SDR Enabled C-RAN Implementation using OpenAirInterface

Akeem Olapade Mufutau (aomufutau@ua.pt)
Instituto de Telecomunicações: Instituto de Telecomunicacoes https://orcid.org/0000-0001-8413-4732
Fernando Pedro Guiomar
Instituto de Telecomunicações: Instituto de Telecomunicacoes
Arnaldo Oliveira
Instituto de Telecomunicações: Instituto de Telecomunicacoes
Paulo Pereira Monteiro
Instituto de Telecomunicações: Instituto de Telecomunicacoes

Research Article

Keywords: softwarization , software-defined radio , flexible RAN , OAI

Posted Date: May 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-486360/v1

Noname manuscript No.
(will be inserted by the editor)

SDR Enabled C-RAN Implementation using OpenAirInterface

Akeem O. Mufutau · Fernando P. Guiomar · Arnaldo Oliveira · Paulo P. Monteiro

Received: date / Accepted: date

Abstract Towards enabling 5G radio access technologies and beyond to meet the requirements for continuous dynamic and diverse services, flexibility and scalability of the cellular network are therefore pertinent. The utilization of software-defined radio (SDR) aided with an open-source platform and virtualization techniques are increasingly exposing the realization of desirable flexibility for radio access network (RAN) while enabling the development of a prototype which can be directed at fostering further mobile network research activities. In this paper, we review OpenAirInterface (OAI) implementation and present an OAI based cloud RAN (C-RAN) testbed with which mobile fronthaul (MFH) solutions can be tested.

Keywords softwarization · software-defined radio · flexible RAN · OAI

Akeem O. Mufutau
Instituto de Telecomunicações, Departamento de Electrónica, Telecomunicações e Informática, Universidade de Aveiro, 3810-193 Aveiro, Portugal
E-mail: aomufutau@ua.pt

Fernando P. Guiomar
Instituto de Telecomunicações, Departamento de Electrónica, Telecomunicações e Informática, Universidade de Aveiro, 3810-193 Aveiro, Portugal

Arnaldo Oliveira
Instituto de Telecomunicações, Departamento de Electrónica, Telecomunicações e Informática, Universidade de Aveiro, 3810-193 Aveiro, Portugal

Paulo P. Monteiro
Instituto de Telecomunicações, Departamento de Electrónica, Telecomunicações e Informática, Universidade de Aveiro, 3810-193 Aveiro, Portugal

1 Introduction

The increasing prevalence of service diversity in response to a variety of innovative applications and use cases, has paved an interesting and challenging path for enabling unprecedented flexibility in cellular network architectures and functionalities. Consequently, requirements for network flexibility among other contending prerequisites, contribute to a paradigm shift from the static and monolithic approach of 4G cellular networks, thus motivating consideration for the adoption of softwarization and virtualization techniques as key technologies for supporting use cases of 5G and beyond networks. With the advent of 5G, telecom operators are considering a redefinition of radio access network (RAN) architecture to scale with the continuous challenges that are emanating from the need to support recurrent dynamic and diverse services as envisaged for 5G and future mobile network. As such, RAN architecture is evolving from the existing distributed RAN (DRAN) for 3G/4G to centralized/cloud RAN (C-RAN) due to the inadequacy of the former to support 5G services [1]. Therefore, to provide a baseline architectural transition to 5G, the concept of C-RAN was introduced for 4G because of its potential benefits, which include: support to new functionalities and management of computational resources, realization of statistical multiplexing gain from a pool of baseband unit (BBU) through sharing of radio resources and cooperative signal processing, improvement of spectral efficiency and interference management with faster handover interactions for cells within the same pool, support for coordinated multipoint (CoMP) operation, enhanced network scalability and energy efficiency [2, 3]. In addition, C-RAN brings about noticeable reduction in the total cost of ownership (TCO) by scaling down operational expenditures (OPEX) and capital expenditures (CAPEX) [4, 5].

Despite the captivating benefits offered by C-RAN, its adoption is threatened by the stringent requirements imposed on the fronthaul. In attempts to ameliorate this challenge, several solutions have been proposed [1, 6], which include functional decomposition of the BBU processing between the central unit (CU) and digital unit (DU) while others functions are left with the radio unit (RU) to handle [7]. This paved way for seamless utilization of software and virtualization techniques to create cloud based baseband processing of the decomposed entities of the BBU, softwarized network component in order to achieve the required flexibility and fast reconfiguration of cellular networks [8].

Motivated by the foregoing, several research efforts are geared towards realization of C-RAN by exploiting the benefits of software-defined radio and open-source software platform to prototype C-RAN for engendering future research activities. In the same vein, this article addresses some of the implementations and research that explore the adoption of commodity devices and open-source software with support of virtualization techniques for the realization of C-RAN, since softwarization and virtualization technologies are championing a race to open-source and programmable 5G ecosystem and could be extended to future generations of cellular network [9]. The rest of this paper is organized as follows: Section II provides a brief review of key technologies for enabling

RAN flexibility with emphasis on softwarization and virtualization. In section 3, an overview of OAI implementation is presented and development of OAI enabled C-RAN laboratory testbed is described. With the testbed depicted in foregoing section, an experimental fronthaul based on PON is demonstrated in section 4. Finally, conclusions are presented in section 5.

2 Flexibility Enhancement Approach for 5G and Beyond Network

As technology evolves towards 5G and presumably beyond, there is a growing concern for flexibility and fast reconfiguration of the cellular networks that are derived from the openness and programmability of individual network component. To engender the foregoing, the concepts of virtualization and softwarization of the cellular networks are very important. Furthermore, the success of softwarization and virtualization in cloud and edge computing including network function virtualization (NFV) is encouraging the adoption of these technologies for 5G and B5G to achieve unprecedented flexibility, while supporting diverse services arising from the growing densification of cellular deployments and users. In basic terms, softwarization refers to the concept of running a specific functionality in software platform rather than hardware as traditionally exhibited; whereas virtualization is a process that allows the creation of a virtual instance or software-based abstraction of the actual computer hardware and virtual hardware platform, storage devices, computer network resources and operating systems. In addition, the race to open-source and programable network is bringing enhancement of operational efficiency and optimization of network configuration, thereby contributing to a reduction of TCO [10].

2.1 RAN Softwarization

Softwarization paradigms are evoking revolutionary strides in the telecommunication industry, thus enabling more flexibility, scalability, programmability, and also boosting the security of cellular networks. The adoption of software-defined networking (SDN) and NFV are key enablers for achieving cellular networks softwarization. Therefore, the extensive use of SDN with necessary virtualization is craving out software-defined mobile networks (SDMN) to effectuate cloud processing of the network functionalities and services [11–14]. By these means, decomposition of the control plane and data plane are achieved by the use of clearly defined application programming interfaces (API) [15].

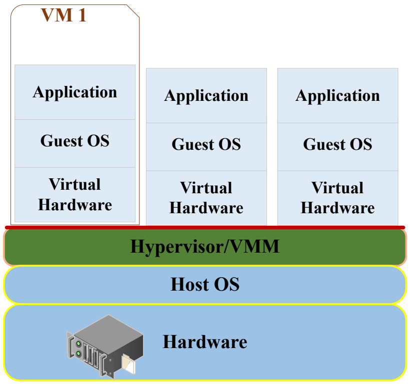
SDN and NFV as complementary technologies bring about less dependence on traditional hardware components, thereby reducing the cost of cellular network deployment [16]. Considering the ability of the SDN/NFV approach to enhance open-source integration of cellular networks, significant research efforts are directed towards the exploitation of these technologies to realize network softwarization as an essential aspect in the advancement of 5G and B5G networks [17, 18]. While providing an enabling support for the ecosystem, open-source platforms are gaining widespread patronage by telecommunication operators and researchers for implementing softwarized cellular networks. For example, the open-source project [19] has been evolving and more recently, a collaboration between O-RAN Alliance and Linux Foundation emerged as the O-RAN software community to develop software for the radio access network [20]. A similar effort is being made by OpenAirInterface Software Alliance (OSA) [21] on the application of the open-source on 5G system architecture in accordance with 3rd Generation Partnership Project (3GPP) Release 15 standard [22]. Albeit, there are other contemporary open-source software for RAN prototyping include the srsLTE, OpenLTE, NextEPC and LTE sidelink. In this work, we are considering the OpenAirInterface (OAI) implementation because of its robustness and flexibility. Starting with 4G, OAI implements the full communication stack, which is depicted in Figure 2, and there has been a consistent effort in upgrading the software to implement 5G stack [23].

In the ensuing sections, we describe the development of a laboratory prototype of a real-time cellular network based on open-source software platform and enabling hardware resources.

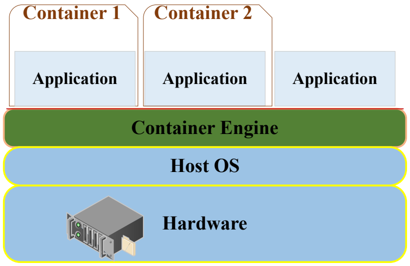
2.2 Virtualization Paradigm

Among its numerous applications, virtualization has come to play as its adoption is prevalent and increasingly relevant in the design, deployment and operation of mobile networks, more specifically 5G and the incoming 6G. Virtualization has already found its root in networking as an enabler for cloud computing with the development of virtual local area networks(VLAN), virtual network interface controllers (NIC) and virtual private networks (VPN) to mention only a few. As mobile network is revolutionising towards softwarization, adoption of virtualization does not only contribute to lower TCO but would greatly engender ecosystem and openness of mobile networks. More importantly, considering the involvement of multi-RAT to drive 5G and beyond networks, virtualization is therefore desirable to lessen critical functional and architectural complexities, thus bringing elasticity and flexibility to mobile networks in a way to realizing flexible RAN. In addition, fully virtualized and cloud RAN architecture is evolving with potentiality to enable virtualized baseband unit (vBBU), remote radio units (RRUs) and dynamic fronthaul. Virtual RAN (vRAN) is getting predominant as virtualization tools are advancing to produce improve abstraction of hardware entities.

Diving into the network, virtualization is exploited to arrive at the concept of NFV as proposed by the European Telecommunications Standards Institute (ETSI) in 2012 [24]. With NFV, traditional heavy dependence on single-purpose infrastructure is reduced by implementing hardware-built functions in software that can be hosted on COTS systems for providing network services in virtual machines to create virtual network functions (VNFs).



(a) Hypervisor-based (Type 2).



(b) Container-based.

Fig. 1: Virtualization approach.

2.2.1 Basic Virtualization Approaches

Hypervisor-based and containers-based methods as depicted in Figure 1, are two prominent approaches for implementing virtualization, both showing different trade-offs [25, 26]. For the hypervisor-based approach, establishing virtualization depends on the software platform often refers to as hypervisor or virtual machine monitor (VMM). Depending on the type of hypervisor-based virtualization being considered, hypervisor could be deployed directly on top of a hardware (*bare-metal*) called host which runs the hypervisor, while other emulated hardware inside a host is called the Guest. Having enabled the creation of virtual hardware or machine which possesses emulated version of real hardware resources, the hypervisor facilitates a virtual environment to real hardware interactions by intercepting the system calls of the virtual machine. This type of hypervisor-based approach that involves *bare-metal* is often called paravirtualization (PV) [25, 27]. The second hypervisor-based approach tagged type 2, is also called full virtualization as represented in Figure 1a. For type 2, the hypervisor runs on top of the host's OS instead of the *bare-metal*. Hypervisor-based virtualization offers strong isolation even with each virtual machine exhibiting logical separation among its peers, thus contributing to the timing overhead that is normally associated with this virtualization approach.

On the other hand, container-based virtualization exploits the kernel features on the host's OS to create an isolated environment for running multiple guest instances called containers. A graphical description of container-based virtualization is presented in Figure 1b. The ensuing isolation allows each container to have its own root file system, process and network stack. Unlike hypervisor-based virtualization, containers use hardware of the host and do not require individual hardware emulation, thus lowering complexities that are attributed to application processes while supporting scalability and agility of the virtualization system [28, 29]. Furthermore, container-based virtualization appears to be more efficient, faster and offers better performance in contrast to hypervisor-based virtualization, since hardware emulation is not required uniquely for each container [28, 30]. Considering the performance of container-based virtualization, it is widely used for time-sensitive deployments, thus making a promising candidate for realizing virtualization of mobile networks [31–33].

