI) and the corresponding key, so that the 5GC can identify and authenticate subscribers such as UEs. An interface called $demo - oai$ which contains all the network components and the static IP address configuration is created when the 5GC is launched. The $2024.w03$ branch is used to configure the access network for the gNodeB and the UE; it can handle up to 16 UEs. The same SIM details must be used in the gNodeB configuration file ($gnb.sa.band78.fr1.106PRB.usrpb210.conf$), as added to the 5GC. The same mobile country code (MCC) and mobile network code (MNC) as those used when defining the IMSI should be used. The UE information details are as follow: $uicc0 = \{imsi = “208950000000031”; key = “0C0A34601D4F07677303652C0462535B”; opc = “63bfa50ee6523365ff14c1f45f88737d”; dnn = “oai”; nssai\_sst = 1; nssai\_sd = 0xFFFFFF; \}$ where dnn is the domain name, OPC is the operator cipher key, nssai is the Network Slice Selection Assistance Information, sst is the slice/service type and sd is the slice differentiator. Deployment is for one slice.

2.2 5G SA Network Deployment Assessment

Successful deployment is assessed by verifying that (1) all NFs are well configured, healthy and registered with the NRF, (2) downlink and uplink synchronisation are performed, (3) the gNodeB is successfully linked to the AMF, (4) the UE is registered to the AMF and, IMSI, downlink and uplink IDs, PLMN, MNC and cell ID are specified, (5) the PDU session is established, and an IP address is assigned to the UE. The proofs of successful implementation of these steps are given in Fig. 3, 4, 5 and 6.



```
[2023-06-13 21:14:15,597] root:DEBUG:  AUSF, UDM, UDR, AMF, SMF and UPF are registered to NRF....
[2023-06-13 21:14:15,597] root:DEBUG:  Checking if SMF is able to connect with UPF....
[2023-06-13 21:14:15,646] root:DEBUG:  UPF did answer to N4 Association request from SMF....
[2023-06-13 21:14:15,658] root:DEBUG:  SMF receiving heathbeats from UPF....
[2023-06-13 21:14:15,659] root:DEBUG:  OAI 5G Core network is configured and healthy....
```

