

# OpenAirInterface: Democratizing innovation in the 5G Era

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## ABSTRACT

OpenAirInterface™ (OAI) is an open-source project that implements the 3rd Generation Partnership Project (3GPP) technology on general purpose x86 computing hardware and Off-The-Shelf (COTS) Software Defined Radio (SDR) cards like the Universal Software Radio Peripheral (USRP). It makes it possible to deploy and operate a 4G Long-Term Evolution (LTE) network today and 5G New Radio (NR) networks in the future at a very low cost. Moreover, the open-source code can be adapted to different use cases and deployment and new functionality can be implemented, making it an ideal platform for both industrial and academic research. The OAI Software Alliance (OSA) is a non-profit consortium fostering a community of industrial as well as research contributors. It also developed the OAI public license which is an open source license that allows contributors to implement their own patented technology without having to relinquish their intellectual property rights. This new clause is in agreement with the Fair, Reasonable And Non-Discriminatory (FRAND) clause found in 3GPP. This paper describes the current OAI state-of-the-art of the development, the OAI community and development process, as well as the OAI public license and its usage by academia and industry.

## 1. Introduction

OpenAirInterface (OAI) is an open source initiative that today provides a 3GPP compliant reference implementations of key elements of 4G and 5G Radio Access Network (RAN) and core network that run on general purpose computing platforms (x86) together with Off-The-Shelf (COTS) Software Defined Radio (SDR) cards like the ETTUS Universal Software Radio Peripheral (USRP).<sup>1</sup> It allows users to set up a compliant 4G/5G network and inter-operate with commercial equipment.

OAI distinguishes itself from other similar projects through its unique open-source license, the OAI public license v1.1, which was created by the OAI Software Alliance (OSA)<sup>2</sup> in 2017. This license is a modified version of Apache v2.0 License, with an additional clause that allows contributing parties to make patent licenses available to third parties under FRAND terms similar to 3GPP for commercial exploitation. The usage of OAI code is free for non-commercial/academic research purposes. The main reason for this modification is to allow companies/individuals which own significant portfolio of patents to be able to contribute to the

OAI source code and still be able to keep their patent rights. Such a license allows contributions from 3GPP member companies while at the same allowing commercial exploitation of the code, which is not at all possible with other open-source projects.

From a feature set point of view, Software Radio System Long Term Evolution (srsLTE) [1] is also an open-source project and it is very close to OAI (see [2] for a more detailed overview of features), but it uses a GNU Affero General Public License (AGPL) version 3 and commercial licenses which allow the copyright holder, Software Radio Systems, to also commercially exploit the code in their products. OpenLTE [3] also provides a set of tools to detect and decode LTE signals and also works together with GNU radio [4], but cannot be run in real-time or establish an end-to-end link with commercial equipment. OpenLTE also employs a AGPL v3 license. Another competitor to OAI which is completely closed source is Amarisoft [5]. For the older 2G and 3G standards there also exist open-source solutions that are also commercially deployed, such as openBTS [6], Osmocom [7], and openUMTS [8].

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<sup>2</sup> [www.openairinterface.org](http://www.openairinterface.org)

Despite not constituting complete 5G systems, these open-source platforms (the most popular: OAI and srsLTE) have been employed successfully for the development of several 5G technologies (i.e. LTE unlabeled, network slicing or disaggregated LTE, neutral host deployment and RAN sharing just to cite some). While there is no consensus about the pros and cons of each of these platforms, namely, OAI being more computationally efficient than srsLTE, srsLTE's code base being more modular and easier to customize than OAI, OAI's code being complex and difficult for a user to modify or customize, there have been limited previous efforts to formally analyze and describe their 5G roadmap.

5G is also known by Release 15 of 3GPP. This release includes a brand new core network and radio interface, called 5G New Radio (5G-NR). The network has been designed from ground up to support enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), as well as Massive Machine Type Communications (mMTC) enabling new use cases for a large variety of industries. This has been achieved by a large number of new features compared to 4G LTE, such as flexible subcarrier spacing and slot lengths (also called numerology), increased bandwidth (up to 400MHz), flexible slot structure (including mini-slots and slot aggregation). 5G-NR also includes new channel codes: polar codes for control and Low Density Parity Check (LDPC) for data. A good overview of all new features is given in [9,10].

Initial deployments of 5G-NR will use the architecture option 3 of 3GPP, also called Evolved Universal Terrestrial Radio Access (EUTRA-NR) Dual Connectivity (EN-DC). In this option the 5G cell is connected to a 4G evolved packet core network and is operating under the control of a 4G cell, which serves as an anchor to the system and carries all Control Plane (CP) traffic. User Equipment (UE)s first need to connect to the 4G network and will receive all the necessary configuration to connect to a 5G cell through Radio Resource Control (RRC) signaling on the 4G link. This setup will allow a smooth migration from 4G to 5G. This scenario is also the one that OAI is currently focusing on and which will be described in more detail in Section 2.

3GPP has also defined a new 5G Core (5GC) architecture that supports service delivery over wireless, fixed or converged networks. This new 5GC uses a cloud-aligned Service-Based Architecture (SBA) that supports CP function interaction, re-usability, flexible connections and service discovery that spans all functions [11]. This new core network allows for so called standalone operation of 5G NR, i.e. it does not rely anymore on a 4G network.

A first pre-5G demonstration was given at Mobile World Congress (MWC) 2018 where OAI has shown the feasibility of maintaining a throughput of 300Mbps over a 80MHz channel using the new 5G-NR LDPC channel coding. This was achieved by offloading the most computationally expensive task, the LDPC decoder, to an Field Programmable Gate Array (FPGA). Using a software-only implementation of the LDPC decoder, a throughput of 150Mbps can be supported.

Since then the OAI team has been working to provide a standard compliant version of a 5G gNB that together with an updated version of the eNB will provide Non-Standalone Access (NSA) with a target completion in Q1 2020. Development of a 5GC network is also underway and in 2020 OAI is planning to support the Standalone Access (SA) mode of 5G.

Considering the OAI functionalities, capabilities and continued evolution, this paper describes the current state-of-the-art of the 5G implementation efforts of OAI, both on the radio network side and the core network side. Section 2 describes how OAI fits in both SA and NSA scenarios. Section 3 provides implementation details about OAI 5G gNB. In Section 4 the 4G Evolved Packet Core (EPC), the Control and User Plane Separation (CUPS) of EPC and the 5GC are discussed taking into account OAI implementation and 3GPP view. Section 5 describes preliminary results regarding some of the introduced 5G NR features deployed in an outdoor testbed at Eurecom that can give the reader a flavor and a properly understanding of what can be done with the improved version of OAI. The overall OAI roadmap regarding to 5G RAN and Core are reported in Section 6. A fundamental discussion about OAI license and its

impact on industry use cases is presented in Section 7. The state-of-the-art of OAI in research and development is presented in Section 8 from the point of view of academia and industry. Finally, we summarize the paper in Section 9.

## 2. 5G Deployment scenarios

3GPP has defined both a new 5GC network and a new radio access technology called 5G "New Radio" (NR). The gNB is the logical 5G radio node, where 'g' stands for "next Generation". Unlike previous generations that required that both access and core network of the same generation to be deployed (i.e. EPC and LTE together formed a 4G system), with 5G it is possible to integrate elements of different generations in different configurations as follows.

1. *Non-Standalone* combining multiple radio access technologies; and
2. *Standalone* using only one radio access technology.

### 2.1. Non-standalone mode (NSA)

The architecture of the EN-DC network is depicted in Fig. 1. Here the LTE eNB takes the role of the master and the 5G gNB the role of the slave, and they are connected over the Xn interface. In this architecture, the anchors of the CP are always located in the LTE eNB, that is, the S1-MME interface is terminated by the eNB. The S1-U interface for user plane data can either be terminated at the eNB, in which case user-plane data would need to be forwarded over the Xn interface, or at the gNB, in which case the eNB would only handle control-plane traffic.