3 Overview of OpenAirInterface Implementation

Although, there are multitudes of network simulation software that are evolving, their ability to fully capture real-world phenomenon still remains a challenge for now. However, while it is essential to have a real-time replica of real world cellular network in the laboratory to foster research and teaching, the likes of OAI are advancing to bringing this to reality. OAI is an open-source software written in C language and made available to the public under Public License version 2 for delivery of real-time features with the implementation of the 3GPP protocol stack encompassing the RAN and the core network [21]. However, the source code is continually undergoing regular upgrades and development processing; beginning with its support for long term evolution (LTE) Release 8, then LTE-Advanced (Releases 10 to 12), LTE-Advanced-Pro (Releases 13 and 14) and currently developing the 5G (Release 15) features for the code. It is worth mentioning that OAI is structured along these two subsystems to develop full-fledged E2E networks for experimenting with features of the network as depicted in the communication stack shown in Figure 2. OAI is capable of emulating and simulating RAN and core network functionalities. Also, OAI supports off-the-shelf software-defined radio (SDR) like USRP devices, Lime SDR, BladeRF and Eurecom express MIMO RF [21]. Meanwhile, the deployment of OAI software especially the OAI-RAN depends on the available computing power of commodity PC to process the OAI instructions and universal software radio peripheral (USRP) hardware driver (UHD) software of SDR for USRP-based implementation. In other words, OAI software deployment requires adequate processing resources to support the heavy digital signal processing required of the baseband signal and other layers of the protocol stack. Therefore, the supporting hardware requirement is subject to the network implementation to be achieved [34].

With the efficacy of OAI in enabling the development of laboratory prototypes for facilitating understanding of mobile network functionalities across layers of communication stack, OAI has attracted enormous attention for adoption in various wireless network studies from higher layers to the physical layer. Table 1 provides a brief list of the research efforts that utilize OAI and SDR.

3.1 OpenAirInterface Based C-RAN Implementation

The orchestration of open software solutions and COTS equipment is increasingly making practical experimentation of cellular systems available and less

Table 1: Some selected OAI and SDR based Implementations

Focus	Summary	Reference
channel measurement.	The authors exploited OAI and SDR to develop LTE channel measurement technique for validating an UL transmission channel prediction algorithm.	[35]
An initiation of a real-time 5G NR on an SDR platform.	The first implementation of OAI based 5G NR is introduced to showcase a basic DL functionality at both gNB and UE to expose feasibility of running 5G NR in real-time on a SDR platform. The work exposes a possibility of implementing an OAI based 5G-NR on a software radio platform supported by the use of highly advanced LDPC and Polar decoders	[36, 37]
Centralized/Cloud Radio Access Network (C-RAN).	OAI based C-RAN with functional split capability that is based on NGFI and 3GPP is demonstrated.	[38–41]
Vehicle-to-everything (V2X).	Attempt is made to prototype V2X with OAI based LTE-V2X schedulers to deliver packets to the UEs depending on statistical packet loss and delay models that can assess V2X applications in high traffic density environments.	[42]
Carrier Aggregation (CA).	CA based on OAI and application programming interface are presented for schedulers of an LTE 4G system.	[43]
Fog Radio Access Networks (F-RAN).	OAI capability for designing and implementing F-RAN architecture based testbed is described to demonstrate support for augmented reality applications and facilitate F-RAN research that involve evaluation and analysis of new techniques and intelligent algorithms.	[44, 45]
Network Slicing.	An OAI based testbed that uses an LTE architecture and additional 5G elements with orchestration of OpenStack platform. for supporting network slicing.	[46–49]
Virtualized 5G Infrastructure .	Virtualization using containerized OAI is employed for a flexible RAN development with capability of supporting extensive slicing radio support.	[34, 50]

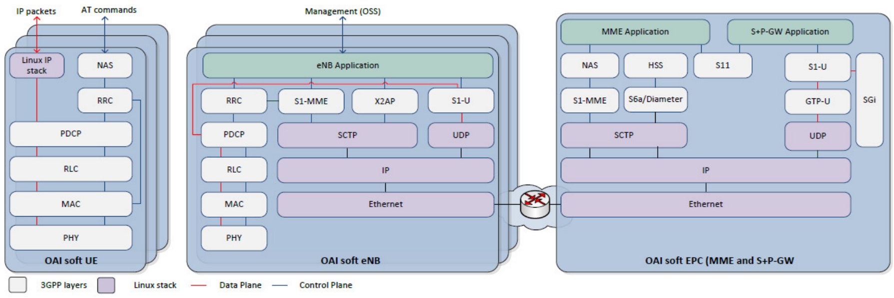


Fig. 2: OAI Communication Stack [23]

cumbersome to access for research purposes. Unlike in the past, constraints arising from the high cost of equipment and radio frequency licensing requirements limited the extent to which practical experimentation could be performed on a real cellular network. In light of the foregoing circumstance, this work focuses on research efforts that exploit and adopt OAI stack for establishing an end-to-end (E2E) network based on C-RAN architecture by following the 3GPP specification. To illustrate the C-RAN implementation-based OAI platform, the architecture is tailored to adopt functional split options shown in Figure 3. Option 8 represents monolithic baseband processing which is a typical representation of centralized RAN. Also, 3GPP option 7.1 indicated in Figure 3 is equivalent to NGFI's functional split 4.5. Interestingly, both options 8 and 7.1 are supported by OAI for 4G LTE development which shall be described in the ensuing sections. Option split 8 includes antenna-air interfacing, analog RF precoding or RF combining and D/A or A/D conversion functions and are processed at the RRU. However, for split 7.1, an additional function of resource element mapping/demapping & IFFT/FFT are included in the RRU processing.

The experimental setup shown in Figure 4a is implemented to realize an LTE network by deploying the OAI codes on general-purpose x86 computing hardware. To generate real-time mobile traffic and examine characteristics of an end-to-end cellular network, we begin with the implementation of the basic setup in Figure 4a. Subsequently, virtualization techniques are employed to practically demonstrate the possibility of cloud processing of cellular network specific traffics and exemplifying ecosystem scenario in the laboratory, while also optimally utilizing the computing power of the high-end PC used.

3.2 Emulation of Monolithic Baseband Processing

To implement the eNB, OAI source code is deployed on a microcomputer system by following the instructions provided on the tutorial page of OpenAirInterface Software Alliance website [21]. For successful deployment, OAI software operates on top of a compatible Linux operating system (OS), typ-

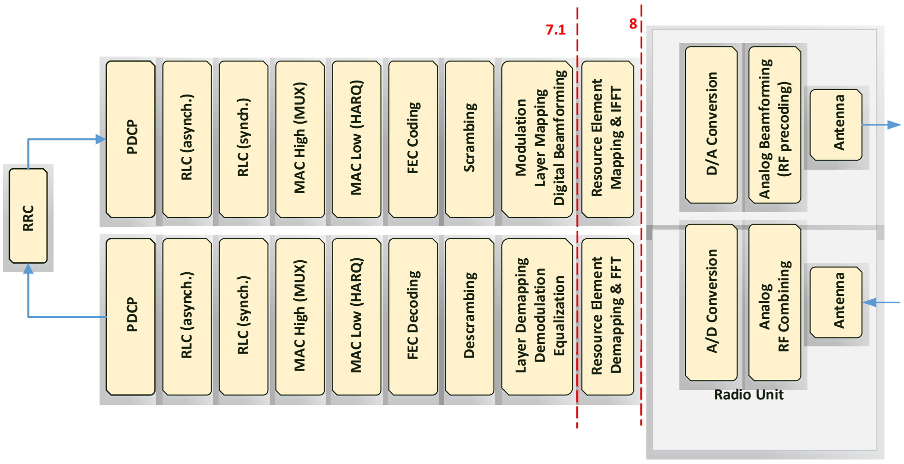
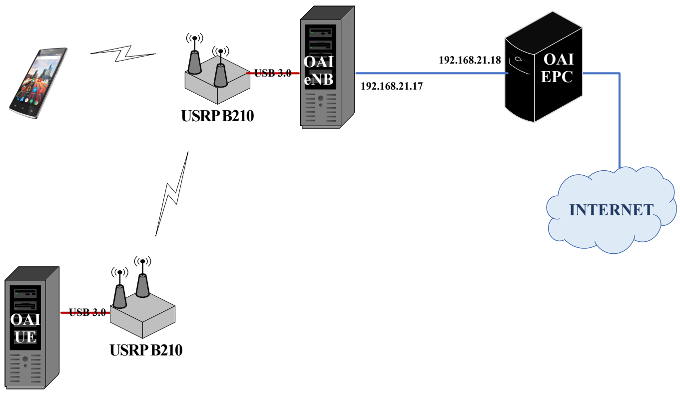


Fig. 3: Functional split options according to 3GPP [51].

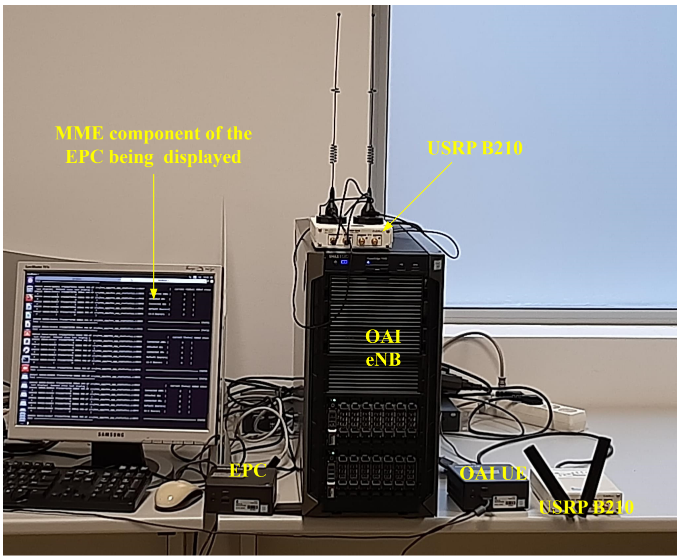
ically Ubuntu 14.04, 16.04, and recently version 18.04. For the experimental setup shown in Figure 4, all baseband processing is handled by the computer system with an SDR attached as RF front-end to perform RF processing including analog/digital conversion.

Following the 3GPP standard release, the eNB can operate on 5, 10, and 20 MHz channel bandwidths with FDD and TDD configurations. Specifically, the experimental setups presented in Figure 4 are configured to operate on FDD mode. Moreover, OAI provides both the downlink and uplink processing chains with OFDMA and SC-FDMA for FDD configuration. Also supported transmission mode of the OAI-RAN includes transmit diversity, SISO, 2 x 2 MIMO, closed-loop spatial multiplexing, multi-user multiple input, multiple output (MU-MIMO) and other LTE MIMO modes. The eNB also processes media access control (MAC), radio link control (RLC), packet data convergence protocol (PDCP), radio resource control (RRC) as well as non access stratum (NAS) drivers which enable interconnection to the OAI-evolved packet core (OAI-EPC) or IP network through IPv4/IPv6 connectivity [34]. For the downlink (DL) and uplink (UL) transmission, a maximum of 64 QAM and 16 QAM respectively is supported, including QPSK corresponding to 27, 16 and 9 modulation and coding scheme (MCS), which is subject to radio link quality and it indicates useful bits transmittable per resource element (RE).

For the UL transmission, the channels carrying reference signals including sounding reference signal (SRS) and discovery reference signal (DRS) through the physical random access channel (PRACH) allow UE to request uplink allocation from the eNB. While data is carried by physical (PHY) uplink shared channel (PUSCH) from the UE to the eNB, the UL control information is transmitted through a physical uplink control channel (PUCCH). In the DL, a primary synchronization signal (PSS) and secondary synchronization signal (SSS) are used by the UE to obtain symbol frequency synchronization, while the physical broadcast channel (PBCH) and physical control format indicator channel (PCFICH) that carry DL control information and scheduling assignments of the UEs are implemented on the physical downlink control channel (PDCCH) by the eNB. Furthermore, the data is transported via PDSCH from the eNB to the specific UEs, while the ACKs or NACKs information for the data are delivered through the physical hybrid ARQ indicator channel (PHICH). In addition, the physical multicast channel (PMCH) provides broadcast and multicast services.



(a) Block diagram



(b) Laboratory Experimental setup

Fig. 4: C-RAN Laboratory Prototype featuring functional split 8 (Monolithic)

3.3 Functional Split Based Architecture

OAI attempts at implementing functional splitting of the fronthaul began with the development of source code for next-generation fronthaul interface (NGFI) architecture and later updated to include 3GPP's 5G NR architecture. The NGFI OAI version contains remote cloud center (RCC) and remote radio units (RRU) applications which are installed on a different host machine and with Ethernet technology, RCC is connected to RRU with Ethernet cable (minimum of category 5e) via 1 Gigabit/s NIC of each host machine as illustrated in Figure 5. However, functional split options 6, 7.1 and 8 are supported by OAI [21, 36, 37]. Following the same framework, OAI has been upgraded to comply with the 5G NR architecture paradigm with the inclusion codes for CU and DU, starting from master branch tag v1.1.0. In line with 3GPP specification, OAI adopts a split option F1 interface between the CU and DU and this is implemented with a soft LTE modem like other OAI implementations. In that case, while the CU carries out processing including PDCP, RRC and SDAP; the DU processes RLC, MAC and PHY. However, OAI currently allows only one DU mapping to a single CU functionality.