Fig. 3. Core network successfully deployed. All NFs are registered with the NRF.

```
[NR_MAC]   Frame.Slot 768.0

[NR_PHY]   [gNB 0][RAPROC] Frame 837, slot 19 Initiating RA procedure with preamble 7, energy
  55.7 dB (I0 69, thres 120), delay 8 start symbol 0 freq index 0
[MAC]   UL_info[Frame 837, Slot 19] Calling initiate_ra_proc RACH:SFN/SLOT:837/19
[NR_MAC]   [gNB 0][RAPROC] CC_id 0 Frame 837 Activating Msg2 generation in frame 838, slot 7
  using RA rnti 10b SSB, new rnti e021 index 0 RA index 0
[NR_MAC]   [gNB 0][RAPROC] CC_id 0 Frame 838, slotP 7: Generating RA-Msg2 DCI, rnti 0x10b,
  state 1, CoreSetType 2
[NR_MAC]   [RAPROC] Msg3 slot 17: current slot 7 Msg3 frame 838 k2 7 Msg3_tda_id 3
[NR_MAC]   [gNB 0][RAPROC] Frame 838, Subframe 7: rnti e021 RA state 2
[NR_MAC]   Adding UE with rnti 0xe021
[NR_MAC]   [gNB 0][RAPROC] PUSCH with TC_RNTI 0xe021 received correctly, adding UE MAC
  Context RNTI 0xe021
[NR_MAC]   [RAPROC] RA-Msg3 received (sdu_lenP 7)
[MAC]   [RAPROC] Received SDU for CCCH length 6 for UE e021
[NR_MAC]   Added new CBRA process for UE RNTI e021 with initial CellGroup
[RLC]   activated srb0 for UE with RNTI 0xe021
[RLC]   ../../../openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:693:nr_rlc_add_srb: added srb 1 to
  UE with RNTI 0xe021
[NR_MAC]   Activating scheduling RA-Msg4 for TC_RNTI 0xe021 (state 2)
[NR_MAC]   Unexpected ULSCH HARQ PID 0 (have -1) for RNTI 0xe021 (ignore this warning for RA)
[RRC]   initial UL RRC message nr_cellid 0 does not match RRC's 12345678
[NR_RRC]   Decoding CCCH: RNTI e021, payload_size 6
[NR_RRC]   search by rnti not found e021
[NR_RRC]   search by rnti not found e021
[NR_RRC]   Returning new RRC UE context RRC ue id: 0
[NR_RRC]    Created new UE context rnti: e021, random ue id 444365f5e2000000, RRC ue id 0
[NR_RRC]   rrc_gNB_generate_RRCSetup for RNTI e021
[NR_MAC]   ( 839. 6) SRB0 has 157 bytes
[NR_MAC]   ( 839. 7) SRB0 has 157 bytes
[NR_MAC]   ( 839.10) SRB0 has 157 bytes
[NR_MAC]   Generate msg4, rnti: e021
[NR_MAC]   Encoded RRCSetup Piggyback (157 + 2 bytes), mac_pdu_length 166
[NR_MAC]   (UE RNTI 0xe021) Received Ack of RA-Msg4. CBRA procedure succeeded!
[NR_MAC]   (840.3) Activating RRC processing timer for UE e021 with 10 ms
[NR_MAC]   (841.3) De-activating RRC processing timer for UE e021
[NR_MAC]   Modified rnti e021 with CellGroup
[NR_MAC]   Added new CBRA process for UE RNTI e021 with initial CellGroup
[NR_RRC]   Received rrcSetupComplete, 5g_s_TMSI: 0x123456789ABC, amf_set_id: 0x48(72),
  amf_pointer: 0x34(52), 5g TMSI: 0x56789ABC
[NR_RRC]   [FRAME 00000][gNB][MOD 00][RNTI e021] [RAPROC] Logical Channel UL-DCCH, processing
  NR_RRCSetupComplete from UE (SRB1 Active)
[NR_RRC]   [FRAME 00000][gNB][MOD 00][RNTI e021] UE State = NR_RRC_CONNECTED
[NGAP]   [gNB 0] Chose AMF 'OAI-AMF' (assoc_id 17) through selected PLMN Identity index 0 MCC
  208 MNC 95
[NGAP]   NGAP_FIND_PROTOCOLIE_BY_ID ie is NULL (searching for ie: 110)
[NGAP]   could not found NGAP_ProtocolIE_ID_id_UEAggregateMaximumBitRate
[NGAP]   NGAP_FIND_PROTOCOLIE_BY_ID ie is NULL (searching for ie: 71)
[NGAP]   AllowedNSSAI.list.count 1
[NGAP]   NGAP_FIND_PROTOCOLIE_BY_ID ie is NULL (searching for ie: 36)
```

```
[NR_PHY]   Starting sync detection
[PHY]   [UE thread Synch] Running Initial Synch
[PHY]   [UE] nr_synchro_time: Sync source = 0, Peak found at pos 321344, val = 51793954186 (107 dB)
  avg 69 dB, ffo 0.010267
[PHY]   PSS execution duration 38043 microseconds
[PHY]   [UE0] Initial sync : Estimated PSS position 321344, Nid2 0
[PHY]   sync_pos 321344 ssb_offset 321236
[PHY]   Calling sss detection (normal CP)
[NR_PHY]   ffo_pss 0.010267 (308 Hz), ffo_sss -0.001309 (-39 Hz),  ffo_pss+ffo_sss 0.008957 (268 Hz)
[PHY]   [UE0] Initial sync: starting PBCH detection (rx_offset 0)
[NR_RRC]   Configuring MAC for first MIB reception
[PHY]   [UE0] Initial sync: pbch decoded sucessfully
[PHY]   TDD Normal prefix: CellId 0 metric 272873, phase 8, pbch 0
[PHY]   [UE0] In synch, rx_offset 317924 samples
[PHY]   HW: Configuring channel 0 (rf_chain 0): setting tx_freq 3619200269 Hz, rx_freq 3619200269
  Hz, tune_offset 0
[PHY]   Got synch: hw_slot_offset 28, carrier off 269 Hz, rxgain 110.000000 (DL 3619200269.000000
  Hz, UL 3619200269.000000 Hz)
Setting USRP TX Freq 3619200269.000000, RX Freq 3619200269.000000, tune_offset: 0.000000
[NR_RRC]   SIB1 decoded
[NR_MAC]   NR band duplex spacing is 0 KHz (nr_bandtable[37].band = 78)
[NR_MAC]   NR band 78, duplex mode TDD, duplex spacing = 0 KHz
[NR_MAC]   TDD has been properly configured
[NR_RRC]   [UE 0] : Logical Channel UL-CCCH (SRB0), Generating RRCSetupRequest (bytes 6, gNB 0)
[PHY]   UE synchronized decoded_frame_rx=2147483647 UE->init_sync_frame=1 trashed_frames=8
[PHY]   Resynchronizing RX by 317924 samples
[NR_PHY]   ============================================
[NR_PHY]   Harq round stats for Downlink: 1/0/0
[NR_PHY]   ============================================
[NR_PHY]   ============================================
[NR_PHY]   Harq round stats for Downlink: 1/0/0
[NR_PHY]   ============================================
[NR_PHY]   ============================================
[NR_PHY]   Harq round stats for Downlink: 1/0/0
[NR_PHY]   ============================================
[NR_MAC]   NR band duplex spacing is 0 KHz (nr_bandtable[37].band = 78)
[NR_MAC]   NR band 78, duplex mode TDD, duplex spacing = 0 KHz
[MAC]   Initialization of 4-step contention-based random access procedure
[NR_MAC]   PRACH scheduler: Selected RO Frame 837, Slot 19, Symbol 0, Fdm 0
[PHY]   PRACH [UE 0] in frame.slot 837.19, placing PRACH in position 1804, msg1 frequency start 0
  (k1 0), preamble_offset 1, first_nonzero_root_idx 0
[NR_MAC]   [UE 0][RAPROC] Got BI RAR subPDU 5 ms
[NR_MAC]   [UE 0][RAPROC] Got RAPID RAR subPDU
[NR_MAC]   [UE 0][RAPROC][838.7] Found RAR with the intended RAPID 7
[MAC]   received TA command [illegible]
[NR_MAC]   [RAPROC][838.17] RA-Msg3 transmitted
[MAC]   [UE 0][RAPROC] Frame 839 : received contention resolution identity: 0x1e2f56543446
  Terminating RA procedure
[MAC]   [UE 0][839.10][RAPROC] RA procedure succeeded. CB-RA: Contention Resolution is successful.
<DL-CCCH-Message>
```

