How to Get Away with OpenAirInterface:
A practical Guide to 5G RAN Configuration

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Abstract—In contrast to legacy 5G RAN solutions, Open-RAN and especially open-source RAN projects provide enhanced configuration possibilities. This enables an operator to tailor the network more specific to its needs. At the same time, this complicates the process of setting up the network, since this configuration requires more in-depth understanding of 5G. There is a gap between the 3GPP specifications, representing the theoretical aspects and the actual deployment of a 3GPP compliant network. Therefore, we present a novel explanation drawing the link between these specifications and a practical open-source 5G network, using OpenAirInterface. We further illustrate the operability of the network in different configurations with commercial UEs, by applying the presented relations.

Index Terms—5G, Open-RAN, Virtualized RAN, open-source

I. INTRODUCTION

Traditionally, cellular networks consist of closed-source software and hardware components. With the increased level of softwarization in 5G networks, new concepts like virtualized Radio Access Network (vRAN) and disaggregated Radio Access Network (dRAN) are becoming more feasible and gain importance. By now, next generation NodeBs (gNBs) can run completely in software on Commercial off-the-shelf (CotS) server hardware. Therefore, previously proprietary black-box base stations emerge into disaggregated and open components. The Open Radio Access Network (O-RAN) specifications [1] provide the definition of open interfaces and a reference architecture for the Radio Access Network (RAN) on top of the 3rd Generation Partnership Project (3GPP) standards. This extension enables more specific network configurations due to the increased configuration possibilities and an increased number of available network components. Additionally, it accelerates the open-source development in the area of the RAN.

While there is a rather large number of open-source Core Networks (CNs), there are only two relevant RAN projects:

Software Radio System (srsRAN) [2] and OpenAirInterface (OAI) [3]. At the moment, the OAI software stack is more complete with respect to the 3GPP specifications, implementing Release 16 (e.g. downlink (DL) localization signals) and even Release 17 (e.g. non-terrestrial networks) features. OAI also strives for O-RAN compliance. For now, it contains the *F1* and *E2* interface with support for *FlexRIC* and *µONOS RIC*, while the *O1* and *E1* interface is under development. In addition, there is also a corresponding OAI-CN implementation. Thus, the availability of open-source projects enables more researchers to set up their own low-cost, experimental 5G network.

Proposing the usage of OAI to provide a low-cost 5G non-public network solution, specialized for industrial applications, [4] shows the competitiveness between softwarized and traditional 5G systems in certain use cases. As a result, 5G enabled robotics control utilizing Multi-Access Edge Computing (MEC) [5]–[8], can be realised with significantly less expenditure. Furthermore, two companies use this open-source software in their commercial products: *allbesmart* [9] and *firecell* [10]. Both of them offer pre-configured workstations running their own forked OAI version, in order to improve different aspects in contrast to a pure OAI setup. While *allbesmart* aims for academia and other researchers, *firecell* addresses industrial customers. These products facilitate the RAN configuration but at the price of reduced possibilities foiling one of the key ideas of O-RAN.

In contrast to legacy 5G systems, O-RAN systems provide enhanced configuration possibilities [4] that can be modified by the operator. This applies even more to open-source systems like OAI, since it is possible to alter every aspect of the implementation. The increased configurability has its price, because the complexity of establishing a working setup also increases. It is more difficult configure a network fulfilling certain desired
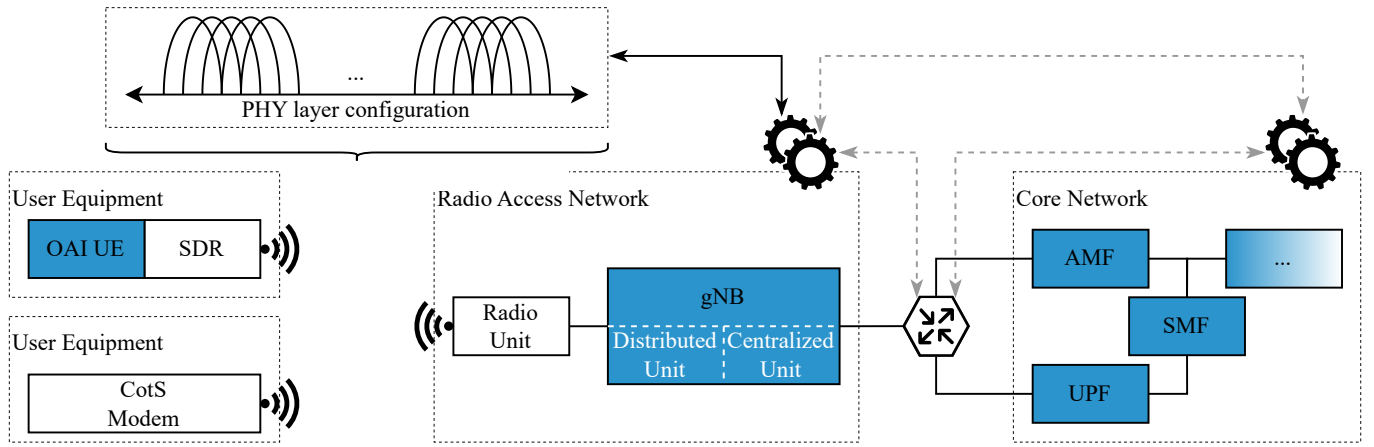
Fig. 1. Overview of an end-to-end 5G system including OAI-based parts highlighted in blue. The RAN and CN configuration set the IP-based network connection between these two parts, whereas only the RAN configuration determines the physical transmission of the gNB.