Compared to a 4G eNB, a 5G gNB can be separated into a Centralized Unit (CU) and one or more Distributed Units (DUs), which are connected over the F1 interface. The CU contains the functionality of the Packet Data Convergence Protocol (PDCP) as well as RRC and has interfaces to the LTE eNB (Xn) and optionally also to the core network (S1-U). The DU contains the functionality of Radio Link Control (RLC), Medium Access Control (MAC), and PHYSICAL layer (PHY).

Further splits can be employed within the DU, but this is out of the scope of 3GPP. In OAI we have decided to use the 5G Functional Application Platform Interface (FAPPI) interface between PHY and MAC specified by the Small Cell Forum (SCF) [12]. This interface provides a clean separation of the two layers. Moreover, in the future this can be extended to become a networked FAPPI (nFAPPI) interface, which will allow to physically separate the PHY and the MAC.

### 2.2. Standalone mode (SA)

3GPP has also defined a SA mode, where the 5G gNB connects to a new 5GC network, which supports service delivery over wireless, fixed or converged networks. This new 5GC uses a cloud-aligned SBA that supports CP function interaction, re-usability, flexible connections and service discovery that spans all functions [11]. In particular, SA version envisions a totally new RAN and core network. Like NSA, standalone will use millimeter wave bands, as well as low- and mid-band frequencies, to deliver wide-area coverage and multi-gigabit connections.

In a SA scenario, the 5G NR or the evolved LTE (eLTE) radio cells and the core network are operated alone. This means that the NR or eLTE radio cells are used for both Control Plane (CP) and User Plane (UP). The SA option is a simple solution for operators to manage and may be deployed as an independent network using normal handover between 4G and 5G for service continuity.

The advantage of SA is simplification and improved efficiency, which will lower cost, and improve performance in throughput up to the edge of the network, while also assisting development of new cellular use cases (i.e. URLLC). The migration from 5G NSA to SA by operators is expected to be transparent to the user.

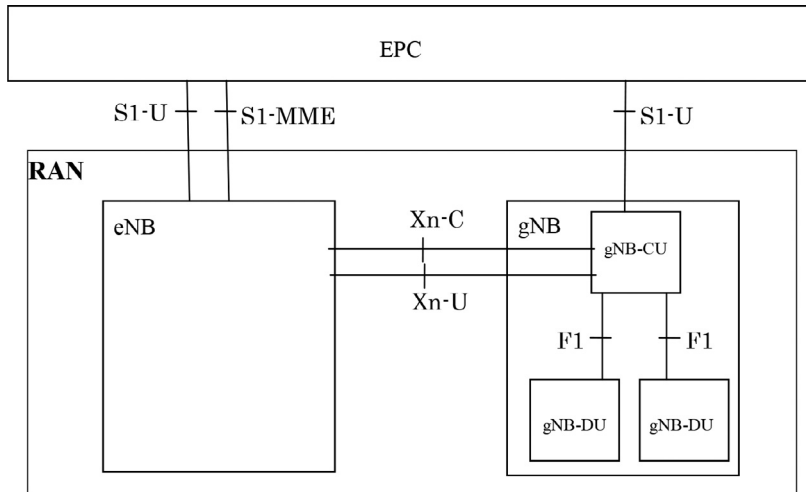


Fig. 1. Architecture of the EUTRA-NR dual connectivity (EN-DC) network.

### 3. OAI 5G RAN Implementation status

The current focus of OAI is on the development of a 5G NSA solution using the EN-DC architecture where the eNB handles all the CP and the gNB only needs to handle the user-plane traffic. This section describes the implementation status of the RAN (eNB, gNB and UE) implemented by OAI as of December 2019. This project is under active development and the updates can be found at the webpage.<sup>3</sup>

Unless otherwise noted, all the features implemented and described in this section apply to both the gNB and the UE.

#### 3.1. Supported hardware targets

The most popular hardware target used with OAI are the USRP devices from ETTUS research. The most commonly used ones are the *B210*, the *X310*, and the *N310* [13].

For LTE, which supports channel bandwidths up to 20 MHz, the most commonly used platform is the *USRP B210*, but any of the other devices will work too. NR supports channel bandwidths up to 100 MHz in the sub-6GHz spectrum (called Frequency Range 1 (FR1) in 3GPP), but can also be configured for 80 MHz or 40 MHz wide channels. The usability of the device for NR mainly depends on the supported master clock rates and sampling rates,<sup>4</sup> which has to be compatible with the ones specified by 3GPP, and not the maximum supported bandwidth.

The *USRP B210* can be used for 40 MHz channel configuration<sup>5</sup> but only with 1 channel due to the limit of the Universal Serial Bus 3 (USB3) interface with the host. The *X3x0* can be used for 80MHz channel configurations<sup>6</sup> with up to 2 channels. The *N3x0* can be used for 100MHz bandwidth configuration with up to 4 channels.<sup>7</sup>

Of course OAI also works with other platforms. This is achieved by an abstraction layer that is common to all hardware platforms and pro-

<sup>3</sup> <https://gitlab.eurecom.fr/oai/openairinterface5g/wikis/5g-nr-development-and-releases>.

<sup>4</sup> The master clock rate is the clock rate at which the RF chip is driven and the sampling rate which is the rate at which samples are transferred to the host and is obtained through resampling and filtering in the FPGA

<sup>5</sup> This is achieved by choosing a master clock rate and a sampling rate of 46.08 MHz, and using a Fast Fourier Transform (FFT) size which is 3/4 of the classical FFT size used for this numerology (i.e. a 1536 point FFT instead of 2048 point FFT).

<sup>6</sup> This is achieved by choosing a master clock rate of 184.32 MHz, a sampling rate which is half of that (92.16MHz) and using a Fast Fourier Transform (FFT) size which is 3/4 of the classical FFT size used for this numerology (i.e. a 3072 point FFT instead of 4096 point FFT).

<sup>7</sup> This is achieved using a master clock rate and sampling rate of 122.88 MHz and an FFT size of 4096.

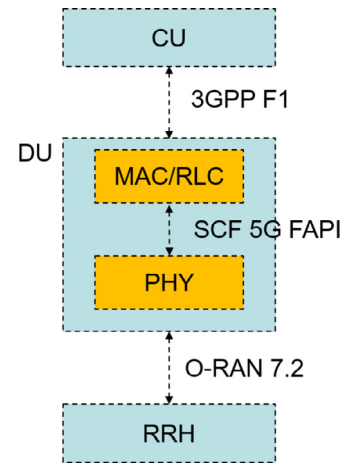


Fig. 2. gNB Functional split architecture.

vides a generic interface for initialization, parametrization, read and write access. Just as an example we would like to mention here the SDR platform developed by SYRTEM<sup>8</sup> which is based on the Xilinx ZYNQ-7000 ZC706 evaluation kit and an RF daughterboard based on the Analog Devices ADRV9371 chip (the same chipset as the USRP N3x0). It therefore has the same capabilities as the N300, but the communication with the host is over Peripheral Component Interconnect (PCI) express rather than 10Gbit Ethernet. However, not all parts of the driver are open source and need to be purchased from SYRTEM.

#### 3.2. eNB

The eNB has been the core part of OAI for a long time and shall not be discussed in detail here. For the purpose of 5G NSA we have upgraded the implementation of the RRC to Rel.15 in order to support all of the required signaling to the 5G UE. Also the X2 interface has been adopted to Rel.15 in order to support the signaling between eNB and gNB.

#### 3.3. gNB

The gNB incorporates three main functional modules: the CU implementing the RRC and PDCP layers, the DU implementing PHY, MAC and RLC, and the Radio Unit (RU) - (RRH) (see Fig. 2). The interface between

<sup>8</sup> <http://www.syrtem.com>.

CU and DU has been standardized by 3GPP as the F1 interface whereas for the interface between the DU and the RU the O-RAN 7.2 interface [14] is becoming the de-facto standard. There is also an interface within the DU between the MAC/RLC and the PHY specified by the Small Cell Forum [12].

Today, the OAI gNB only supports a “monolithic” mode, meaning that all the different components of the gNB are part of a single application. Inside this application, the 5G FAPI interface is used to implement the interface between PHY and MAC, while the F1 and the O-RAN 7.2 interfaces are under development to allow for a physical separation of the different elements of the gNB.