The control plane and data plane separation are achieved through F1-C and F1-U logical interfaces respectively. For successful implementation of the control plane through the F1-C interface, *F1 setup request* and *F1 setup response* are enabled. Furthermore, the current OAI support for CU - DU implementation includes the initial UL RRC message transfer, UL/DL RRC message transfer, and release request, command or complete of F1 UE context. Also, google protocol buffers are used in the OAI code to encapsulate RLC packets otherwise called SDU for transportation over UDP tunnel. With this setting, a stable 70 Mbps user data rate for enabled single CU-DU link with 100 PRBs in TM1 mode configuration over a wireless channel to the UE is achievable.

Meanwhile, for our setup represented in Figure 5 and its laboratory setup in Figure 6, the logical F1 interfacing is achieved with the aid of physical connection by using a standard single-mode optical fiber (SMF) which is terminated at each end to a 10 Gb small form-factor pluggable plus (SFP+) and connected to an Ethernet NIC of each host machine. Further attached to the DU is USRP B210, an RF frontend that provides an air-interface to the COTS UE used for this setup. Connection to the OAI-EPC is achieved through a 1 Gigabit Ethernet link to establish an E2E network.

The EPC, CU and DU are realised by deploying the respective OAI software application for each network entity on Ubuntu terminal of the host PC. To have the system operational, the EPC must be first initiated. The PHY parameters including bandwidth, band, frequency are configured for the CU, while MAC, address and ports are set for DU to locate the CU on control and data plane level.

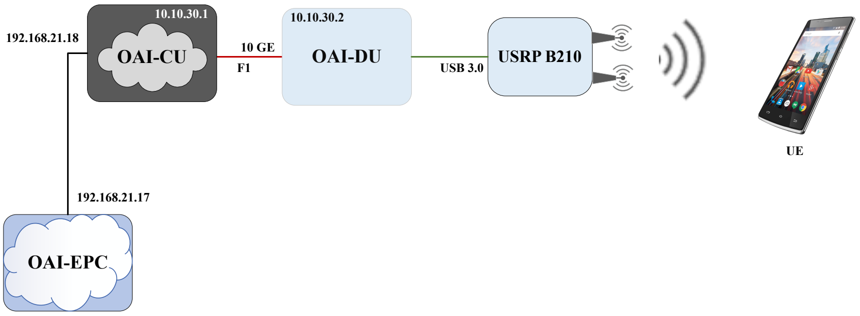


Fig. 5: Basic Representation of OAI Based Functional Split Architecture

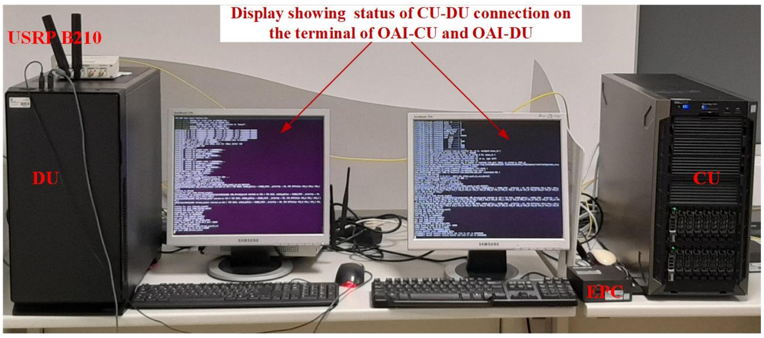


Fig. 6: Laboratory Setup for OAI Based Functional Split Architecture

4 Experimental Fronthaul Demonstration based on PON

PON is a suitable architecture for fronthaul and midhaul in C-RAN applications, benefiting from the inherently centralized system and its popularity throughout the world [52]. However, the native transport of digital RoF signals in conventional PON systems, such as EPON and xGPON, presents several issues, in terms of data capacity, latency and jitter, usually not compatible with the fronthaul requirements [52, 53]. To overcome these issues, the optical communication group at the Instituto de Telecomunicações, Aveiro has investigated and tested different solutions including mobile fronthaul RoF Transceivers for point-to-point wavelength overlay channel (PtP WDM PON) [53–56] and Dynamic Bandwidth Allocation (DBA) algorithms for next-generation PONs to support 5G Fronthaul services [57, 58]. The Mobile Laboratory Setup based on OAI implemented in infrastructure ORCIP (Optical Radio Convergence Infrastructure for Communications and Power Delivering) [59] is an important tool to study and experimentally validate different X-haul options.

An experimental demonstration of RF transmission over a passive optical network (PON) system as fronthaul is presented in this section. Utilizing the setup in Figure 7, specifically the functional split setup component, a next-

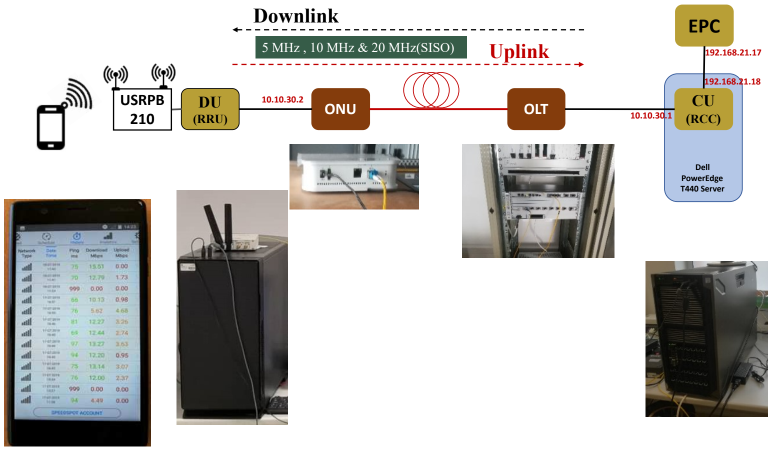
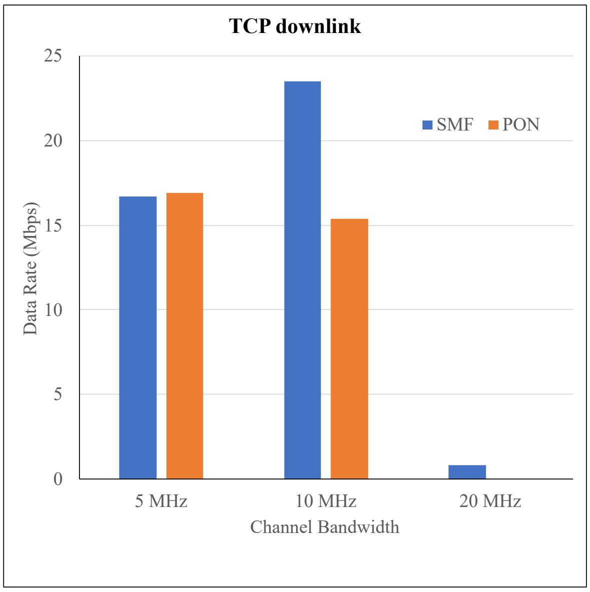


Fig. 7: Demonstration of real-time RF over PON.

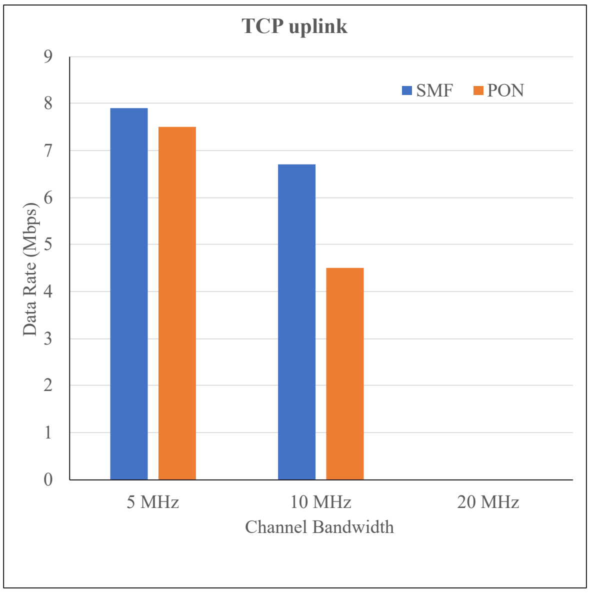
generation PON stage 2 (NG-PON2) system is integrated as a link between the CU and DU. The OLT is connected to the CU via a 10G SFP+ interface and to a 10G SFP+ of the ONU through a single-mode optical fiber (SMF). Similarly, the other interface of the OLT is connected to the ONU which is connected to DU to establish an E2E real-time mobile network with a PON system as the mobile fronthaul (MFH)

Adopting a functional split option 7.1 for the fronthaul configuration, the system parameters including the LTE channel bandwidth of 5 MHz, 10 MHz and 20 MHz are used in the experimental tests. Furthermore, connectivity from the CU to DU is achieved using basic TCP/IP configurations with the indicated IP addresses as shown in Figure 7. The network is operated sequentially, starting with 5 MHz channel bandwidth, then 10 MHz and 20 MHz. As a preliminary step towards the operation of the network, throughput test is conducted on the NG-PON2 system using *iperf* tool and NG-PON2 's line rate is measured as 5.36 Gbps and 8.16 Gbps for the upstream (US) and downstream (DS) traffic respectively. A similar measurement is carried out for maximum transmission unit (MTU) as 3424 bytes.

Next, the network is operated at each configured channel bandwidth and a successful connection is established between the UE and EPC, while the downlink and uplink throughput for each channel bandwidth are measured both for TCP and UDP traffics as shown in Figures 8 and 9 respectively. It should be noted that the PON system is used as a MFH to validate possible limitations due to timing delays that are normally associated with PON systems. This is therefore reflected in the results as shown in Figure 9 and discussed in the subsequent section. In addition, to examine the quality of the signal received by the UE, a Keysight N9041B vector signal analysis (VSA) is employed to obtain the constellation, signal waveform and error vector magnitude (EVM) as shown in Figure 10.

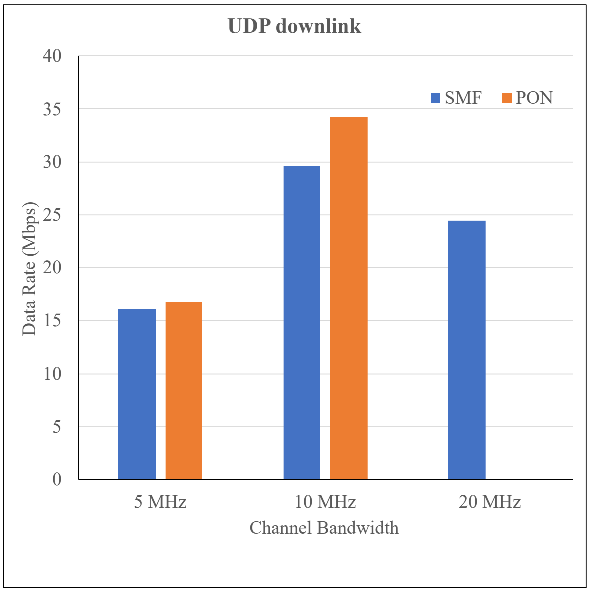


(a) TCP downlink.

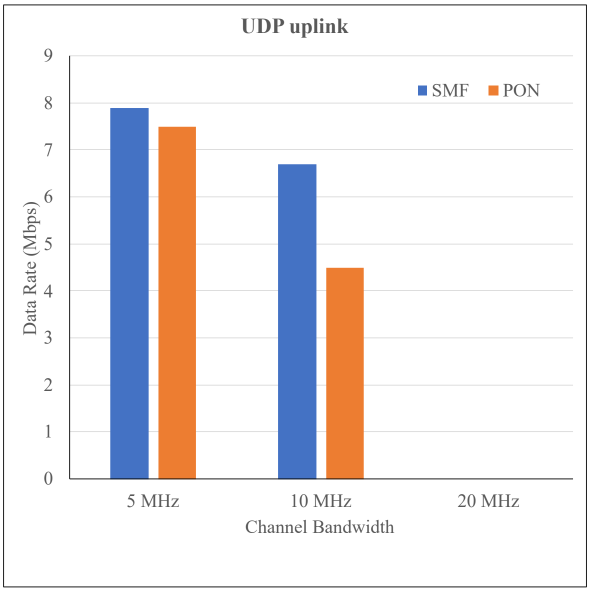


(b) TCP uplink.