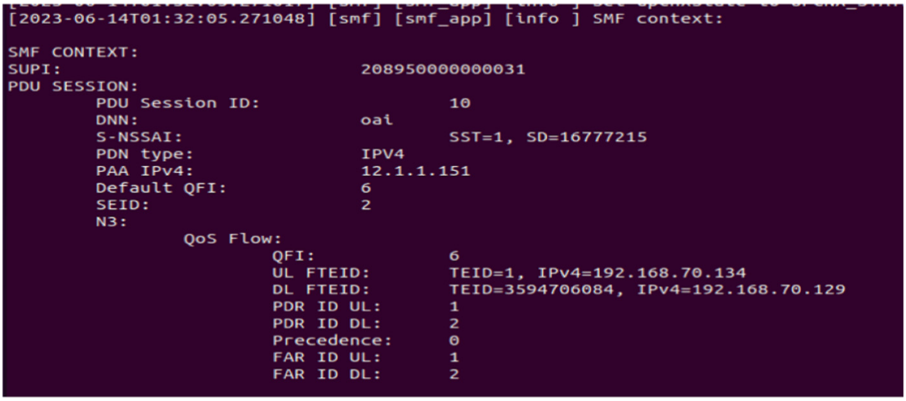
Fig. 4. Downlink and uplink synchronisations procedure after 5G RAN and UE deployment and random access procedure execution with contention resolution (msg1, msg2, msg3, msg4). Shown in gNodeB-log file and UE-log file.

3 Experimentation and Validation

In this section we perform experiments to validate the performance of the testbed. Once the 5GC is successfully deployed with all the NFs well configured and healthy, synchronisation is successfully completed for downlink and uplink channels, the 5G SA network is ready for use. The UE communicates with the gNodeB which transmits information to the AMF in the 5GC. The

```
[AMF] [amf_app] [info ] |----------------------------------------------------------------------------------------------------|
[AMF] [amf_app] [info ] |---------------------------------------------gNBs' information--------------------------------------|
[AMF] [amf_app] [info ] |    Index    |      Status      |       Global ID       |       gNB Name       |           PLMN           |
[AMF] [amf_app] [info ] |      1      |    Connected     |        0xe000         |       gNB-OAI        |          208, 95          |
[AMF] [amf_app] [info ] |----------------------------------------------------------------------------------------------------|
[AMF] [amf_app] [info ]
[AMF] [amf_app] [info ] |----------------------------------------------------------------------------------------------------|
[AMF] [amf_app] [info ] |---------------------------------------------UEs' information---------------------------------------|
[AMF] [amf_app] [info ] | Index |      5GMM state      |      IMSI       |      GUTI      | RAN UE NGAP ID | AMF UE ID |  PLMN   |Cell ID|
[AMF] [amf_app] [info ] |      1|      5GMM-REGISTERED|  208950000000031|                |               0|          1| 208, 95 |14680064|
[AMF] [amf_app] [info ] |----------------------------------------------------------------------------------------------------|
```

Fig. 5. gNodeB and UE registration shown in the AMF-log file, PLMN = 208, MNC = 95, IMSI = 200950000000031, downlink channel ID = 0, uplink channel ID = 1, cell ID = 14680064.



```
[2023-06-14T01:32:05.271048] [smf] [smf_app] [info ] SMF context:

SMF CONTEXT:
SUPI:                           208950000000031
PDU SESSION:
        PDU Session ID:                 10
        DNN:                    oai
        S-NSSAI:                        SST=1, SD=16777215
        PDN type:               IPV4
        PAA IPv4:               12.1.1.151
        Default QFI:            6
        SEID:                   2
        N3:
                QoS Flow:
                        QFI:            6
                        UL FTEID:       TEID=1, IPv4=192.168.70.134
                        DL FTEID:       TEID=3594706084, IPv4=192.168.70.129
                        PDR ID UL:      1
                        PDR ID DL:      2
                        Precedence:     0
                        FAR ID UL:      1
                        FAR ID DL:      2
```

Fig. 6. An IP address = 12.1.1.151 assigned to the UE in the SMF-log file after PDU session establishment.

information is mainly transmitted using the next generation application protocol (NGAP) located on the N2 reference point between the gNodeB and the AMF and related to the authentication and configuration of radio communication established between the gNodeB and the UE.