### 3.3.1. PHY

The physical layer today supports numerologies 1 (30 kHz subcarrier spacing) with 40, 80, and 100 MHz bandwidth (106, 217, and 273 Physical Resource Blocks (PRBs)) and numerology 3 (120 kHz subcarrier spacing) with 50 and 100 MHz bandwidth (32 and 66 PRB). All of the main physical downlink and uplink channels are supported corresponding to the 3GPP specifications [15].

- **NR-Primary Synchronization Signal (PSS) and NR-Secondary Synchronization Signal (SSS)** Corresponds to the initial synchronization procedure at UE. After power-up, the UE tries to obtain time and frequency synchronization with the system. For this purpose, NR has defined two type of synchronization signals: PSS and SSS.
- **NR-Physical Broadcast Channel (PBCH)** This physical channel carries the Master Information Block (MIB) information for UEs requiring to access the network. The MIB message on the PBCH is mapped onto the central 72 subcarriers or six central resource blocks regardless of the overall system bandwidth. The MIB utilizes the Broadcast Transport Channel and Broadcast Control Logical Channel. The PBCH uses new polar codes for channel coding. The PSS, SSS and PBCH channels together for the Synchronization Signal Block (SSB). Up to 64 SSBs can be transmitted in one frame and each SSB can be transmitted on a different beam. This mechanism allows for initial beam acquisition during initial access.
- **NR-Physical Downlink Control Channel (PDCCH)** The main purpose of this physical channel is to carry mainly scheduling information of different types (Downlink Resource Scheduling (DRS), uplink power control instructions, uplink resource grant and indication for paging or system information). The PDCCH contains a message known as the Downlink Control Information (DCI) which carries the control information for a particular UE or group of UEs. The DCI format has several different types which are defined with different sizes [16]. For instance, *Type 0 PDCCH Common Search Space* is a subset of *NR PDCCH Search Space*<sup>9</sup> that is dedicated to transmit the PDCCH for System Information Block (SIB) message decoding.
- **NR-Physical Downlink Shared Channel (PDSCH)** This physical channel carries user data and paging information to the UE. It uses an adaptive modulation format dependent on the link conditions (i.e. signal to noise ratio). It also uses a new channel coding scheme named LDPC. Like all NR channels, PDSCH has its own Demodulation Reference Symbols (DMRS). In LTE (at least in Transmission Mode (TM) 1, 2, 3, 4), we don't need this kind of special DMRS for PDSCH because we can use Cell Specific Reference Signal (CRS) for PDSCH decoding. However, in 5G NR there is no CRS and therefore we need the DMRS dedicated for PDSCH decoding. Basically, the DMRS symbols (can be either 1 or 2) are located at: a) Slot based (DMRS mapping type A) fixed Orthogonal Frequency-Division Multiplexing (OFDM) symbol regardless of the PDSCH assignment; b)

Non-slot based (DMRS mapping type B) first OFDM symbol assigned for PDSCH.

- **NR-Physical Random Access Channel (PRACH)** This channel is used for random access functions. It transmits an initial random access preamble consisting of sequences which may be of two different lengths: 1) a long sequence is 839 which is applied to the subcarrier spacings of 1.25 kHz and 5 kHz; and 2) a short sequence lengths of 139 are applied to subcarrier spacings of 15 kHz and 30 kHz (FR1 bands) and 60 kHz and 120 kHz (Frequency Range 2 (FR2) bands).
- **NR-Physical Uplink Shared Channel (PUSCH)** This channel is the complement of the PDSCH. It is used to carry data from the UL-SCH and its higher mapped channels on a frequency and time-shared basis. In summary, PUSCH carries user data and Uplink Control Information (UCI). Similar to the PDSCH, the PUSCH also has a very flexible format and used LDPC channel coding. The allocation of frequency resources uses RBs along with a flexible modulation and coding scheme.
- **NR-Physical Uplink Control Channel (PUCCH)** This channel is used to transport UCI (i.e. Hybrid Automatic Repeat Request (HARQ) feedback, CSI (Channel State Information) and SR (Scheduling Request)). It is also possible that dependent upon the resource allocation the uplink control information or data may also be sent on the PUSCH.

One of the main challenges of 5G NR compared to 5G LTE are the new LDPC channel codes for the downlink and uplink shared channels and the high throughput requirements. OAI provides highly optimized LDPC encoder and decoder supporting Base Graph 1 (BG1) and Base Graph 2 (BG2). They take advantage of the Advanced Vector eXtension 2 (AVX2) Single Instruction Multiple Data (SIMD) instruction set of the Intel x86 architecture. The decoder [17] has an average latency of 200 $\mu$ s for 8 segments of 8448 bits each (largest segment size in NR) on a single core<sup>10</sup> providing a theoretical average throughput of 338Mbps.<sup>11</sup> More than 8 segments can be parallelized over multiple cores. The LDPC decoder can also be offloaded to an FPGA board<sup>12</sup> or to a graphics processor unit (GPU).<sup>13</sup>

Also the channel codes for the control channels are different in 5G NR compared to 4G LTE and now use polar codes. The polar decoder implemented in OAI uses a standard Successive-Cancellation (SC) list decoder algorithm [18]. This algorithm is not optimal in Block Error Rate (BLER) performance but it is extremely fast. The decoding time for (i.e. PBCH) payload of 32bits is less than 4  $\mu$ s. In the future we might improve the algorithm based on [19].

### 3.3.2. MAC/RLC/PDCP

The MAC receives the configuration from higher layers and further configures the PHY using the Femto Application Programming Interface (FAPI) P5 interface. At the moment the gNB still uses a static scheduler with a single pre-configured UE and statically allocated resources. Using the FAPI P7 interface it can generate all the parameters necessary for the physical channels mentioned above and can transmit random data on the PDSCH and PUSCH. The Random Access (RA) procedure and the generation of the Msg2 (RA response) is currently being integrated.

At the UE the MAC also stimulates the PHY via the FAPI interface and configures the receivers for all the physical channels mentioned above.

As in the 4G version, a so-called “noS1” mode is supported, meaning that traffic can be injected/extracted through a TUN (TUNnel) network interface at the level of the PDCP. This allows testing of OAI gNB and UE without the support of a core network.

<sup>10</sup> Tested with “ldpctest -l8448 -s10 -n1000 -S8” on an Intel Xeon Gold 6154 CPU 3.00 GHz.

<sup>11</sup> Due to other limitations in the code, we have not yet managed to achieve this throughput with the full NR modem yet.

<sup>12</sup> Provided by <http://www.syrtem.com>.

<sup>13</sup> Contributed by Center for Open Intelligent Connectivity of National Chiao Tung University and Ministry of Education, Taiwan.

<sup>9</sup> PDCCH Search Space refers to the area in the downlink resource grid where PDCCH may be carried. UE performs blind decoding throughout these search spaces trying to find PDCCH data (i.e., DCI). At high level view, NR Search Space concept is similar to LTE Search Space.



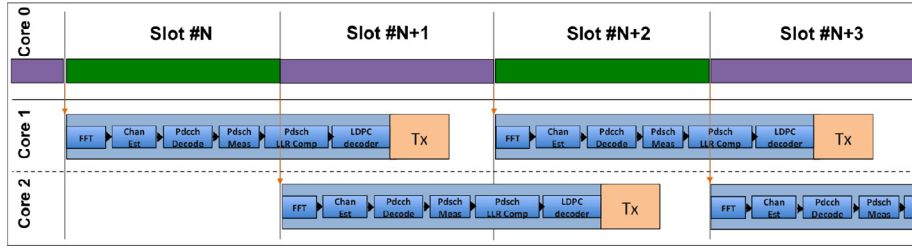


Fig. 3. UE threading structure.

The RLC and PDCP have been updated to the 5G NR specifications.

### 3.3.3. RRC

In the EN-DC architecture the RRC in the gNB receives an additional request from the master eNB over the X2 interface. It replies with an addition request acknowledge message that also includes the NR RRC configuration message that includes all the parameters of the gNB. This message is embedded in the RRC connection reconfiguration message at the eNB and sent to the UE over the LTE link. The only RRC message that is directly sent over the NR link in the EN-DC architecture is the MIB, which is also generated in the RRC.