Fig. 8: Measured data rate for TCP traffic.



(a) UDP downlink.

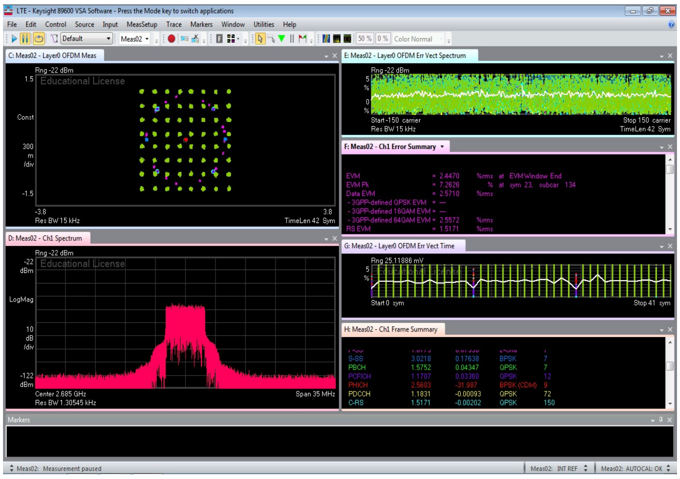


(b) UDP uplink.

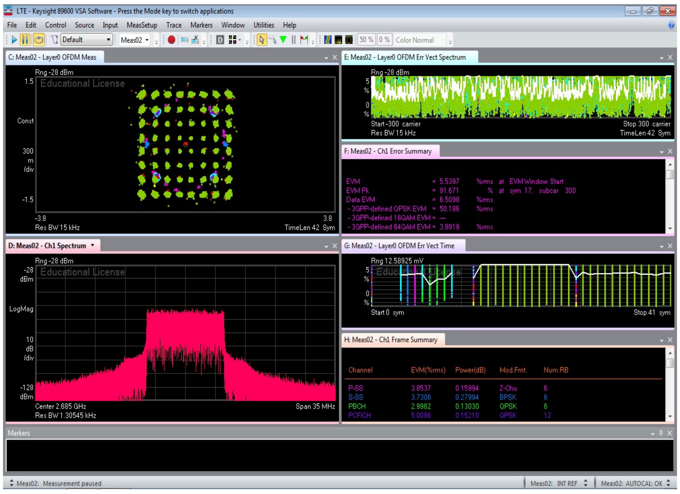
Fig. 9: Measured data rate for UDP traffic.

4.1 Results and Discussions

While establishing E2E connectivity with NG-PON2 adopted as MBF between CU and DU, successful transmission is achieved for both DL and UL



(a) 5 MHz Channel Bandwidth.



(b) 10 MHz Channel Bandwidth

Fig. 10: Over-the-Air signal capture by the VSA, showing modulation constellation points, signal waveform and EVM while data traffic is being transmitted.

at 5 MHz and 10 MHz LTE channel bandwidths. However, transmission at 20 MHz suffers signal degradation due to inadequacy of computing resources required for heavy digital signal processing and inherent delay overhead of the PON system. Considering this limitation, higher layer data rates are measured as presented in Figure 8 and Figure 9. For comparative performance analysis, fiber MFH is used in the same setup and measurement was repeated sequentially. UDP and TCP throughput tests are conducted to study the MFH capability to transport the real-time signal.

On one hand, for the TCP test, data is transmitted on connection-oriented (bidirectional) protocol and follows error-checking, delivery guaranteed, packets order preservation and re-transmission (of lost packets) processes. On the other hand, the UDP test is faster than TCP because error-checking and data recovery are not required while the data rate is being measured, thus exposing the maximum attainable data rate of the channel. This is justified with the measurement indicated in Figure 9, particularly in Figure 9a showing about 25 Mbps at the DL but none at the UL for 20 MHz channel bandwidth when fiber MFH is used while no success transmission is recorded at 20 MHz bandwidth for PON-based MFH. However, the data rate measured with fiber-based MFH and PON based MFH connections shows approximately similar trends for 5 MHz and 10 MHz channel bandwidths. In view of the preceding, modulation constellation is examined and EVM measured using a VSA when transmitting real-time RF signal over PON based MFH and an instance is shown in Figure 10. As expected 5 MHZ shows clearer constellation than 10 MHz, indicating 2.5% and 6.5% EVM respectively which are within the tolerable EVM range for 256 QAM modulation as recommended by 3GPPP [60].

5 Conclusions

C-RAN has attracted tremendous attention because of its benefits including improved flexibility and centralized processing, unlike conventional radio access networks. With appropriate open-source software and virtualization techniques supported by SDR, mobile network functionalities can be realized. In this paper, we have reviewed some of the research contributions of OpenAirInterface (OAI) and demonstrated the use of OAI and SDR to develop a C-RAN testbed. Furthermore, the OAI based C-RAN not only demonstrates functional splits but also allow MFH solutions to be tested. Consequently, one of the possible MFH experimentation is demonstrated and the preliminary results were presented.

Acknowledgements This work is supported by the European Regional Development Fund (FEDER), through the Regional Operational Programme of Centre (CENTRO 2020) of the Portugal 2020 framework, provided by projects ORCIP (CENTRO-01-0145-FEDER-022141), 5GO (POCI-01-0247-FEDER-024539), SOCA (CENTRO-01-0145-FEDER-000010), Project, RETIOT (POCI-01-0145-FEDER-016432) and LandMark (POCI-01-0145-FEDER-031527).

6 Funding

The European Regional Development Fund (FEDER), through the Regional Operational Programme of Centre (CENTRO 2020) of the Portugal 2020 framework, provided by projects ORCIP (CENTRO-01-0145-FEDER-022141), 5GO (POCI-01-0247-FEDER-024539), SOCA (CENTRO-01-0145-FEDER-000010), Project, RETIOT (POCI-01-0145-FEDER-016432) and LandMark (POCI-01-0145-FEDER-031527)

7 Conflicts of interest/Competing interests

Not applicable

8 Availability of data and material

Not applicable

9 Code availability

Not applicable

10 Authors' contributions

Not applicable

References

1. Gilson M., Mackenzie R., Sutton A., Huang J. (2018) NGMN Overview on 5G RAN Functional Decomposition by NGMN Alliance. Tech. rep., Next Generation Mobile Networks Ltd, [Online; accessed 2021-04-20]
2. Chabbouh O., Rejeb S., Agoulmine N., Choukair Z. (2017) Cloud ran architecture model based upon flexible ran functionalities split for 5g networks. In: 2017 31st International Conference on Advanced Information Networking and Applications: Workshops (WAINA), IEEE Computer Society, Los Alamitos, CA, USA, pp. 184–188, DOI 10.1109/WAINA.2017.107, URL https://doi.ieeecomputersociety.org/10.1109/WAINA.2017.107
3. de la Oliva A., Hernandez J. A., Larrabeiti D., Azcorra A. (2016) An overview of the CPRI specification and its application to C-RAN-based LTE scenarios. *IEEE Communications Magazine* 54(2):152–159, DOI 10.1109/MCOM.2016.7402275
4. Zeng D., Zhang J., Gu L., Guo S., Luo J. (2018) Energy-efficient coordinated multipoint scheduling in green cloud radio access network. *IEEE Transactions on Vehicular Technology* 67(10):9922–9930, DOI 10.1109/TVT.2018.2863246
5. Checko A., Avramova A. P., Berger M. S., Christiansen H. L. (2016) Evaluating C-RAN fronthaul functional splits in terms of network level energy and cost savings. *Journal of Communications and Networks* 18(2):162–172, DOI 10.1109/JCN.2016.000025
6. Larsen L. M. P., Checko A., Christiansen H. L. (2019) A Survey of the Functional Splits Proposed for 5G Mobile Crosshaul Networks. *IEEE Communications Surveys Tutorials* 21(1):146–172, DOI 10.1109/COMST.2018.2868805

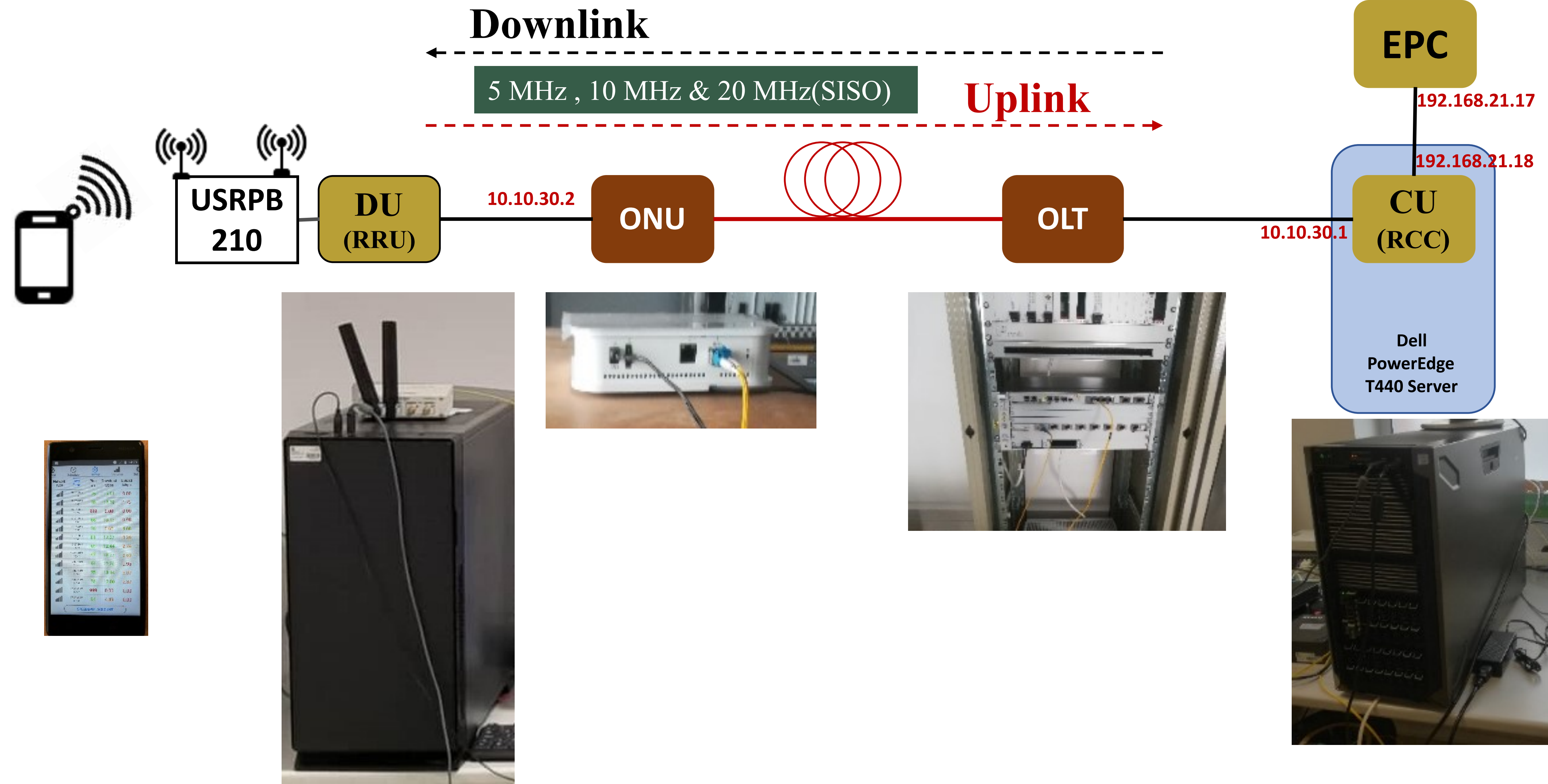
7. TSGR (2018) TS 138 401 - V15.2.0 - 5G; NG-RAN; Architecture description (3GPP TS 38.401 version 15.2.0 Release 15). Tech. rep., 3rd Generation Partnership Project, URL https://portal.etsi.org/TB/ETSIDeliverableStatus.aspx
8. Zanferrari Morais F., André da Costa C., Alberti A. M., Bonato Both C., da Rosa Righi R. (2020) When sdn meets c-ran: A survey exploring multipoint coordination, interference, and performance. *Journal of Network and Computer Applications* 162:102,655, DOI https://doi.org/10.1016/j.jnca.2020.102655, URL http://www.sciencedirect.com/science/article/pii/S1084804520301296
9. Lee W., Na T., Kim J. (2019) How to Create a Network Slice? - A 5G Core Network Perspective. In: 21st International Conference on Advanced Communication Technology (ICACT), pp. 616–619, DOI 10.23919/ICACT.2019.8701936
10. Ding A. Y., Crowcroft J., Tarkoma S., Flinck H. (2014) Software defined networking for security enhancement in wireless mobile networks. *Computer Networks* 66:94 – 101, DOI https://doi.org/10.1016/j.comnet.2014.03.009, URL http://www.sciencedirect.com/science/article/pii/S1389128614001133, n Leonard Kleinrock Tribute Issue: A Collection of Papers by his Students
11. Chen T., Matinmikko M., Chen X., Zhou X., Ahokangas P. (2015) Software defined mobile networks: concept, survey, and research directions. *IEEE Communications Magazine* 53(11):126–133
12. Benkhelifa E., Welsh T., Tawalbeh L., Jararweh Y., Al-Ayyoub M. (2016) Leveraging Software-Defined-Networking for Energy Optimisation in Mobile-Cloud-Computing. *Procedia Computer Science* 94:479 – 484, DOI https://doi.org/10.1016/j.procs.2016.08.074, URL http://www.sciencedirect.com/science/article/pii/S1877050916318245, the 11th International Conference on Future Networks and Communications (FNC 2016) / The 13th International Conference on Mobile Systems and Pervasive Computing (MobiSPC 2016) / Affiliated Workshops
13. Khan Tayyaba S., Shah M. A. (2017) 5G cellular network integration with SDN: Challenges, issues and beyond. In: 2017 International Conference on Communication, Computing and Digital Systems (C-CODE), pp. 48–53
14. Narmanlioglu O., Zeydan E. (2017) Software-defined networking based network virtualization for mobile operators. *Computers & Electrical Engineering* 57:134 – 146, DOI https://doi.org/10.1016/j.compeleceng.2016.09.011, URL http://www.sciencedirect.com/science/article/pii/S0045790616302543
15. Özbek B., Aydoğmuş Y., Ulaş A., Görkemli B. (2019) Joint routing and resource allocation for software defined mobile networks. In: 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), pp. 1–6
16. Martínez R., Mayoral A., Vilalta R., Casellas R., noz R. M., Pachnicke S., Szyrkowiec T., Autenrieth A. (2017) Integrated sdn/nfv orchestration for the dynamic deployment of mobile virtual backhaul networks