The first experiment assessed the network capability of the testbed by evaluating (1) handshake validation, UE connection, and network traffic with Wireshark tool, (2) internet connectivity and network latency with the ping command and (3) jitter and throughput performances with the Iperf3 tool. VoNR is implemented in the second experiment and web browsing and video streaming are tested.

Experiment 1 Tests with an OAI-UE: The main goal of this experiment is to test and validate the functioning of the 5G SA testbed. As such, UE connection to the 5G deployed network, data traffic and low latency capabilities are tested to validate the deployment with an OAI-UE. The handshake and session establishment through the NGAP protocol which is used in the communication between the gNB and the AMF are shown on Fig. 7. The gNodeB (IP 192.168.70.129) first synchronises with the AMF (IP 192.168.70.132) and sends registration request to the AMF on behalf of the UE. The process for authentication and security for downlink (DL) and uplink (UL) resource reservation is then initiated along with overall initial UE context. Once radio communications are established, the core network components exchange messages using the HTTP protocol and check whether the UE's SIM information is correctly configured. The SMF (192.168.70.133) finally establishes the PDU session. The involved components are the gNodeB (IP 192.168.70.129), the AMF (IP 192.168.70.132) and the SMF (192.168.70.133) which finally establishes the PDU session after the UE registration.

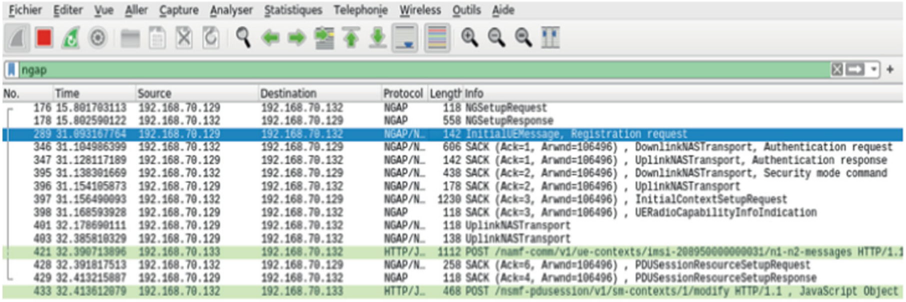
Internet connectivity is tested by pinging the google's DNS server (8.8.8.8) with an average round-trip time (RTT) of 61.078 ms as shown in Fig. 8.

The Iperf3 tool is used to generate TCP/UDP data streams and measure the throughput, and the jitter. To this end, we started two Iperf processes in the UE and the external data network $oai-ext-dn$ (an Ubuntu Linux container with a WiFi Internet connection). For the downstream flow test, the UE/$oai-ext-dn$ is used as the server/client. For the upload test, the UE/$oai - ext - dn$ is used as the client/server. We measured the uplink and downlink throughputs with target throughput of 35 Mbits. The system achieved an average jitter of 0.7 ms and an average throughput of 30 Mbps on the uplink channel, as shown in Fig. 9 while an average jitter of 0.5 ms and a throughput of 35 Mbps were achieved on the downlink. Theory calculations, give a minimum throughput of 17.40/12.41 Mbit/s and a maximum throughput of 72.91/52 Mbit/s on the downlink and the uplink channels, respectively. The throughput values could appear somewhat low but this can be attributed to several factors including the performance of the computers and the bandwidth limitation of the USRP B210 devices with no amplification and MIMO. As for the jitter, the values are way below the cisco limit recommandation of 30 ms for VoIP.

For latency tests, we sent ping messages, consecutively within 10 s, between the $oai - ext - dn$ container on the 5G network core machine and the UE. We obtained a RTT in the interval [5.481,13.902] ms with an average value of 9.161 ms. These values are significantly lower than typical values in LTE networks at around 100 ms and can be lowered in subsequent system improvement.

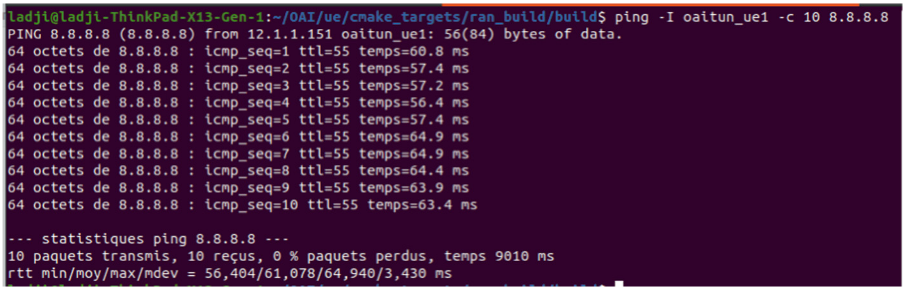
Experiment 2 Web Browsing, Video Streaming and VoNR Tests with a Commercial 5G Phone: The goal of this experiment is to test the common user needs like web browsing and video streaming with the 5G SA testbed using a commercial UE, namely the oppo 5G phone. In addition VoNR is also implemented and tested.