The RRC at the gNB is further responsible to read the configuration file and to configure MAC and the PHY according to the configuration parameters.

### 3.3.4. gNB Software Architecture

The software architecture for the gNB has been completely revised to meet the more stringent requirements of 5G-NR. We have introduced a pipeline structure that distributes the processing of different blocks in the processing chain over different threads. Additionally some computational expensive tasks, like the Fast Fourier Transforms (FFTs) of the front-end processor or the LDPC encoder can be further parallelized using worker threads. The architecture can be adapted to the number of cores available on the system. More details are described in [20].

## 3.4. UE Software architecture

OAI also provides a simple implementation of a 5G NR UE. This UE will work together with the OAI gNB in the aforementioned "noS1" mode, but it at this point it is not compliant with either the NSA or the SA 5G deployments.

At the UE, the highest computational complexity is in the receiver of the PDSCH. Even though many computational expensive modules have been already optimized, it is still hard to perform all process within one slot period. Since there is no dependency between slots, it is possible to parallelize them over different parallel threads.

In our current implementation, one thread is dedicated to the reading and writing samples to and from the SDR, and one or more worker threads are responsible of processing the downlink signal of slot  $N$  and prepare the uplink signal of slot  $N + 4$ , where  $N = t \bmod T$ ,  $t$  is the current thread and  $T$  is the total number of threads. The number of threads is configurable to adapt the different requirement in 5G standard and different hardware execution time. An example for  $T = 2$  threads is shown in Fig. 3: the processing time allowed for each slot is doubled from 1 slot to 2 slots. Further the UE parallelized the LDPC decoding over segments.

## 4. Core network

### 4.1. 4G EPC

The 4G EPC is a framework for providing converged voice and data on a 4G LTE network. The basic components of an EPC are a Home Subscriber Server (HSS), a Mobility Management Entity (MME), as well as a

Serving Data Gateway (S-PGW). In OAI, HSS and MME are distributed in the openairCN (where CN stands for Core Network) repository<sup>14</sup> while the S-PGW are distributed under the openair-cn-cups repository<sup>15</sup>. It is important to emphasize that OAI implements the functionality of the Packet Data Network Gateway (PGW) and Serving Gateway (SGW) in one module: the S-PGW, and it must have the General Packet Radio Service (GPRS) Tunneling Protocol (GTP) Linux kernel module to work correctly.

### 4.2. Control and user plane separation (CUPS)

CUPS of EPC nodes is one of the main items of 3GPP Release 14. An Architectural enhancement feature that introduces the concept of separation between CP and UP of EPC nodes (SGW, PGW, Traffic Detection Function (TDF)). Separating the control and data plane functions of PGW and SGW into separate entities gives the service providers more flexibility in dealing with UP latency. Opposite to the expectations of having the new interfaces (Sxa, Sxb) based on GTP; the reference points introduced a new protocol, named Packet Forwarding Control Plane (PFCP), as the CP-UP interface standard.

CUPS is not a new concept in the wireless world and it has quickly becoming an integral part of the 5G network development. It allows operators to separate the EPC into a CP that can sit in a centralized location, for example the middle of the country, and for the UP to be placed closer to the application it is supporting. Because the core UP is located closer to the end user the operator does not have to backhaul traffic all the way to central hub and therefore saves resources.

Fig. 4 shows a logical view of the OAI CN software composition. The SGi interface has to be a physical network interface from the kernel point of view. eNB has two interfaces to MME and SPGW: S1-C is the control interface to exchange message with MME and S1-U is a data plane interface for data packets. The HSS communicates with MME via S6a interface. The public interface is used as the SPGW-U's SGI interface for Internet access. The MME is connected to the Serving Gateway (SGW) through S11-C interface. S5 and S8 interfaces can be used for communication between SGW and Packet Gateway (PGW).

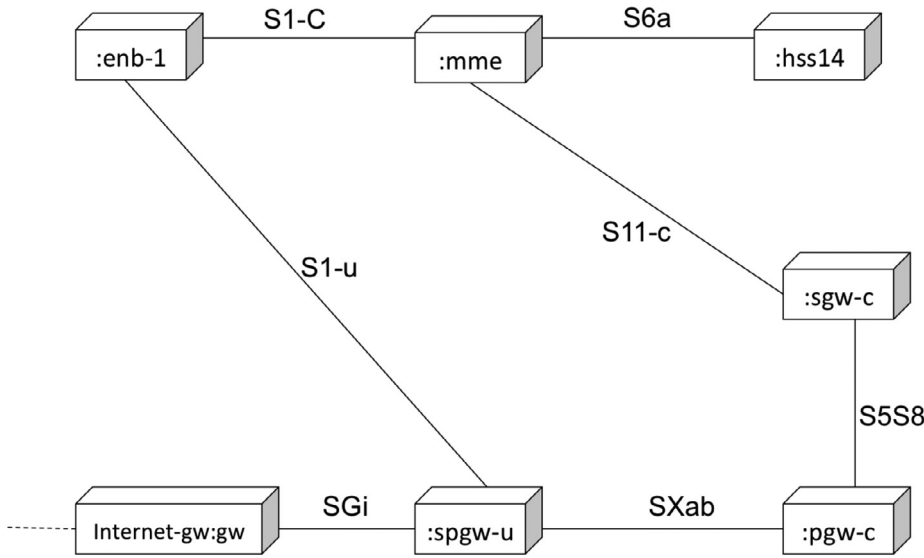
### 4.3. 5G Core (5GC)

5GC network has realized the separation of UP and CP. At the same time, mobility management functions and session management functions are no longer concentrated in the same network element (such as MME in LTE), which enables the network function to provide a specific function.

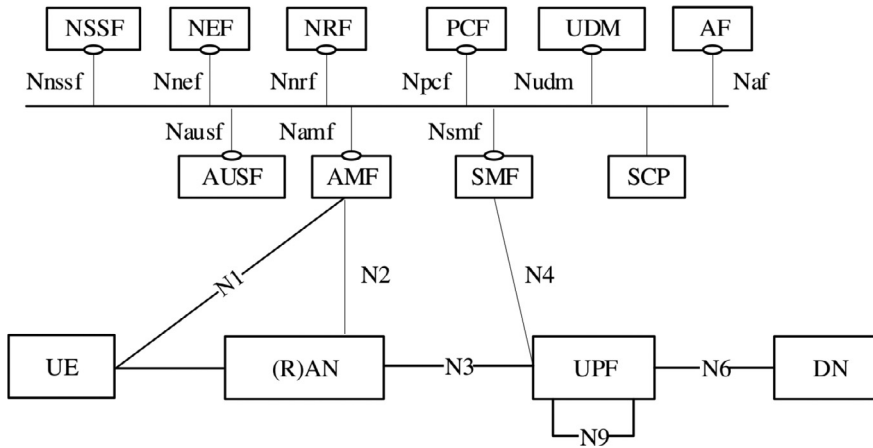
The new 5G system architecture relies on the SBA in which the system functionality is achieved by a set of Network Functions (NFs), providing services to other authorized NFs to access their services [22]. In this architecture, the 5GC components have been simplified with most of them being software based so that they could be adapted according to the need. Also, the CP functions are separated from the UP in order to make them scaling independently allowing operators to use these

<sup>14</sup> <https://github.com/OPENAIRINTERFACE/openair-cn/>.

<sup>15</sup> <https://github.com/OPENAIRINTERFACE/openair-cn-cups/>.