over a multilayer (packet/optical) aggregation infrastructure. *J Opt Commun Netw* 9(2):A135–A142, DOI 10.1364/JOCN.9.00A135, URL http://jocn.osa.org/abstract.cfm?URI=jocn-9-2-A135
17. Afolabi I., Taleb T., Samdanis K., Ksentini A., Flinck H. (2018) Network slicing and softwarization: A survey on principles, enabling technologies, and solutions. *IEEE Communications Surveys Tutorials* 20(3):2429–2453
18. Rostami A., Ohlen P., Wang K., Ghebretensae Z., Skubic B., Santos M., Vidal A. (2017) Orchestration of ran and transport networks for 5g: An sdn approach. *IEEE Communications Magazine* 55(4):64–70
19. Bertz L., Pankajakshan B. (2019) The Status of Open Source for 5G. Tech. rep., 5G Americas, URL https://www.5gamericas.org/the-status-of-open-source-for-5g/
20. ORAN Alliance (2020) Open & Intelligent Software for the Radio Access Networks. https://www.o-ran.org/software, [Online; accessed 2021-04-20]
21. OAISA (2020) The open-air-interface project. https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/home, accessed: 2021-04-26
22. 3GPP Technical Specifications Groups (2018) Submission of initial 5G description for IMT-2020. URL http://www.3gpp.org/NEWS-EVENTS/3GPP-NEWS/1937-5G{_}DESCRIPTION
23. Nikaein N., Marina M. K., Manickam S., Dawson A., Knopp R., Bonnet C. (2014) Openairinterface: A flexible platform for 5g research. *SIGCOMM Comput Commun Rev* 44(5):33–38, DOI 10.1145/2677046.2677053, URL https://doi.org/10.1145/2677046.2677053
24. Craik G. (2019) Network Transformation; (Orchestration, Network and Service Management Framework) Network Transformation; (Orchestration, Network and Service Management Framework) 3. Tech. rep., European Telecommunications Standards Institute, [Online; accessed 2021-04-20]
25. Bouali L., Abd-Elrahman E., Afifi H., Bouzefrane S., Daoui M. (2016) Virtualization techniques: Challenges and opportunities. In: Boumerdassi S., Renault É., Bouzefrane S. (eds) Mobile, Secure, and Programmable Networking, Springer International Publishing, Cham, pp. 49–62
26. Kim T.-H., Jiang K., Rajput V. (2016) Adoption of container-based virtualization in it education
27. Ageyev D., Bondarenko O., Radivilova T., Alfroukh W. (2018) Classification of existing virtualization methods used in telecommunication networks. pp. 83–86, DOI 10.1109/DESSERT.2018.8409104
28. Mavridis I., Karatza H. (2019) Lightweight virtualization approaches for software-defined systems and cloud computing: An evaluation of unikernels and containers. In: 2019 Sixth International Conference on Software Defined Systems (SDS), pp. 171–178, DOI 10.1109/SDS.2019.8768586
29. Eder M. (2016) Hypervisor-vs . container-based virtualization
30. Doan T. V., Nguyen G. T., Salah H., Pandi S., Jarschel M., Pries R., Fitzek F. H. P. (2019) Containers vs virtual machines: Choosing the right virtualization technology for mobile edge cloud. In: 2019 IEEE 2nd 5G

World Forum (5GWF), pp. 46–52, DOI 10.1109/5GWF.2019.8911715
31. Gopalasingham A., Herculea D. G., Chen C. S., Roullet L. (2017) Virtualization of radio access network by virtual machine and docker: Practice and performance analysis. In: 2017 IFIP/IEEE Symposium on Integrated Network and Service Management (IM), pp. 680–685, DOI 10.23919/INM.2017.7987358
32. Behravesh R., Coronado E., Riggio R. (2019) Performance evaluation on virtualization technologies for nfv deployment in 5g networks. In: 2019 IEEE Conference on Network Softwarization (NetSoft), pp. 24–29, DOI 10.1109/NETSOFT.2019.8806664
33. Potdar A. M., D G N., Kengond S., Mulla M. M. (2020) Performance evaluation of docker container and virtual machine. *Procedia Computer Science* 171:1419–1428, DOI https://doi.org/10.1016/j.procs.2020.04.152, URL https://www.sciencedirect.com/science/article/pii/S1877050920311315, third International Conference on Computing and Network Communications (CoCoNet'19)
34. Bonati L., Polese M., D'oro S., Basagni S., Melodia T. (2020) Open, Programmable, and Virtualized 5G Networks: State-of-the-Art and the Road Ahead. Tech. rep., 2005.10027v4
35. Zhou Q., Jiang W. (2021) Implementation of openairinterface-based realworld channel measurement for evaluating wireless transmission algorithms. 2101.04608
36. Kaltenberger F., Silva A. P., Gosain A., Wang L., Nguyen T. T. (2020) OpenAirInterface: Democratizing innovation in the 5G Era. *Computer Networks* 176:107,284, DOI 10.1016/j.comnet.2020.107284, URL https://doi.org/10.1016/j.comnet.2020.107284
37. Kaltenberger F., Souza G. d., Knopp R., Wang H. (2019) The openairinterface 5g new radio implementation: Current status and roadmap. In: WSA 2019; 23rd International ITG Workshop on Smart Antennas, pp. 1–5
38. Ariza Vesga L. F., Knopp R., Garzon S. E. (2019) Real-time emulation methodologies for centralized radio access networks. In: 2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), pp. 1–5, DOI 10.1109/SPAWC.2019.8815535
39. Salama A. I., Elmesalawy M. M. (2019) Experimental oai-based testbed for evaluating the impact of different functional splits on c-ran performance. In: 2019 Novel Intelligent and Leading Emerging Sciences Conference (NILES), vol 1, pp. 170–173, DOI 10.1109/NILES.2019.8909310
40. Pawar U., Singh A. K., Malde K., Tamma B. R., Antony Franklin A. (2020) Understanding energy consumption of cloud radio access networks: an experimental study. In: 2020 IEEE 3rd 5G World Forum (5GWF), pp. 407–412, DOI 10.1109/5GWF49715.2020.9221114
41. Lin P.-C., Huang S.-L. (2018) Performance profiling of cloud radio access networks using openairinterface. In: 2018 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC), pp. 454–458, DOI 10.23919/APSIPA.2018.8659532

42. Manco J., Baños G. G., Härri J., Sepulcre M. (2020) Prototyping v2x applications in large-scale scenarios using openairinterface. In: 2020 IEEE Vehicular Networking Conference (VNC), pp. 1–4, DOI 10.1109/VNC51378.2020.9318327
43. Kaltenberger F., Roux C., Buczkowski M., Wewior M. (2016) The openairinterface application programming interface for schedulers using carrier aggregation. In: 2016 International Symposium on Wireless Communication Systems (ISWCS), pp. 497–500, DOI 10.1109/ISWCS.2016.7600955
44. Mai S., Liu Y. (2019) Implementation of web ar applications with fog radio access networks based on openairinterface platform. In: 2019 5th International Conference on Control, Automation and Robotics (ICCAR), pp. 639–643, DOI 10.1109/ICCAR.2019.8813710
45. Lu Z., Hu Z., Han Z., Wang L., Knopp R., Zhang Y. (2020) An artificial intelligence enabled f-ran testbed. *IEEE Wireless Communications* 27(2):65–71, DOI 10.1109/MWC.001.1900386
46. Shorov A. (2019) 5g testbed development for network slicing evaluation. In: 2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), pp. 39–44, DOI 10.1109/EIConRus.2019.8656861
47. Gebremariam A. A., Usman M., Du P., Nakao A., Granelli F. (2017) Towards e2e slicing in 5g: A spectrum slicing testbed and its extension to the packet core. In: 2017 IEEE Globecom Workshops (GC Wkshps), pp. 1–6, DOI 10.1109/GLOCOMW.2017.8269212
48. Chen S., Lee C.-N., Lee M.-F. (2020) Realization of 5g network slicing using open source softwares. In: 2020 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC), pp. 1549–1556
49. Yala L., Iordache M., Bousselmi A., Imadali S. (2019) 5g mobile network orchestration and management using open-source. In: 2019 IEEE 2nd 5G World Forum (5GWF), pp. 421–426, DOI 10.1109/5GWF.2019.8911690
50. Wiranata F. A., Shalannanda W., Mulyawan R., Adiono T. (2020) Automation of virtualized 5g infrastructure using mosaic 5g operator over kubernetes supporting network slicing. In: 2020 14th International Conference on Telecommunication Systems, Services, and Applications (TSSA, pp. 1–5, DOI 10.1109/TSSA51342.2020.9310895
51. 3GPP (2017) Technical specification group radio access network; study on cu-du lower layer split for nr; (release 15). Tech. rep., 3rd Generation Partnership Project, [Online; accessed 2021-04-21]
52. Monteiro P. P., Gameiro A. (2016) Opportunities in 5G Networks, CRC Press, Florida, USA, chap Convergence of Optical and Wireless Technologies for 5G, p. 179–215
53. Monteiro P. P., Gameiro A. (2014) Hybrid fibre infrastructures for cloud radio access networks. In: 2014 16th International Conference on Transparent Optical Networks (ICTON), pp. 1–4, DOI 10.1109/ICTON.2014.6876549