Video Streaming: Similarly, we successfully implemented the video streaming application using the StreamLink Python library, as illustrated in Fig. 10. StreamLink is a command-line utility that enables users to access and stream



No.	Time	Source	Destination	Protocol	Length	Info
176	15.801703113	192.168.70.129	192.168.70.132	NGAP	118	NGSetupRequest
178	15.802590122	192.168.70.132	192.168.70.129	NGAP	558	NGSetupResponse
289	31.093167764	192.168.70.129	192.168.70.132	NGAP/N…	142	InitialUEMessage, Registration request
346	31.104986399	192.168.70.132	192.168.70.129	NGAP/N…	606	SACK (Ack=1, Arwnd=106496) , DownlinkNASTransport, Authentication request
347	31.128117189	192.168.70.129	192.168.70.132	NGAP/N…	142	SACK (Ack=1, Arwnd=106496) , UplinkNASTransport, Authentication response
395	31.138301669	192.168.70.132	192.168.70.129	NGAP/N…	438	SACK (Ack=2, Arwnd=106496) , DownlinkNASTransport, Security mode command
396	31.154105873	192.168.70.129	192.168.70.132	NGAP/N…	178	SACK (Ack=2, Arwnd=106496) , UplinkNASTransport
397	31.156490093	192.168.70.132	192.168.70.129	NGAP/N…	1230	SACK (Ack=3, Arwnd=106496) , InitialContextSetupRequest
398	31.168593928	192.168.70.129	192.168.70.132	NGAP	118	SACK (Ack=3, Arwnd=106496) , UERadioCapabilityInfoIndication
401	32.178690111	192.168.70.129	192.168.70.132	NGAP/N…	118	UplinkNASTransport
403	32.385810329	192.168.70.129	192.168.70.132	NGAP/N…	138	UplinkNASTransport
421	32.390713896	192.168.70.133	192.168.70.132	HTTP/J…	1112	POST /namf-comm/v1/ue-contexts/imsi-208950000000031/n1-n2-messages HTTP/1.1
428	32.391817513	192.168.70.132	192.168.70.129	NGAP/N…	258	SACK (Ack=6, Arwnd=106496) , PDUSessionResourceSetupRequest
429	32.413215887	192.168.70.129	192.168.70.132	NGAP	118	SACK (Ack=4, Arwnd=106496) , PDUSessionResourceSetupResponse
433	32.413612079	192.168.70.132	192.168.70.133	HTTP/J…	468	POST /nsmf-pdusession/v1/sm-contexts/1/modify HTTP/1.1 , JavaScript Object

Fig. 7. NGAP messages between gNodeB and AMF for authentication, security and PDU establishment.



```
ladji@ladji-ThinkPad-X13-Gen-1:~/OAI/ue/cmake_targets/ran_build/build$ ping -I oaitun_ue1 -c 10 8.8.8.8
PING 8.8.8.8 (8.8.8.8) from 12.1.1.151 oaitun_ue1: 56(84) bytes of data.
64 octets de 8.8.8.8 : icmp_seq=1 ttl=55 temps=60.8 ms
64 octets de 8.8.8.8 : icmp_seq=2 ttl=55 temps=57.4 ms
64 octets de 8.8.8.8 : icmp_seq=3 ttl=55 temps=57.2 ms
64 octets de 8.8.8.8 : icmp_seq=4 ttl=55 temps=56.4 ms
64 octets de 8.8.8.8 : icmp_seq=5 ttl=55 temps=57.4 ms
64 octets de 8.8.8.8 : icmp_seq=6 ttl=55 temps=64.9 ms
64 octets de 8.8.8.8 : icmp_seq=7 ttl=55 temps=64.9 ms
64 octets de 8.8.8.8 : icmp_seq=8 ttl=55 temps=64.4 ms
64 octets de 8.8.8.8 : icmp_seq=9 ttl=55 temps=63.9 ms
64 octets de 8.8.8.8 : icmp_seq=10 ttl=55 temps=63.4 ms

--- statistiques ping 8.8.8.8 ---
10 paquets transmis, 10 reçus, 0 % paquets perdus, temps 9010 ms
rtt min/moy/max/mdev = 56,404/61,078/64,940/3,430 ms
```

Fig. 8. Internet connectivity with an average RTT of 61.078 ms for google DNS ping.