**Fig. 4.** Elements of the 4G evolved packet core (EPC) with control and user plane separation (CUPS).



**Fig. 5.** 5G Standalone System Architecture and Interfaces [21].

components for dimensioning, deploying and adapting the network to their needs easily. Fig. 5 depicts the non-roaming reference architecture for 5GC [21]. This figure illustrates the 5G system architecture which consists of different components. At the bottom, the UP components are sketched. The communication between R(AN) and UP Function (UPF) will be done directly and from there, to the Data Network (DN). The CP components include:

1. Authentication Server Function (AUSF) is to support authentication for 3GPP access and untrusted non-3GPP access;
2. Access and Mobility Management Function (AMF) is responsible for managing access control and mobility;
3. Network Exposure Function (NEF) provides a mechanism to expose services and features of the 5G NFs to external entities;
4. NF Repository Function (NRF) is to provide NF service registration and discovery;
5. Network Slice Selection Function (NSSF) is to assist in the selection of suitable network slice instances for users;
6. Policy Control Function (PCF) is responsible for handling policies and rules in 5G system for network slicing, roaming and mobility management;
7. Session Management Function (SMF) is to set up and manages sessions according to network policy; and
8. Unified Data Management (UDM) generates the Authentication and Key Agreement (AKA) credentials and stores subscriber data and profiles.

**Table 1**

The interface of network functions .

|     | SBI | N1 | N2 | N3 | N4 |
|-----|-----|----|----|----|----|
| AMF | ✓   | ✓  | ✓  |    |    |
| SMF | ✓   |    |    |    | ✓  |
| UPF |     |    |    | ✓  | ✓  |

Currently, we are developing three main NFs, namely AMF, SMF, and UPF to support the minimal functionality of 5GC. When developing the three NFs, there are five types of interfaces (reference points) supposed to be implemented, which are the interface between the UE and the AMF (N1), the interface between the (R)AN and the AMF (N2), the interface between the (R)AN and the UPF (N3), the interface between the SMF and the UPF (N4), and the interface inside 5GC NFs (Service-based interfaces). Table 1 shows what interfaces belonging to each NF, which are described as follows.

- **Service-Based Interface (SBI):** Control Plane Network Functions in the 5G system architecture are based on the service based architecture. A NF service is one type of capability exposed by a NF (NF Service Producer or Server) to other authorized NF (NF Service Consumer or Client) through a service based interface [22]. In other words, NFs communicate with each other via SBI. The protocol stack for the service based interfaces is *Application/HTTP2/TLS/TCP/IP/L2* [22]. By relying on the YAML Ain't

Markup Language (YAML) files provided by 3GPP specifications and an open source OpenAPI generator (OpenAPITools<sup>16</sup>), the source code for SBI can be generated. In our implementation, the Pistache framework<sup>17</sup> has been selected to generate the source code for SBI for both server and client sides. In more details, following the guidelines for services definition in 3GPP TS 29.501[21], the AMF communication service is identified by a specified Uniform Resource Locator (URL) as *apiRoot/namf-comm/v1*. When a NF (e.g., SMF) want to invoke a service operation, e.g., N1N2MessageTransfer, by using HTTP method POST to request the AMF to transfer N1/N2 information to UE/AN, this NF initiates the request with the Uniform Resource Identifier (URI) of "N1 N2 Messages Collection" resource as *apiRoot/namf-comm/v1/ue-contexts/ueContextId/n1-n2-messages* [23] with the N1/N2 content embedded in the message. The N1 and N2 content will be encoded as *application/vnd.3gpp.5gnas* and *application/vnd.3gpp.ngap* respectively.

- **N1 interface:** N1 interface is a logical interface located between the UE and the AMF. The N1 Non-Access Stratum (NAS) signalling messages are used for both mobility management procedures between the UE and the AMF (NAS-MM); and for session management procedures between the UE and the SMF (NAS-SM) [24]. In our implementation, LibNAS is built for encoding/decoding NAS messages, including messages/Information Elements (IEs) definitions, integrity protection algorithm and encryption algorithm.
- **N2 interface:** N2 interface is responsible for signalling interactions between gNB and AMF, of which protocol stack is *Next Generation Application Protocol (NGAP)/ Stream Control Transmission Protocol (SCTP)/ Internet Protocol (IP)/Layer 2 (L2)/L1* [25]. To encode/decode NGAP messages, LibNGAP is implemented by compiling Abstract Syntax Notation One (ANS.1) files provided by 3GPP TS38.413 [25] using an ASN.1 compiler and supports aper/uperm methods.
- **N3 interface:** N3 is the data plane interface between gNB and UPF. Its application protocol is GPRS Tunnelling Protocol User Plane (GTP-U), which can be implemented using open source GTPv1u project.
- **N4 interface:** N4 interface is responsible for signalling interaction between the SMF and the UPF, of which protocol stack is *Packet Forwarding Control Protocol (PFCP)/ User Datagram Protocol (UDP)/IP/L2/L1* [26]. N4 interface is divided into CP function and UP function. The CP function controls the packet processing in the UP function by establishing, modifying or deleting PFCP Session contexts.

## 5. Preliminary results

### 5.1. Interoperability tests with commercial phone

At the time of writing, interoperability tests of the NSA 5G NR with a COTS phone are ongoing. The setup includes the OAI EPC, an OAI eNB based on a USRP B210, and an OAI gNB based on a USRP N310. The eNB has been configured for band 7 (2.6 GHz FDD) while the gNB for band n78 (3.6 GHz TDD). Oppo Reno 5G [27] was used as a phone. Fig. 6 shows a screenshot of logs obtained from the Oppo Reno 5G. The right bottom red circle highlights that the Cyclic Redundancy Check (CRC) of the PDSCH of the Random Access Response (RAR) has been successfully received.

The current validation only includes the initial access on the LTE cell, the configuration and reporting of 5G NR measurements as well

**Table 2**

OAI NR softmodem high level parameters for outdoor test.

| Parameter          | Value   |
|--------------------|---|
| Frequency range    | 3.5 GHz (FR1)   |
| Subcarrier spacing | 30 kHz  |
| Bandwidth          | 40 MHz (106PRB)   |
| Antenna ports      | Single antenna port                                     |
| TDD configuration  | Static with 5ms switching (7 DL, 1 special, 2 UL slots) |
| Configuration      | Phy-test mode with DL only                              |
| DL allocation      | MCS 9, 109 PRB, randomly generated payload,             |

as the configuration of the 5G cell through RRC signaling. We have also validated the initial access on the 5G cell, including the correct reception of the PRACH, the successful reception of the RAR at the UE, and the successful reception of the Msg3, which is the first PUSCH configured by the RAR.

### 5.2. Outdoor tests with OAI UE

In order to test the performance of the OAI gNB and UE we have performed some tests on the 5G platform at Eurecom. Among other elements this platform includes a 5G gNB based on two USRP N310, an external RF that provides switching, Power Amplifiers (PA) and Low Noise Amplifiers (LNAs) for operation in the NR band n78 (3.5 GHz), and two Kathrein 80010922 antennas [28] with 8 ports for operation at 3.5 GHz. The USRPs are and the PA/LNAs are placed close to the antenna on Eurecom's rooftop. The USRPs are further connected via optical fiber to the server room, which runs the gNB in a container platform.

For the UE we use the USRP N300 boards together with a powerful laptop with a Core i7-7900 8 core processor. A special adapter is used to be able to connect the Thunderbolt 3 interface of the laptop with the 2x10Gbit Ethernet interface of the USRP. An additional RF front-end and antenna provides enough output power and amplification to operate indoor and outdoor environment.

The main parameters of the 5G NR protocol stack are given in Table 2. The measurements were done in the so-called phy-test mode, in which the gNB sends a fixed allocation of PDSCH along with the SSBs. The measurement was done in Line Of Sight (LOS) conditions at a distance of about 100m from the base station, between the two lower wings of the Eurecom building, so with significant reflectors around the UE.

In the experiment we verified the basic synchronization of the UE, the proper reception of the PBCH, the PDCCH and the PDSCH (A screenshot of the UE receiver showing these signals is given in Fig. 7). The BER of the PDSCH was measured as almost 0 under these channel conditions. In future work we will also test other channel conditions and 'Modulation and Coding Scheme' (MCS) in order to determine the throughput and the range of the cell.

## 6. Roadmap

While we are moving towards 5G, there is clearly the need for open-source tools in-order to make sure that a common Research and Development (R&D) and prototyping framework for rapid PoC (Proof-of-Concept) and experimentation exist. A previous OAI's road-map has been reported in [29]. This section describes the current OAI's road-map for both RAN and core.