54. Henning L. F., Julião S., Oliveira A. S. R., Monteiro P. P., Pohl A. A. P. (2016) High spectral wavelength agnostic multicarrier d-rof modem based on uncooled rsoa. *IEEE Photonics Technology Letters* 28(9):1010–1013, DOI 10.1109/LPT.2016.2523125
55. Mufutau A. O., Guiomar F. P., Fernandes M. A., Lorences-Riesgo A., Oliveira A., Monteiro P. P. (2020) Demonstration of a hybrid optical fiber–wireless 5g fronthaul coexisting with end-to-end 4g networks. *IEEE/OSA Journal of Optical Communications and Networking* 12(3):72–78, DOI 10.1364/JOCN.382654
56. Monteiro P. P., Viana D., da Silva J., Riscado D., Drummond M., Oliveira A. S. R., Silva N., Jesus P. (2015) Mobile fronthaul rof transceivers for c-ran applications. In: 2015 17th International Conference on Transparent Optical Networks (ICTON), pp. 1–4, DOI 10.1109/ICTON.2015.7193452
57. Zaouga A., de Sousa A. F., Najjar M., Monteiro P. P. (2021) Self-adjusting dba algorithm for next generation pons (ng-pons) to support 5g fronthaul and data services. *Journal of Lightwave Technology* 39(7):1913–1924, DOI 10.1109/JLT.2020.3044704
58. Zaouga A., de Sousa A., Najjar M., Monteiro P. P. (2019) Dynamic bandwidth allocation algorithms for ng-pon2 to support 5g fronthaul services. In: OSA Advanced Photonics Congress (AP) 2019 (IPR, Networks, NOMA, SPPCom, PVLED), Optical Society of America, p. SpT1E.2, DOI 10.1364/SPPCOM.2019.SpT1E.2, URL http://www.osapublishing.org/abstract.cfm?URI=SPPCom-2019-SpT1E.2
59. ORCIP (2021) Optical Radio Convergence Infrastructure for Communications and Power Delivering. https://orcip.pt/, accessed: 2021-04-26
60. TSGR (2018) TS 138 104 - V15.3.0 - 5G; NR; Base Station (BS) radio transmission and reception (3GPP TS 38.104 version 15.3.0 Release 15). Tech. rep., [Online; accessed 2021-04-21]


Downlink
5 MHz , 10 MHz & 20 MHz(SISO)
Uplink
EPC
192.168.21.17
192.168.21.18
USRPB 210
DU (RRU)
10.10.30.2
ONU
OLT
10.10.30.1
CU (RCC)
Dell PowerEdge T440 Server

Akeem O. Mufutau received M.Eng. degree in Communication Engineering from the Federal University of Technology Akure (FUTA), Ondo state, Nigeria in 2013. He joined the services of FUTA as a Senior Network Engineer in 2005 and rose to the position of Chief Network Engineer and Head of Systems & Network Engineering Unit in the Computer Resource Centre of the University before joining academics as a Lecturer in the Department of Electrical and Electronics Engineering, FUTA in 2015. He is currently a Ph.D. student at the Instituto de Telecomunicações, Universidade de Aveiro, Portugal. His research interests include Optical-Wireless Communications, Mobile Networks, Radio Frequency Technologies and Computer Networking.

Fernando Guiomar received the M.Sc. and Ph.D. degrees in Electronics and Telecommunications Engineering from University of Aveiro, Portugal, in 2009 and 2015, respectively. In 2015, he has received a Marie Skłodowska-Curie individual fellowship jointly hosted by Politecnico di Torino, Italy, and CISCO Optical GmbH, Nuremberg. In 2016, he has received the Photonics21 Student Innovation Award, distinguishing industrial-oriented research with high impact in Europe. In 2017, he has joined Instituto de Telecomunicações - Aveiro as an assistant researcher responsible for the national research infrastructure ORCIP, aimed at the testing and prototyping of future 5G solutions involving novel optical and radio technologies. In 2020, he was awarded a 3-year research contract by the "la Caixa" Foundation, within the framework of the highly competitive Postdoctoral Junior Leader Fellowship program (ID 100010434). His main research interests are focused within the area of fiber-based and free-space optical communication systems, including the development of digital signal processing algorithms, advanced modulation and coding, constellation shaping and nonlinear modelling and mitigation. Fernando Guiomar is an IEEE and OSA member and he has authored or co-authored more than 90 scientific publications in leading international journals and conferences.

Arnaldo Oliveira received the Ph.D. degree on Electrical Engineering in 2007 from the University of Aveiro, Portugal. He also holds the B.Sc. and M.Sc. degrees, both on Electronics and Telecommunications, from the same university. He is currently a researcher at Telecommunications Institute – Aveiro and since 2001 he teaches computer architecture, digital systems design, programming languages and embedded systems at the University of Aveiro, where he is now an Assistant Professor. His research interests include reconfigurable digital systems, software defined radio and next generation radio access networks. He participates in several national and European funded research projects. He is the author or co-author of more than 100 journal and international conference papers.

Biography

Paulo P. Monteiro received the diploma “Licenciatura” in Electronics and Telecommunications Engineering from the University of Aveiro in 1988, the M.Sc. in Electronic Engineering, from the University of Wales UK, in 1990 and the Ph.D. in Electrical Engineering, from the University of Aveiro, in 1999. Presently, he is Associate Professor at the University of Aveiro and Group Leader of Optical Communications Systems at the Instituto de Telecomunicações. From October 2002 until March 2007 he was at Siemens S.A, Portugal as a Head of Research of Optical Networks. From April 2007 until December 2009 he was at Nokia Siemens Networks (NSN) Portugal as a Research Manager at Transport, Aggregation and Fixed Access and from January 2010 until June 2012 as a R&D manager of Network Optimization unit at NSN. From July 2012 until May 2013 he was research Manager at NSN Portugal. In May 2013, the Optical Networks business unit of Nokia Siemens Networks began operating as a new company Coriant where he left in June 2013. In 1992, he joined the Department of Electronic and Telecommunications Engineering of University of Aveiro and the Optical Communications Group of Institute for Telecommunications as an Assistant Professor and Researcher, respectively. In 1999, he became an Auxiliary Professor at the University of Aveiro and he was promoted to Associate Professor in 2005. His main research interests include Optical Communication Networks, Microwave Photonic and Electronic Subsystems. He tutored and co-tutored successfully more than 14 PhD’s, having participated in more than 28 projects (national, and international). He was the coordinator of a CELTIC project OPTRONET and a large-scale integrating project FUTON (FP7 ICT-2007–215533). He has authored/co-authored more than 18 patent applications and over 110 papers in journals and 360 conference contributions. He is a member of the ECOC Technical Program Committee and Senior Member of IEEE.

Figures

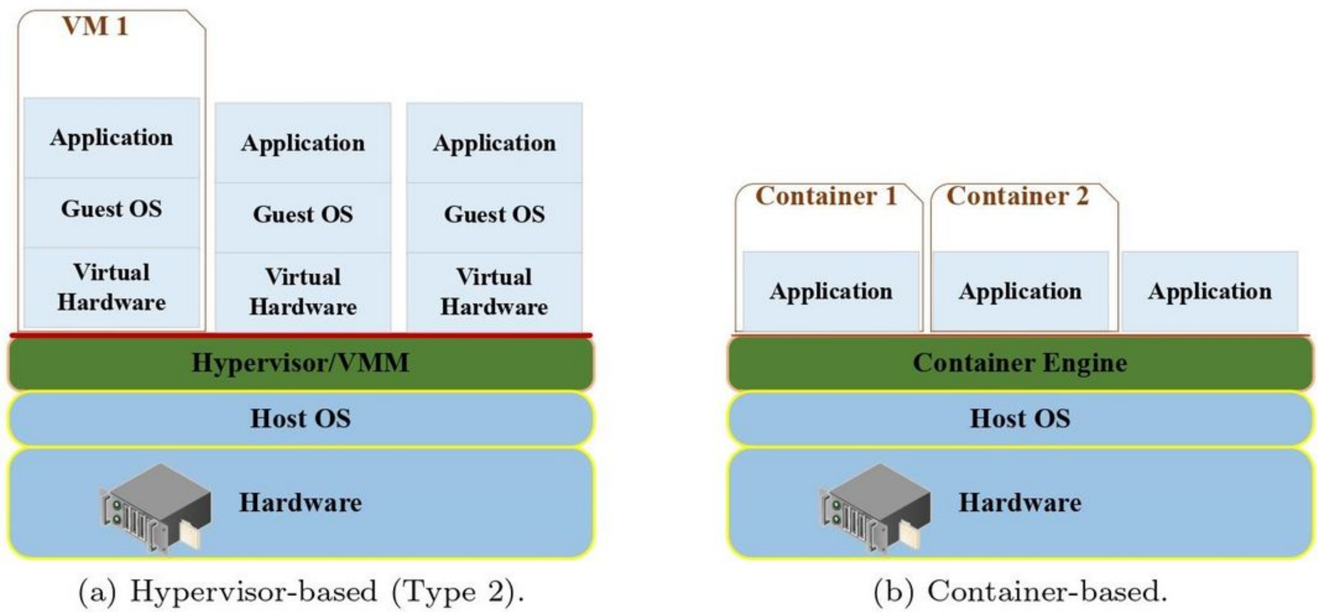


Figure 1

Virtualization approach.

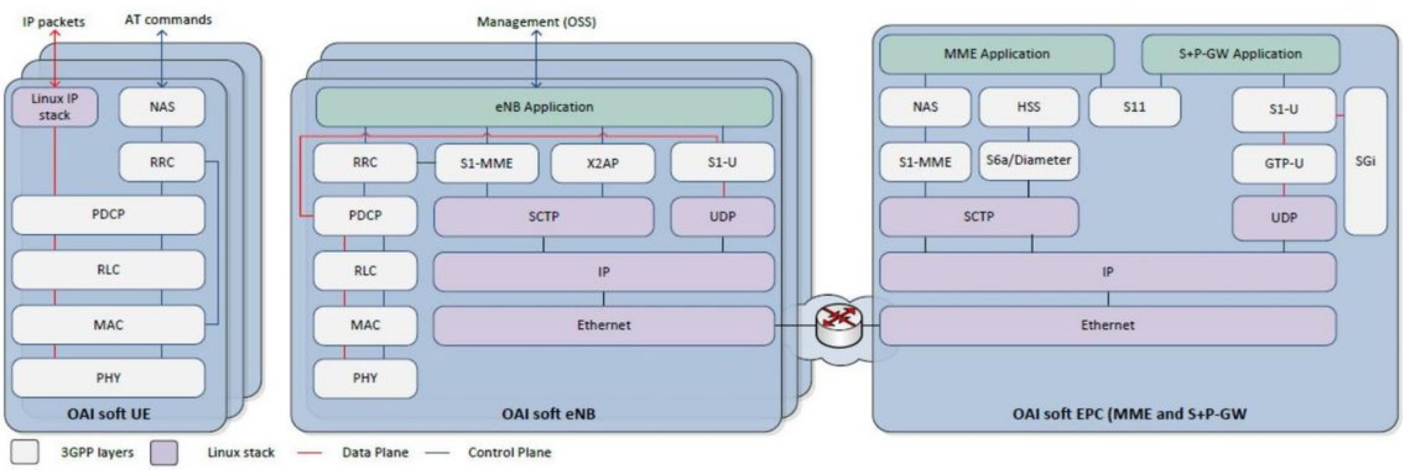


Figure 2

OAI Communication Stack [23]