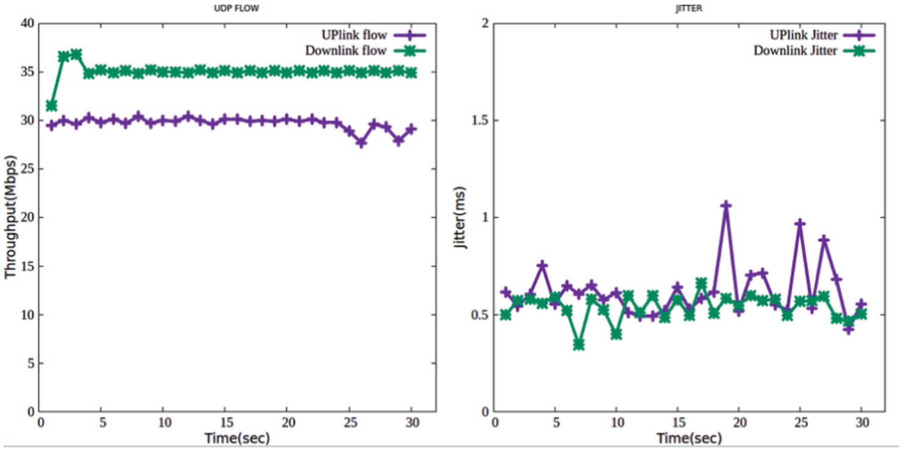
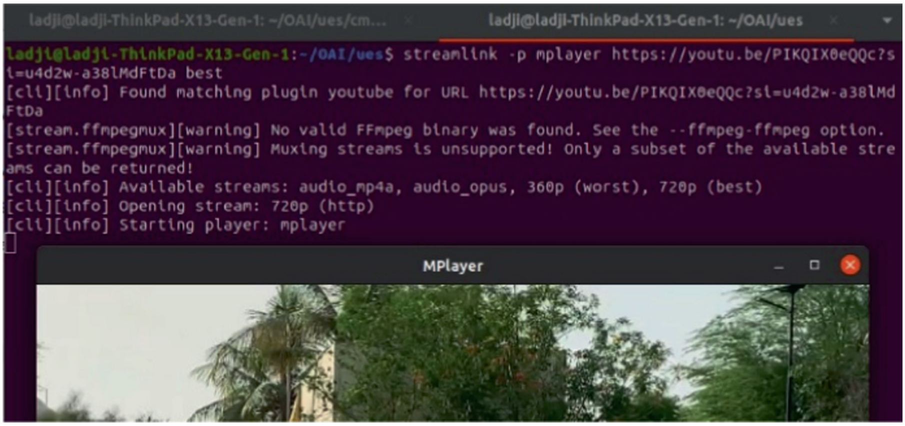
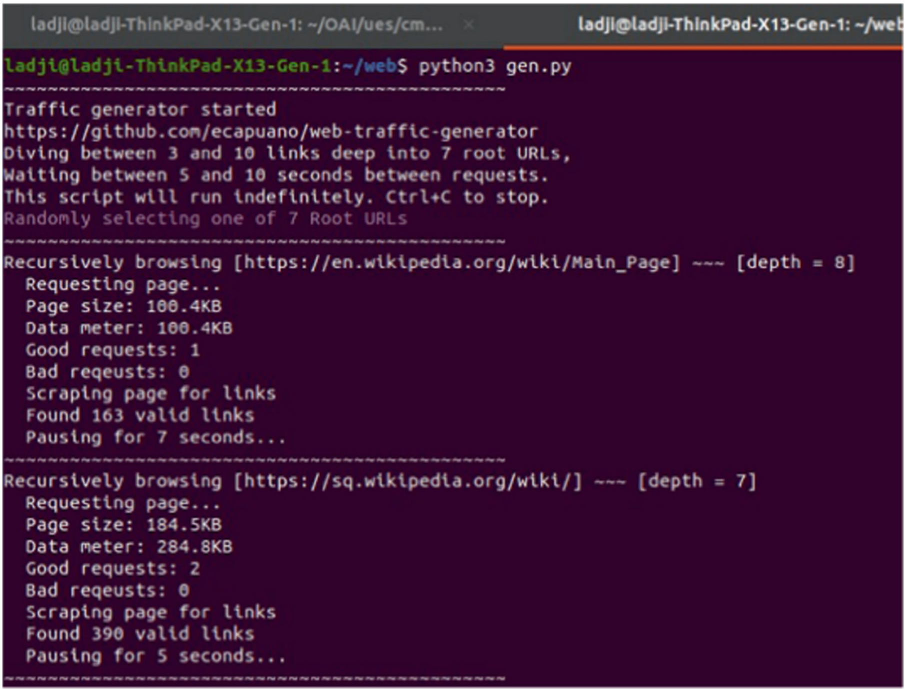


Fig. 9. Downlink, uplink and jitter measurements with Iperf3.



```
ladji@ladji-ThinkPad-X13-Gen-1:~/OAI/ues$ streamlink -p mplayer https://youtu.be/PIKQIX0eQQc?s
i=u4d2w-a38lMdFtDa best
[cli][info] Found matching plugin youtube for URL https://youtu.be/PIKQIX0eQQc?si=u4d2w-a38lMd
FtDa
[stream.ffmpegmux][warning] No valid FFmpeg binary was found. See the --ffmpeg-ffmpeg option.
[stream.ffmpegmux][warning] Muxing streams is unsupported! Only a subset of the available stre
ams can be returned!
[cli][info] Available streams: audio_mp4a, audio_opus, 360p (worst), 720p (best)
[cli][info] Opening stream: 720p (http)
[cli][info] Starting player: mplayer
```

Fig. 10. Video streaming test.