### 6.1. 5G RAN

Once the basic interoperability of existing 5G phones with OAI RAN is validated, we will first focus on performance improvements in both the MAC and the PHY to improve the throughput. In particular we plan to re-write the MAC scheduler to be able to efficiently schedule multiple users. Moreover we will include all necessary features to support beam management and spatial multiplexing to multiple users. The roadmap

<sup>16</sup> OpenAPI Generator, available in <https://github.com/OpenAPITools/openapi-generator>.

<sup>17</sup> Pistache is a C++ REST framework available in <http://pistache.io/>. It is written in pure C++11 with no external dependency and provides a low-level HTTP abstraction. Pistache provides both an HTTP client and server that can be used to create and query complex web and REST APIs.

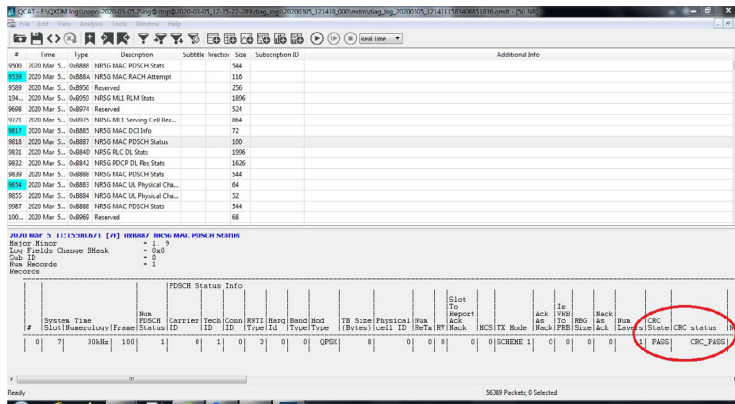


Fig. 6. Screenshot of logs obtained from the Oppo Reno 5G showing initial access procedure (obtained with Qualcomm QCAT). The detailed view at the bottom shows that the CRC of the PDSCH of the random access response (RAR) has been received ok.

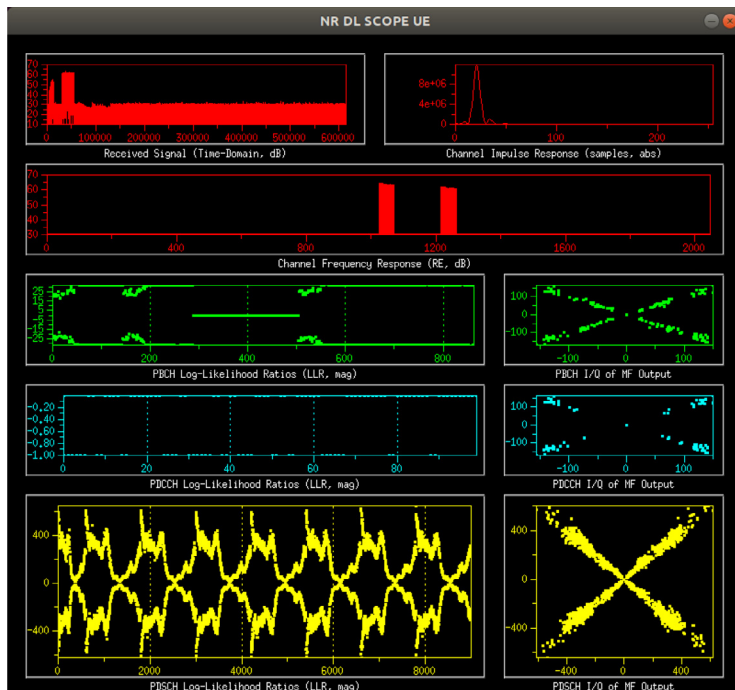


Fig. 7. Screenshot of the OAI NR UE softscope showing (from top left): the time domain signal, the time domain channel estimation (impulse response), the frequency domain channel estimates, the Log Likelihood Ratios (LLR) and IQ plot of the PBCH (green), the PDCCH (blue), and the PDSCH (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

also include the development of at least two-layer MIMO, CSI Reference Signals (CSI-RS), as well as the corresponding procedures. All these developments are planned for FR1 and FR2.

OAI is also working on the implementation of the O-RAN 7.2 fronthaul interface and we plan to support commercial Remote Radio Heads (RRHs).

As noted above the current focus of the development is on the NSA version of 5G NR, which uses the readily available 4G core of OAI. Once the first stable version of the 5GC becomes available, we will start implementing all the necessary functions also in the 5G gNB to support standalone mode. The target date for this is end of 2020.

## 6.2. 5G Core

As a part of the OAI project, the basic components for 5GC are under development. At this stage, the interfaces between the main components (e.g., AMF, SMF, UPF, and NRF) are implemented. However, the functional logic of these components is still under development. More specifically, the AMF is currently based on the latest version of MME (which was intensively tested and prepared for AMF by separating EPS (Evolved Packet System), Mobility Management (EMM) and EPS Session Management (ESM) parts of the NAS layer. The NGAP and NAS

protocols (mobility management part) for 5G systems have been implemented and will be integrated into the AMF. The SMF, on the other hand, relies on the CP part of the PGW implementation from OAI-CUPS. The SM part of the NAS protocol has been implemented as a library and integrated into SMF. The NGAP IEs related to SMF also are implemented. The other components such as UPF and AUSF/UDM will be re-used from the current implementation of the Serving Gateway/PDN Gateway Userplane (SPGWU) (from OAI-CUPS) and HSS (from OAI LTE EPC), respectively. The main objective of this phase is to demonstrate some basic procedures such as the registration, de-registration as well as the Protocol Data Unit (PDU) session establishment by the end of May 2020. Then, additional features such as IPv6 support, paging, handover, multiple PDU sessions, session and service continuity will be considered in the next phase.

## 7. OAI Public license and its influence in industry use cases

"Open source" software communities have now been implementing Radio Access Technology (RAT) software for a number of years. Initially introduced by academics for academic and collaborative research and demo use cases, these open source projects have of late also attracted interest from industry, especially those active in 3GPP. However, 3GPP



technology is heavily based on patents and if such patents are implemented using traditional open-source licenses, the rights to the patent is lost. Therefore, the license under which the code is distributed then becomes a key consideration.

Therefore the OAI Software Alliance has created a new open source software license called the OAI Public License V1.1. This license is based on the Apache V2.0 license but allows companies/individuals which own significant portfolio of patents to be able to contribute to the OAI source code and still be able to keep their patent rights. Such a license will allow close collaboration with 3GPP member companies while at the same allowing commercial exploitation of the code. OAI also follows 3GPP FRAND policy on licensing. For non-commercial/academic research purposes the license guarantees the code is free to use.

Some parts of the OAI code, such as the MME and the HSS still use the Apache V2.0 license directly. This has been decided in order to ease integration with other open-source software communities, such as OpenStack [30], and because revenues from the EPC are less dependent on intellectual property agreements. The 5GC network however, will also use the OAI public license V1.1.

## 8. OAI in research and industrial scenarios

The OSA's research strategy areas can be classified as follows.

- **5G MODEM:** refers to access layer mechanisms including the physical layer and access protocols. Key areas already being introduced into OAI are related to mechanisms in support of the Internet of Things (IoT) such as new waveforms and protocols supporting both broadband radio access for smartphones as well as efficient transport of small and sporadic payloads from future connected objects.
- **Software-Defined 5G System:** The software defined 5G system concerns the "Softwarisation" of hardware and networking functions and comprises areas such as Network Function Virtualisation (NFV), Cloud (C)-RAN, Software-Defined Networking (SDN) and Mobile Edge Computing (MEC).
- **Heterogeneous Networks:** Heterogeneous networks correspond to the harmonization of different RANs under a common 5G framework, in particular the joint control of 802.11 systems with 3GPP standards and the efficient use of unlicensed spectrum.
- **Large-Scale Emulation:** refers to the use of OAI software to deploy mock networks in a simulated non-real-time or emulated real-time environment and aims to look for synergy with other network simulation tools such as Network Simulator 3 (NS3) [31].
- **Test and Measurement:** refers to the use of OAI software in real-time testing systems to facilitate the diverse 5G network elements (radio units, server units, core networking elements) which will predominantly become integrated into a cloud computing environment.
- **RF Platform:** refers to the interfacing and support of various COTS and commercial RF platforms by the OAI tool suite.