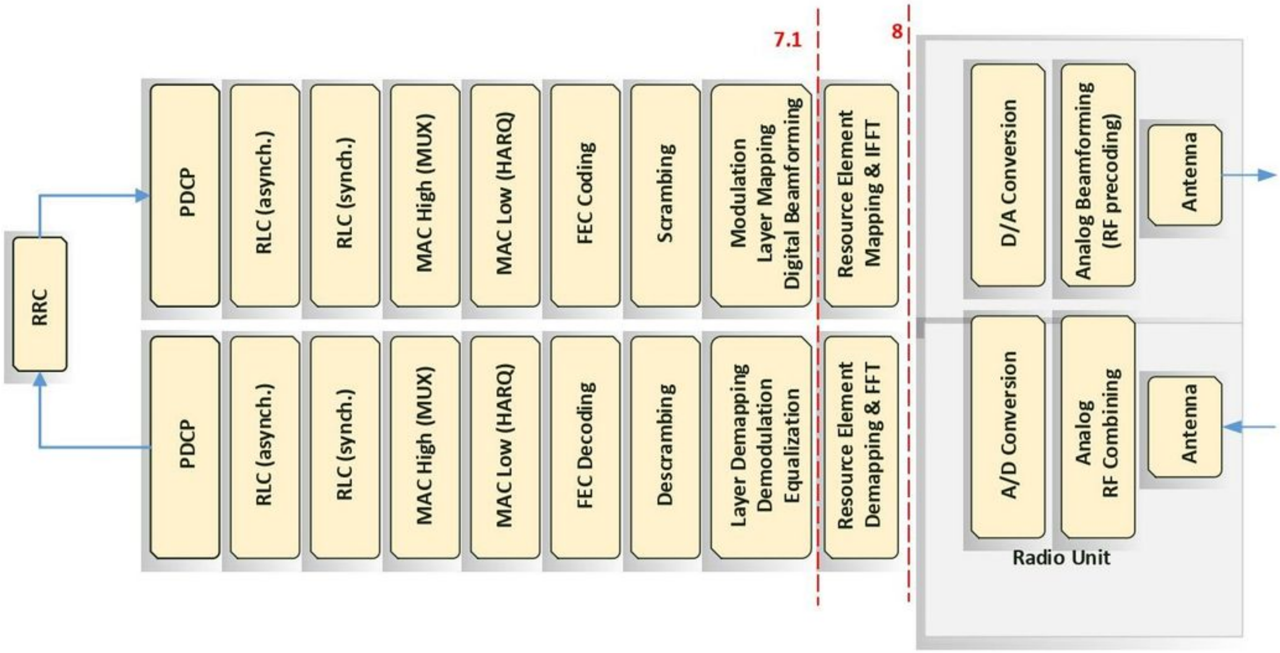
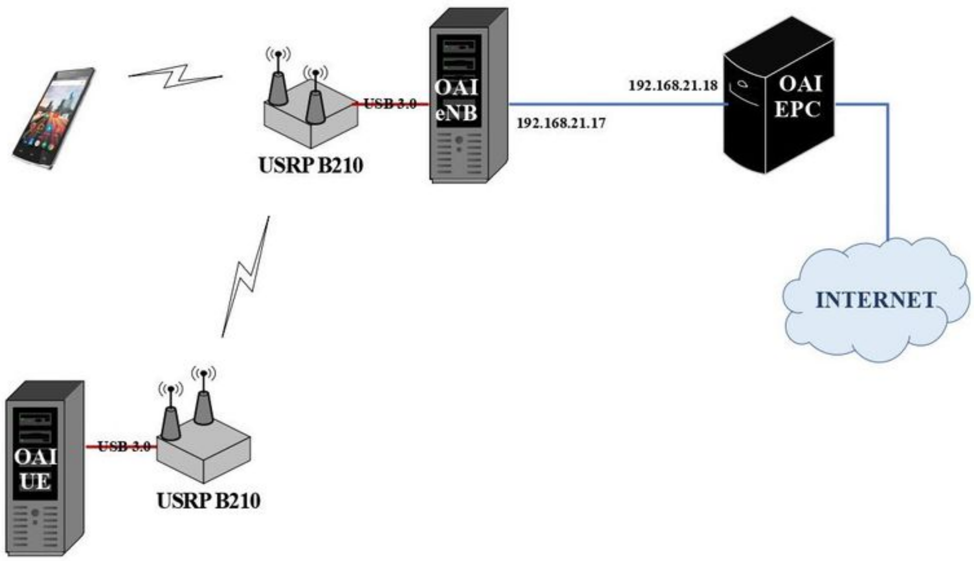
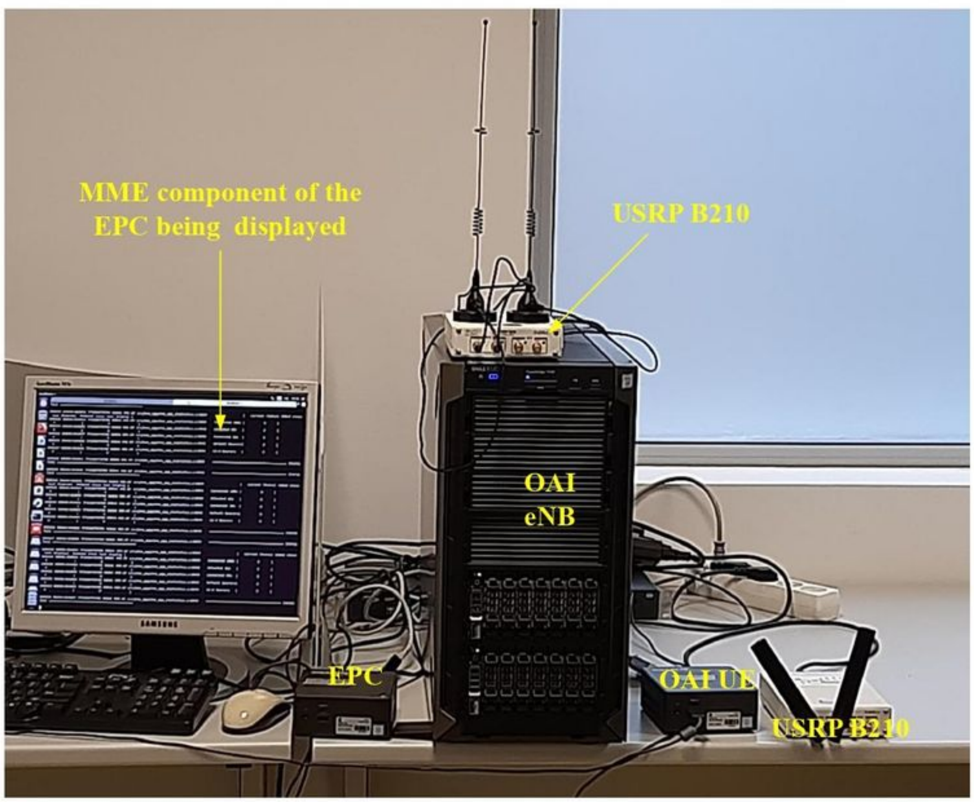


Figure 3

Functional split options according to 3GPP [51]



(a) Block diagram



(b) Laboratory Experimental setup

Figure 4

C-RAN Laboratory Prototype featuring functional split 8 (Monolithic)