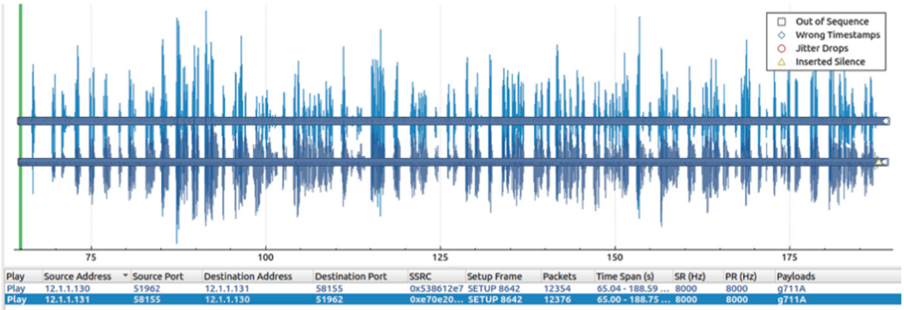
```
ladji@ladji-ThinkPad-X13-Gen-1:~/web$ python3 gen.py
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Traffic generator started
https://github.com/ecapuano/web-traffic-generator
Diving between 3 and 10 links deep into 7 root URLs,
Waiting between 5 and 10 seconds between requests.
This script will run indefinitely. Ctrl+C to stop.
Randomly selecting one of 7 Root URLs
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Recursively browsing [https://en.wikipedia.org/wiki/Main_Page] ~~~ [depth = 8]
  Requesting page...
  Page size: 100.4KB
  Data meter: 100.4KB
  Good requests: 1
  Bad reqeusts: 0
  Scraping page for links
  Found 163 valid links
  Pausing for 7 seconds...
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Recursively browsing [https://sq.wikipedia.org/wiki/] ~~~ [depth = 7]
  Requesting page...
  Page size: 184.5KB
  Data meter: 284.8KB
  Good requests: 2
  Bad reqeusts: 0
  Scraping page for links
  Found 390 valid links
  Pausing for 5 seconds...
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

Fig. 11. Web browsing test.

video feeds from various streaming platforms through their preferred media player, rather than via a web browser. It supports various streaming services, including livestreams, Twitch, YouTube, and many others.

Web Browsing: To assess the web browsing capability with the OAI-UE, we used the web traffic generator module available in GitLab [14] which simulates real user navigation on the internet. Web browsing is illustrated in Fig. 11.

VoNR: When the network is deployed, the oppo 5G phone equipped with an open cell sim card configured to access the 5G network is used to test VoNR implementation. We set up an infrastructure using Asterisk software, hosted in a docker container, acting as an IP Multimedia Subsystem (IMS) server deployed with the 5G system in the same computer. Asterisk is a open source software providing the flexibility needed to develop business applications communication supporting text, voice and video. We established a duplex voice call between the OAI-UE and an oppo 5G phone. Each UE was identified by a distinct IP address after the PDU session establishment. The IP addresses 12.1.1.131, 12.1.1.130, 192.168.70.139 and 192.168.70.134 are assigned to the USRP emulated UE, the COTS phone, the IMS server and the UPF server, respectively. We monitored the traffic with Wireshark to capture the trace of packets exchanged. Figure 12 illustrates the graphical representation of the voice call trace and Fig. 13 shows the flow exchange graph between UEs, UPF, IMS. We conducted performance analysis at the end of the call, revealing an average jitter of 3.30 ms for the outbound voice stream and 3.83 ms for the inbound voice stream. Furthermore, out of the 6177 expected packets, no loss was observed. These results are illustrated in Fig. 14.