[32] demonstrates an example of the use of OAI to deploy a low cost open LTE network using commodity hardware with standard LTE-compatible devices. The authors present an all-in-one LTE network deployment in a PC based on OAI platform. They show the interoperability with commercial LTE enabled USB dongle and smartphones highlighting the complete attach procedure, establishment of default data radio bearer, and a live video transmission in downlink. The authors also show the reconfigurability features of the platform.

The work presented in [33] reviews the basics of OAI along with the tools, protocol stack and applications and brought out the importance of having it as an open source for a better 5G technology and experience.

The need for a structured and statistically sound experiment management, with the goal of reducing errors in both planning and measurement collection is described in [34]. The authors use OAI to solve the problem by integrating a sound, validated software, namely ns2-measure, with OAI, to enable harvesting samples of arbitrary metrics in

a structured way, and they also describe scripts that allow structured experiment management, such as launching a parametric simulation campaign and harvesting its results in a plot-ready format.

OAI has implemented all the necessary functions to support basic downlink functionality at both gNB and UE showing the feasibility to run 5G NR in real-time on a software defined radio platform. The roadmap describing a fully standard compliant implementation of 5G NR that is inter-operable with commercial equipment is discussed in [35].

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PhantomNet infrastructure [36] has been using OAI to create an end-to-end LTE/EPC network. A tutorial that describes this implementation is available in [37]. The radio part is a SDR eNodeB with OAI software running on a USRP B210 connected to a intel-NUC unit via USB. The EPC core network is an OpenEPC [38] instance with SGW, PGW, MME and HSS. The UE used is a Nexus 5 with pre-install and pre-configured SIM card that works with the SDR (i.e., LTE FDD band 4). The Nexus 5's SIM card is registered as a subscriber in the OpenEPC instance. The radio link between the Nexus 5 and the SDR eNodeB is an attenuated link.

An implementation of a virtualized LTE testbed environment of C-RAN by integrating the OAI with Docker is presented in [39]. Using the testbed, the authors conducted a workload study to understand the computation resource demand of C-RAN software.

The OAI eNodeB deployment is generally integrated with National Instrument USRP [13] as a RF hardware. However, in 2019 the Skylark [40] has announced that its Iris SDR has been also supported in the OAI open-source LTE stack.

An investigation about the Next Generation Fronthaul Interface (NGFI) based C-RAN is described in [41]. The authors use the OAI open source 4G/5G mobile communication software and GPP based servers and personal computers to build an OAI C-RAN testbed. They also use the source codes of OAI to run the performance profiling on the OAI C-RAN testbed to understand the behavior of the testbed. The purpose of the paper was to build a comprehensive performance profiling methods and results on the OAI C-RAN system, and to use these results to help designing and optimizing the OAI C-RAN system.

A successful attempt to build an earlier 5G mobile network using OAI, a 4G/LTE open source is described in [42]. However, instead of virtualization a containerization of the OAI was carried out.

An implementation of the FlexRAN framework for OAI is presented in [43]. This work presents an exemplary implementation and initial evaluation results of a corresponding interface between DU and CU for an emulation of 5G NR based bandwidth part adaptation and related physical layer processing time monitoring in LTE eNBs. The authors show that the interface facilitates computational elasticity by means of processing time aware transmission parameter adaptation.

An outline of the procedure needed to configure the Global Environment for Network Innovations (GENI) [44] Test LTE EPC OAI-based located at Rutgers Orbit Winlab is described in [45]. The main goal of this procedure was to create a central EPC that all GENI sites may connect to using their own base stations (eNBs) and UEs without having to configure individual EPCs.

An OAI LTE implementation emphasizing on the UP data flow is reported in [46]. The authors emulated Over-The-Air (OTA) transmission for 1 UE and 1 eNB LTE network supporting both FDD Band 5 and TDD Band 38. The work have also performed a thorough profiling of OAI, in terms of execution time, on the UP data flow.

An implementation of calibration algorithms through the OAI platform is discussed in [47]. It proposes to implement and evaluate a less computationally intensive Multiple-Input Multiple-Output (MIMO) calibration algorithm, according to a realistic scenario based on LTE-TDD specification. The result from OAI simulator shows that it is feasible to

restore the reciprocity after calibration in a non reciprocal channel, and provides an overview of the challenges in the channel estimation in a real time case.

In [2] it is highlighted that practical experimentation with cellular networks has been historically reserved exclusively to operators, primarily due to equipment costs and licensing constraints. In this direction, the state of play has been changing with the advent of open-source cellular stacks based on increasingly more affordable SDR systems. A comprehensive understanding of the performance, limitations, and interoperability of these tools however lacks. The authors show that this gap, can be filled by enabling controlled experiments where the performance of most popular open software eNB solutions can be combined with different commodity UE and an SDR alternative, over a range of practical settings. To evaluate their work the authors use both OAI and srsLTE as open tools and give configuration guidelines that can be used to deploy these solutions effectively. Their results quantify the throughput attainable with each stack, their resource consumption footprint, and their reliability and bootstrap times in view of automating experimentation.

An overview of the OAI both in terms of its hardware and software elements and its usage in cognitive wireless networking applications based on LTE technology is presented in [48]. In particular, the authors show a design of a cognitive radio systems in the LTE framework that enables the deployment of cognitive radio in licensed bands, with no hardware modification and only small software changes in some specific frames for the secondary system.

An on-going work is being done at Platform for Open Wireless Data-driven Experimental Research (POWDER) testbed [49] to integrate OAI RAN to Open Radio Access Network (O-RAN) [50] RAN Intelligent Controller (RIC). The main work is to do an OAI implementation of the E2AP protocol (E2 Agent), which is the CP that connects the near-RealTime RIC to RAN elements (e.g. an OAI eNB/gNB). E2AP is a sort of peer to LTE X2. It uses the same SCTP signaling and ASN.1 encoding, and reuses several of the X2 messages, but also adds its own messages and procedural flow.

## 9. Conclusion

This paper presented the work being performed by Open Air Interface project. OAI is an open source initiative that today provides a 3GPP compliant reference implementation of LTE, eNB, UE, and EPC that runs on general purpose computing platforms (x86) together with COTS SDR cards like the ETTUS USRP.

OAI has been presented over both perspectives Standalone and Non-Standalone scenarios. In particular, describing its evolution regarding 5G and NR technologies. The current OAI development status was described, mainly in terms of 5G gNB, Phy and MAC layers, 4G EPC and 5GC.

From an implementation point of view, 5G is far more challenging than 4G. On one hand 5G has far higher bandwidth and lower latency, which poses challenges on the real-time processing. On the other hand 5G is also more complex from the perspective of algorithms and protocols, especially in the PHY and the MAC. Only very little code was reused from 4G LTE, most notably the low-level PHY functions such as FFTs.

An OAI roadmap covering 2019 and 2020 was discussed looking at standard interfaces like LTE, 5G focusing on spectral, protocol and algorithmic efficiency. We also looked at OAI from the software license point of view and its connection to 3GPP policy.

Some examples of researches and developments using OAI platform were also presented to highlight its usage in both academia and industry.

## Author Statement

This statement is to certify that all Authors have seen and approved the manuscript being submitted. We warrant that the article is the Authors' original work. We warrant that the article has not received prior

publication and is not under consideration for publication elsewhere. On behalf of all Co-Authors, the corresponding Author shall bear full responsibility for the submission. This research has not been submitted for publication nor has it been published in whole or in part elsewhere. We attest to the fact that all Authors listed on the title page have contributed significantly to the work, have read the manuscript, attest to the validity and legitimacy of the data and its interpretation, and agree to its submission to the Computer Network Journal at Elsevier.

## Declaration of Competing Interest

The authors declare that they do not have any financial or nonfinancial conflict of interests.