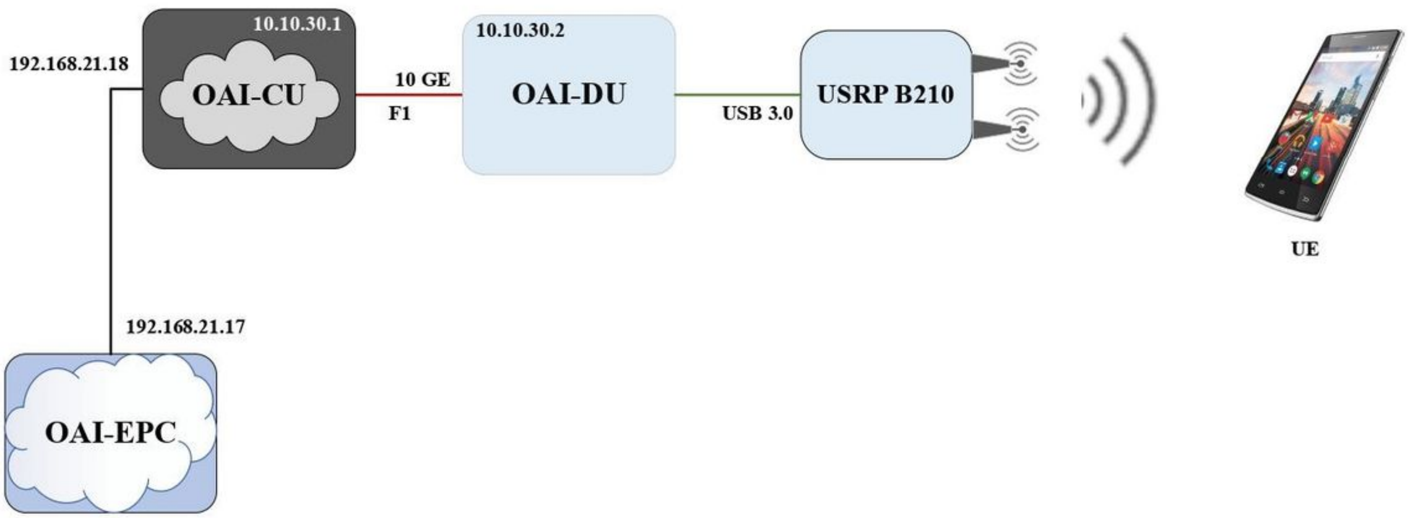


Figure 5

Basic Representation of OAI Based Functional Split Architecture

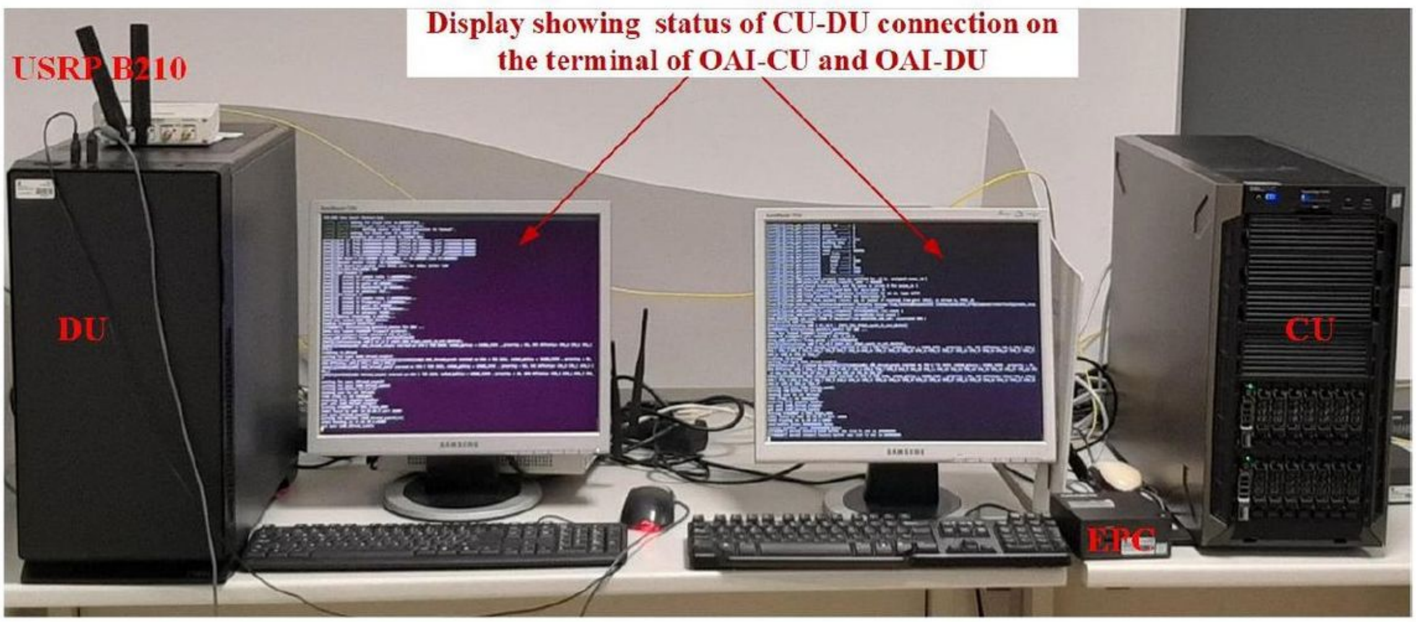


Figure 6

Laboratory Setup for OAI Based Functional Split Architecture

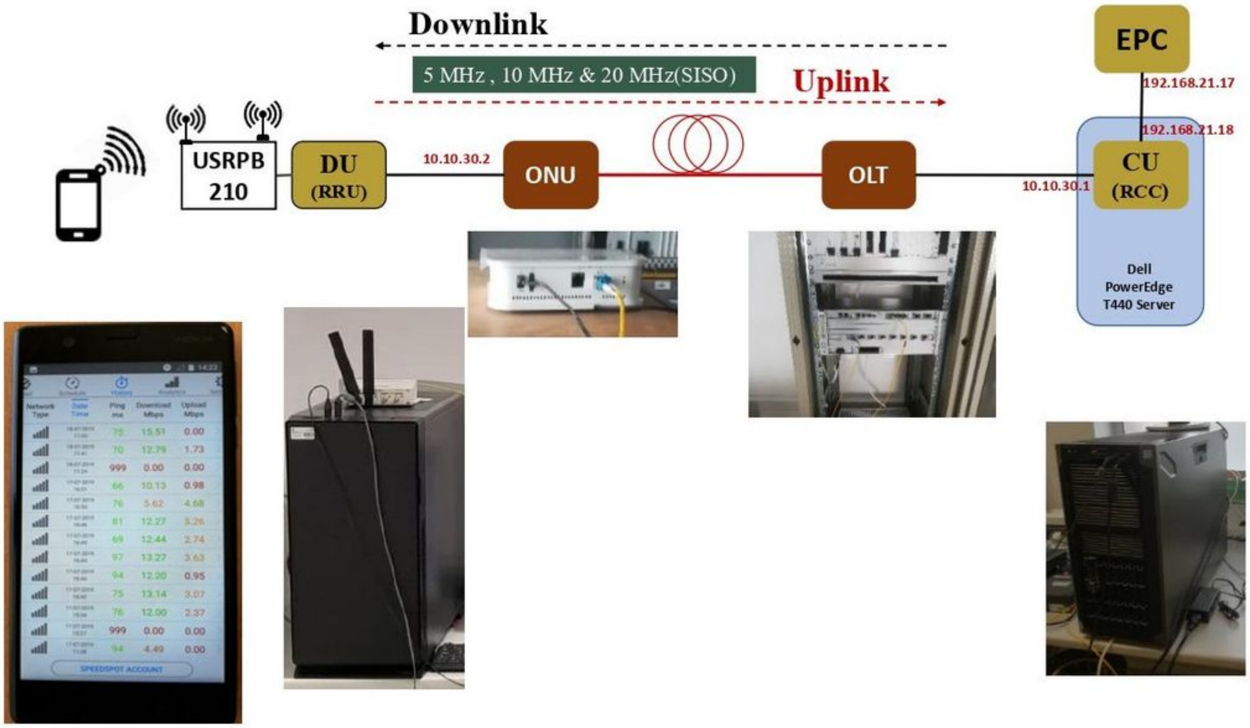
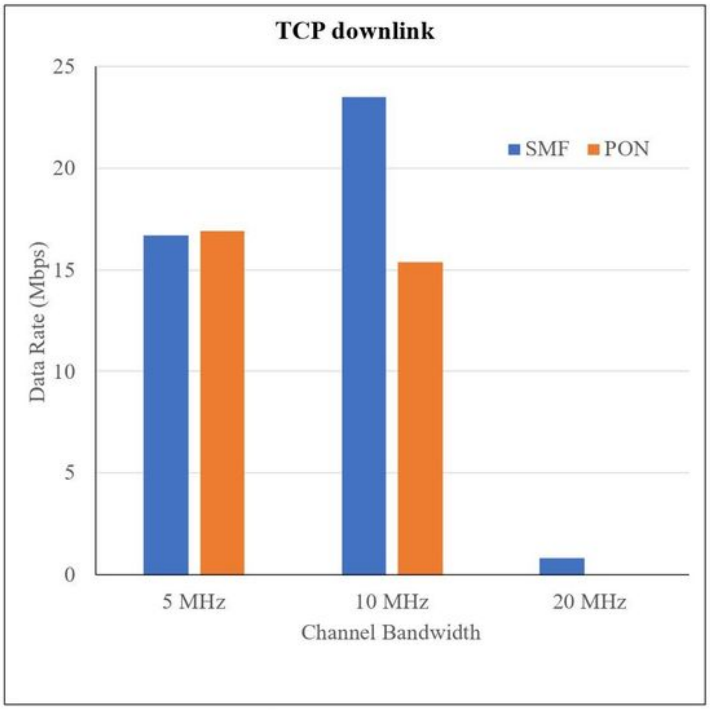
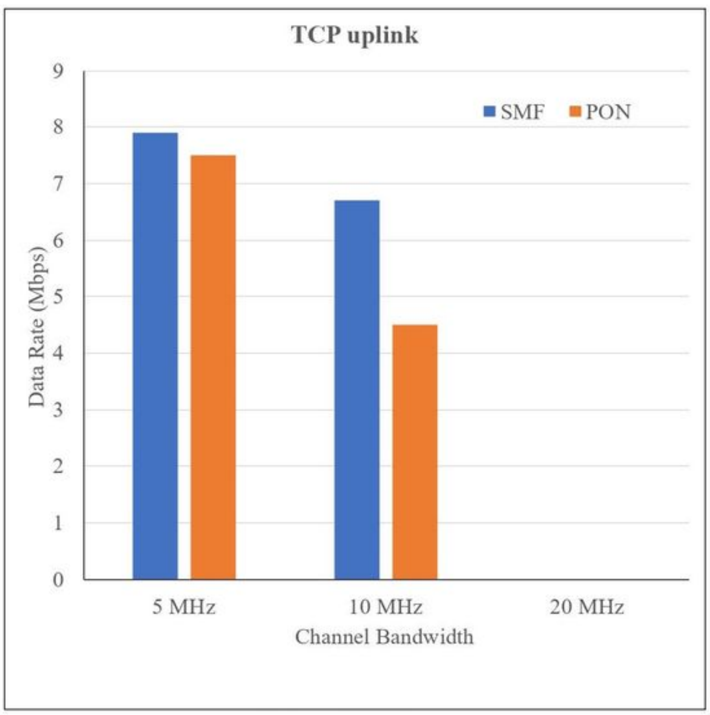


Figure 7

Demonstration of real-time RF over PON.



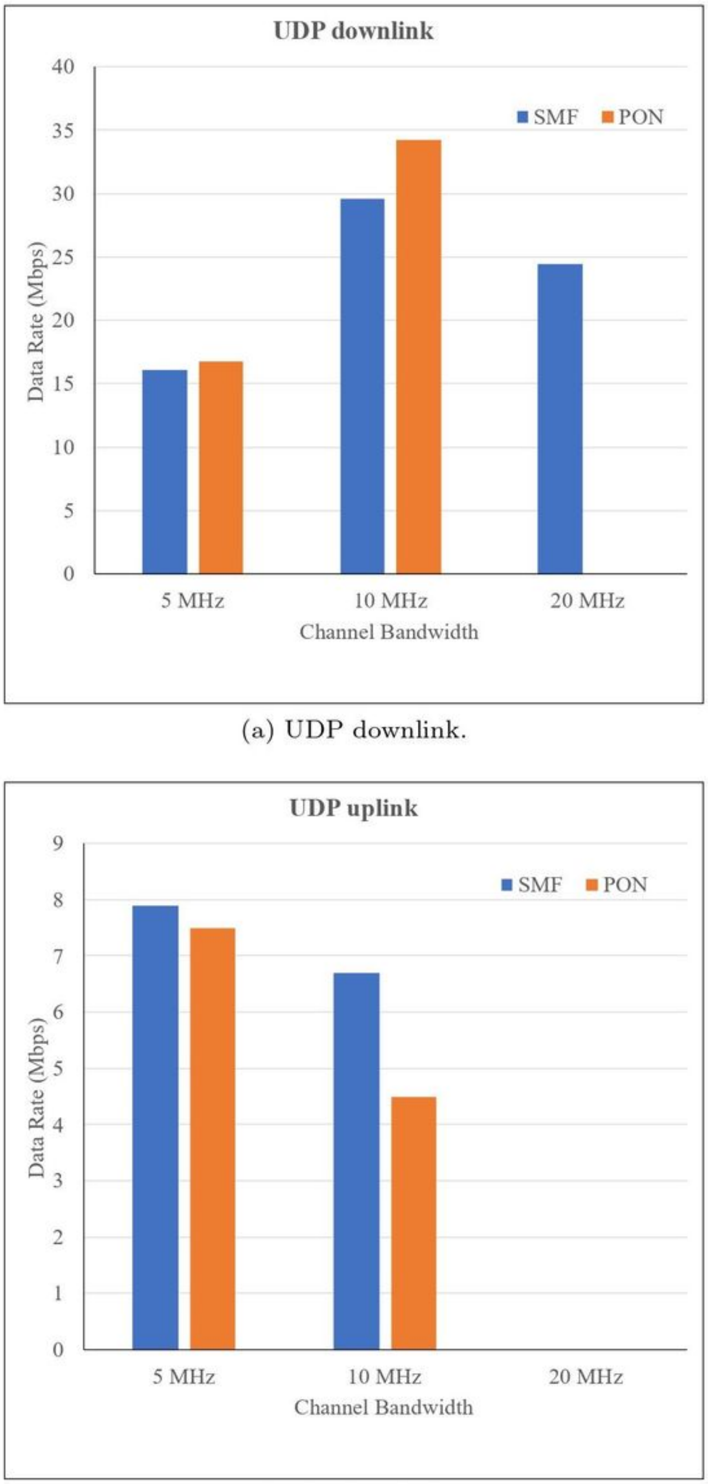
(a) TCP downlink.



(b) TCP uplink.

Figure 8

Measured data rate for TCP traffic.

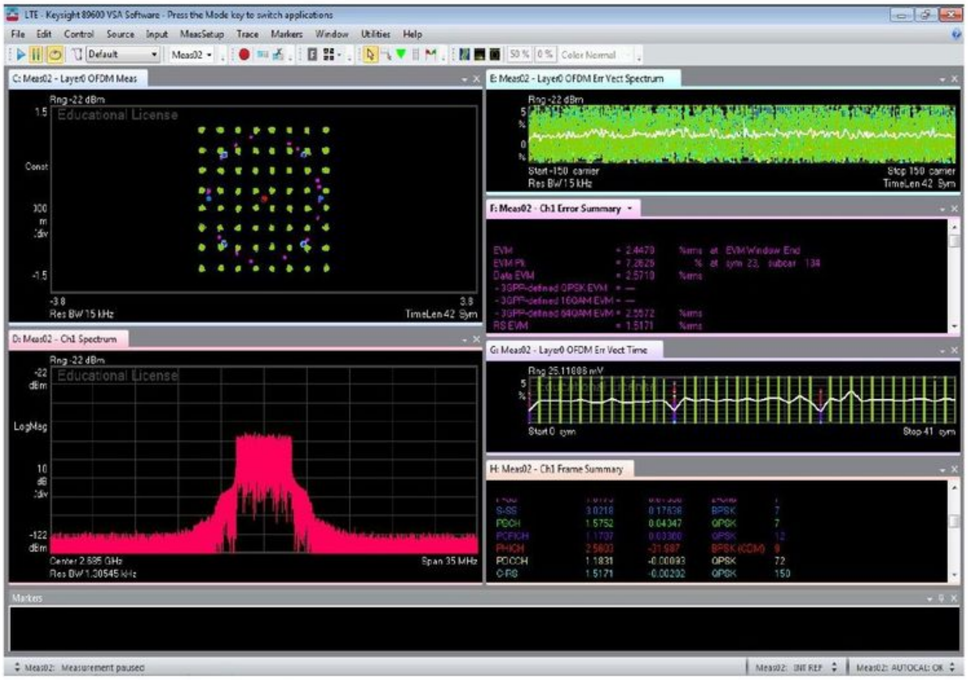


(a) UDP downlink.

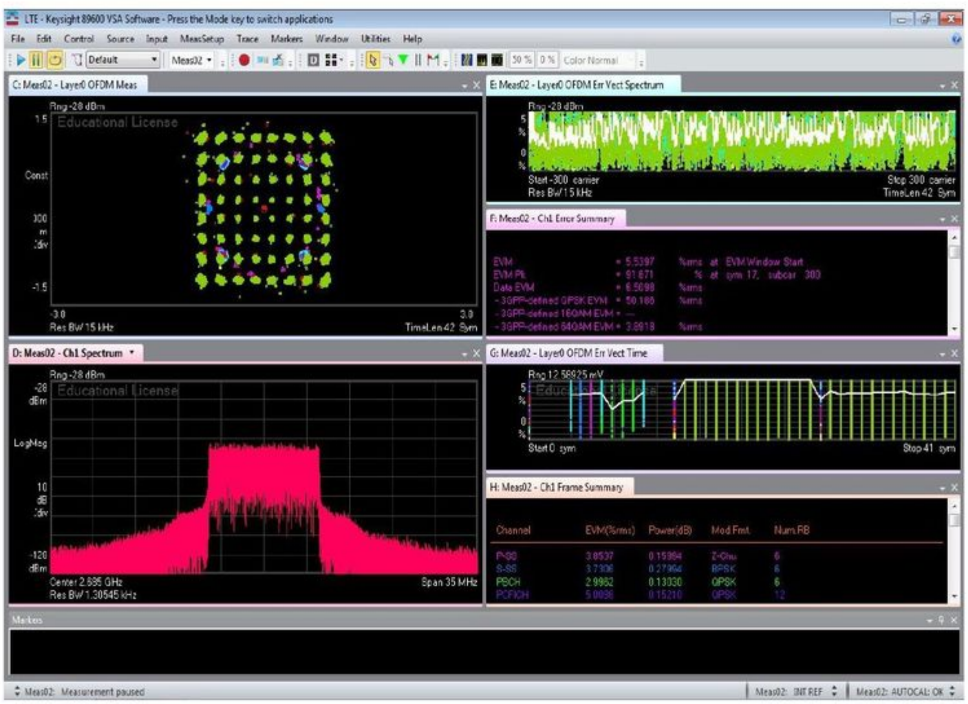
(b) UDP uplink.

Figure 9

Measured data rate for UDP traffic.



(a) 5 MHz Channel Bandwidth.



(b) 10 MHz Channel Bandwidth

Figure 10

Over-the-Air signal capture by the VSA, showing modulation constellation points, signal waveform and EVM while data traffic is being transmitted