Play	Source Address	Source Port	Destination Address	Destination Port	SSRC	Setup Frame	Packets	Time Span (s)	SR (Hz)	PR (Hz)	Payloads
Play	12.1.1.130	51962	12.1.1.131	58155	0x538612e7	SETUP 8642	12354	65.04 - 188.59 ...	8000	8000	g711A
Play	12.1.1.131	58155	12.1.1.130	51962	0xe70e20...	SETUP 8642	12376	65.00 - 188.75 ...	8000	8000	g711A

Fig. 12. Outbound and inbound voice signal traces

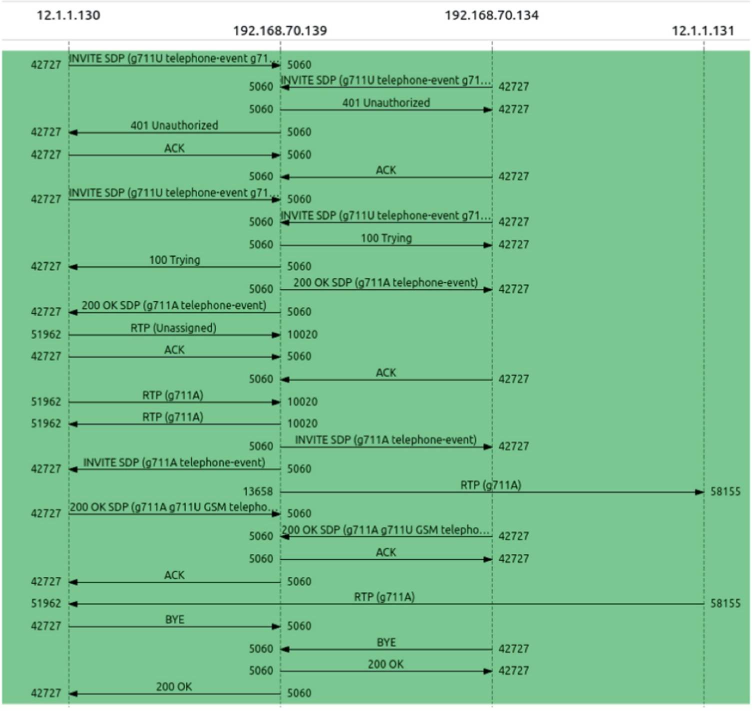
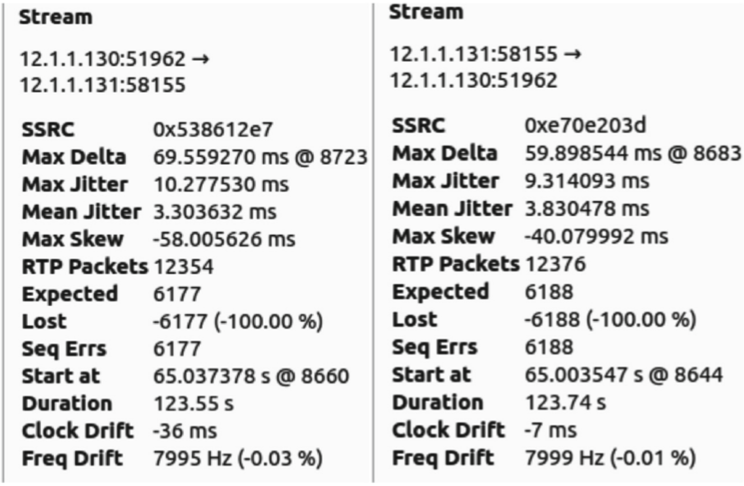


Fig. 13. Flow Exchange Graph between UEs, UPF, IMS



Stream

12.1.1.130:51962 →
12.1.1.131:58155

SSRC 0x538612e7
Max Delta 69.559270 ms @ 8723
Max Jitter 10.277530 ms
Mean Jitter 3.303632 ms
Max Skew -58.005626 ms
RTP Packets 12354
Expected 6177
Lost -6177 (-100.00 %)
Seq Errs 6177
Start at 65.037378 s @ 8660
Duration 123.55 s
Clock Drift -36 ms
Freq Drift 7995 Hz (-0.03 %)

Stream

12.1.1.131:58155 →
12.1.1.130:51962

SSRC 0xe70e203d
Max Delta 59.898544 ms @ 8683
Max Jitter 9.314093 ms
Mean Jitter 3.830478 ms
Max Skew -40.079992 ms
RTP Packets 12376
Expected 6188
Lost -6188 (-100.00 %)
Seq Errs 6188
Start at 65.003547 s @ 8644
Duration 123.74 s
Clock Drift -7 ms
Freq Drift 7999 Hz (-0.01 %)

Fig. 14. Performance analysis of the VoNR call.

4 Concluding Remarks

In this article, we deployed and tested a 5G SA network applicable in rural areas on an ongoing research to help attain the SDG by reducing the digital divide with 5G technology. We carried out a basic deployment of a standalone and low-cost 5G network using the OpenAirInterface open-source implementation and the USRP B210 SDR technology and a commercial 5G phone. In a first experiment we assessed the network performances and obtained satisfactorily results with respect to jitter and throughput. Though the throughput is limited by the characteristics of the used USRP B210, obtained values outperform the characteristics of the local 4G network. The round-trip time and jitters measurements give lower values than those experienced in 4G and required for common needs for digitised societies. In a second experiment we implemented VoNR over the 5G system and tested duplex calls with a commercial phone. Optimisation of the 5G SA testbed is underway for resource sharing and use cases implementation with network slicing, Multi-Access Edge Computing (MEC) for education, agriculture and rescue use cases.

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