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## References

- [1] Open source SDR LTE software suite from Software Radio Systems (SRS). Accessed in: October 14th, 2019.
- [2] F. Gringoli, P. Patras, C. Donato, P. Serrano, Y. Gruenberger, Performance assessment of open software platforms for 5g prototyping, *IEEE Wireless Commun.* 25 (5) (2018) 10–15.
- [3] An open source 3GPP LTE Implementation. Accessed in: October 14th, 2019.
- [4] GNURadio: the Free and open Software Radio Ecosystem. Accessed in: January 10th, 2020.
- [5] Amarisoft: Software LTE base station (LTE). Accessed in: January 10th, 2020.
- [6] Open Base Transceiver Station (OpenBTS). Accessed in: October 14th, 2019.
- [7] Open Source Mobile Communication (osmocom). Accessed in: October 14th, 2019.
- [8] Open Universal Mobile Telecommunication System (OpenUMTS). Accessed in: October 14th, 2019.
- [9] B. Bertyni, S. Nagata, H. Kooropaty, X. Zhou, W. Chen, Y. Kim, X. Dai, X. Xu, 5G NR Radio interface, *J ICT Standard* 6 (1) (2018) 31–58.
- [10] B. Bertyni, R. Burbidge, G. Masini, S. Sirotkin, Y. Gao, NG Radio access network (NG-RAN), *J ICT Standard* 6 (1) (2018) 31–58.
- [11] Nokia Networks, 5G core, 2019.
- [12] Small Cell Forum, 5G FAPI: PHY API Specification, techreport 222.10.01, Small Cell Forum, 2019.
- [13] USRP Software Defined Radio Device. Accessed in: October 14th, 2019.
- [14] O-RAN Alliance, O-RAN Fronthaul Control, User and Synchronization Plane Version 2.0, Technical Report ORAN-WG4.CUS.0-v02.00, O-RAN Alliance, 2019.
- [15] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network - Physical channels and modulation - Release 15, Technical Report 38.211 V15.8.0, 3GPP, 2020.
- [16] K. Takeda, H. Xu, T. Kim, K. Schober, X. Lin, Understanding the heart of the 5G air interface: an overview of physical downlink control channel for 5G new radio (NR), *ArXiv abs/1910.01711* (2019).
- [17] S. Wagner, NR LDPC Decoder, Technical Report, TCL, 2018.
- [18] G. Sarkis, P. Giard, A. Vardy, C. Thibeault, W.J. Gross, Fast list decoders for polar codes, *IEEE J. Sel. Areas Commun.* 34 (2) (2016) 318–328, doi:10.1109/JSAC.2015.2504299.
- [19] Y. Shen, C. Zhang, J. Yang, S. Zhang, X. You, Low-latency software successive cancellation list polar decoder using stage-located copy, in: 2016 IEEE International Conference on Digital Signal Processing (DSP), 2016, pp. 84–88, doi:10.1109/ICDSP.2016.7868521.
- [20] T.-H. Wang, R. Knopp, OpenAirInterface: A pipeline structure for 5G, in: *DSP 2018, IEEE International Conference on Digital Signal Processing*, 19–21 November 2018, Shanghai, China, Shanghai, CHINA, 2018.
- [21] 3GPP, System architecture for the 5G System (5GS), Technical Report, 3GPP, 2019.
- [22] 3GPP, 5G System; Technical Realization of Service Based Architecture; Stage 3, Technical Report, 3GPP, 2019.
- [23] 3GPP, 3rd Generation Partnership Project; Technical Specification Group Core Network and Terminals; 5G System; Access and Mobility Management Services, Technical Report, 3GPP, 2019.
- [24] 3GPP, Non-Access-Stratum (NAS) protocol for 5G System (5GS), Technical Report, 3GPP, 2019.

<sup>18</sup> [https://www.openairinterface.org/?page\\_id=5500](https://www.openairinterface.org/?page_id=5500).

- [25] 3GPP, NG Application Protocol (NGAP), Technical Report, 3GPP, 2019.
- [26] 3GPP, Interface between the Control Plane and the User Plane Nodes, Technical Report, 3GPP, 2019.
- [27] Hands on: Oppo Reno 5G review. Accessed in: April 16th, 2020.
- [28] 80010922 - Kathrein USA Manual. Accessed in: April 15th, 2020.
- [29] F. Kaltenberger, G. De Souza, R. Knopp, H. Wang, The OpenAirInterface 5G new radio implementation: Current status and roadmap, WSA 2019, 23rd ITG Workshop on Smart Antennas, Demo Session, 24–26 April 2019, Vienna, Austria, Vienna, Austria, 2019.
- [30] OpenStack. Accessed in: October 14th, 2019.
- [31] Network Simulator 3 (NS3). Accessed in: October 14th, 2019.
- [32] N. Nikaein, R. Knopp, F. Kaltenberger, L. Gauthier, C. Bonnet, D. Nussbaum, R. Ghaddab, Demo: openairinterface: an open LTE network in a PC, Proceedings of the Annual International Conference on Mobile Computing and Networking, MOBICOM (2014).
- [33] S.K.V. P. Ravali, R.M.D. Sundaram, Open air interface—Adaptability perspective, Indian Journal of Science and Technology 9 (6) (2016).
- [34] N. Iardella, A.V. Giovanni Stea, D. Sabella, A. Frangioni, Statistically sound experiments with openairinterface cloud-RAN prototypes, Cognitive Radio Oriented Wireless Networks (2016) 754–766.
- [35] F. Kaltenberger, G. d. Souza, R. Knopp, H. Wang, The OpenAirInterface 5G new radio implementation: current status and roadmap, WSA 2019; 23rd International ITG Workshop on Smart Antennas, 2019.
- [36] PhantomNet Testbed. Accessed in: October 14th, 2019.
- [37] Using Open Air Interface, SDR hardware and OPEN-EPC core to create an end-to-end experiment in PhantomNet. Accessed in: October 14th, 2019.
- [38] Open Source Evolved Packet Core (openEPC). Accessed in: October 14th, 2019.
- [39] I. Trindade, C. Nahum, C. Novaes, D. Cederholm, G. Patra, A. Klautau, C-RAN Virtualization with OpenAirInterface, 2019. <https://arxiv.org/abs/1908.07503>. Accessed in: October 14th, 2019.
- [40] Official Skylark Iris Support in OpenAirInterface LTE Stack. Accessed in: October 14th, 2019.
- [41] P.-C. Lin, S.-L. Huang, Performance profiling of cloud radio access networks using OpenAirInterface, in: APSIPA Annual Summit and Conference, 2018.
- [42] B. Dzugovic, V.T. Do, B. Feng, T. van Do, Building virtualized 5G networks using open source software. Accessed in: October 14th, 2019.
- [43] Bandwidth Part Adaptation and Processing Time Evaluation with OpenAirInterface, Zenodo, 2019.
- [44] Global Environment for Network Innovations (GENI). Accessed in: October 14th, 2019.
- [45] OpenAirInterface ePC GENI Site Deployment. Accessed in: October 14th, 2019.
- [46] C.Y. Yeoh, M.H. Mokhtar, A.A.A. Rahman, A.K. Samangan, Performance study of LTE experimental testbed using OpenAirInterface, 2016 18th International Conference on Advanced Communication Technology (ICACT) (2016) 617–622.
- [47] B. Kouassi, B. Zayen, I. Ghauri, L. Deneire, Reciprocity calibration techniques, implementation on the OpenAirInterface platform, in: CogART 2011, ACM, 2011, pp. 372–376. number Article No.26 in International Conference Proceeding Series (ICPS)
- [48] B. Zayen, F. Kaltenberger, R. Knopp, Opportunistic Spectrum Sharing and White Space Access: The Practical Reality, Wiley, 2015. Chapter 5: OpenAirInterface and ExpressMIMO2 for Spectrally Agile Communication
- [49] Platform for Open Wireless Data-driven Experimental Research (POWDER). Accessed in: February 18th, 2020.
- [50] Open Radio Access Network (O-RAN). Accessed in: February 18th, 2020.