properties (e.g. frequency band, carrier bandwidth) in a 3GPP-compliant way. This concerns the cell search and initial attach procedures in particular. Without proper configuration the network will not only show reduced performance but an User Equipment (UE) will not be able to connect at all. To create a working RAN configuration, several New Radio (NR) aspects have to be taken into consideration. The synchronization signal block (SSB) [11], providing synchronization to an UE, as well as the control ressource set (CORESET)0 [12], containing the first control channel information for further message reception, have to match 3GPP requirements. In addition, the newly introduced bandwidth parts (BWPs) [13] are present in the initial attach. In addition to papers like the mentioned references [11]–[13], the primary sources about NR details are the 3GPP NR specifications. For instance the TS 38.200 series describes the physical layer aspects while the TS 38.300 series specifies the higher-layer parts [11]. The difficulty with these documents is not only their dense nature, but also the fact that explanations and requirements to the configuration are distributed across multiple specifications.

The remainder of the paper is structured as follows. First, Section II provides information about tutorials and comparable explanations about OAI-based systems. An overview about a generic open-source 5G network, its components and the configuration capabilities succeeds in Section III. We present a detailed explanation of the RAN in Section IV and subsequently show the connection set-up with different frequency bands in Section V. Finally, Section VI shows the conclusion.

II. RELATED WORK

In addition to the 3GPP NR RAN specification many interpretations and explanations are available. As the standards describe the radio interface in a holistic way, explanations which cover a significant part are in form of books [14]–[16]. Others are shorter, picking only one specific topic [11]–[13]. There are also websites [17] providing a lot of knowledge, sometimes including high level of detail. All those sources focus on the theoretical concept behind NR.

Within the context of this work we chose OAI as example for an open-source based RAN, which is highly configurable. The OAI RAN is configured by a single configuration file, which contains every relevant aspect of the gNB configuration. However, Setting up a new OAI instance can be very challenging. OAI offers support in form of some read me files [18], which present example configurations. However, the OAI tutorials do not aim to explain the background or provide further details.

Currently OAI gets more and more attention by a growing community. As a result, not only the interest in building knowledge in this area increases, there are also more people who have the knowledge and are willing to share it [19]. Authors in [19] use a rather expensive setup including two dedicated workstations. Their work focuses on details, in the context of Internet Protocol (IP) routing in the context of the CN and Data Network (DN). Besides this, they mention configuration details regarding the host machine, which are important to reduce jitter in computing times on an unix based x86 machines. However, the configuration of the RAN is not explained in detail, as they use an example configuration provided by the OAI.

Two online tutorials explain details about the OAI configuration process, where one is maintained by the Northeastern University [20] and the other one by National Instruments (NI) [21]. However, at the current point in time, their aiming more for help by reproducing the example setup described at the official OAI repo [18], rather than connecting background knowledge with the configuration process.

The presented publications provide insights from different perspectives. However, none of those publications is connecting the theoretical background to practical application. In the past in-depth knowledge about RAN configuration was not required for users and to some extent even for operators. Most RAN solutions came as a black-box without many configuration options. With today's open-source based vRAN, this is no longer the case. A wider audience wants to build up the required knowledge, to configure their own open-source

based gNB or adapt one to their needs. The novelty of this work is to fill this gap by presenting the theoretical background applied to the actual OAI configuration.

III. BACKGROUND

A. 5G System Architecture

A 5G system consists of three major parts: first the CN that provides connectivity to a DN, second the RAN providing the wireless access and third the UE that connects to this network. OAI provides the software to run each of these components virtualized on CotS server hardware. Fig. 1 shows a generic setup containing these elements where the OAI parts are highlighted in blue. In the figure there are two types of UEs; the first UE uses the virtualized approach, utilizing a Software Defined Radio (SDR), while the second UE uses a CotS modem. Fig. 1 illustrates several key aspects of an open-source 5G network. Despite advancing virtualization, the radio transmission part remains implemented on specialized hardware or SDRs. This is true for both sides, RAN and UE. Moreover, the connection between the RAN and the CN is IP-based. This is reasonable for real-world deployments using multiple gNBs at physically separated locations with a centralized running CN. Nevertheless, RAN and CN can run on the same machine where this connection is purely virtual. In each case, the provided interface parameters have to match between the RAN configuration and the CN configuration to successfully connect the gNB on the control plane to the Access and Mobility Function (AMF) and on the user plane to the User Plane Function (UPF). Additionally, also the slicing information, the Tracking Area Code (TAC) and the Public Land Mobile Network (PLMN) ID have to match in both configurations because these parameters are processed in the gNB and the CN independently.

The largest part of the RAN configuration influences the NR physical layer transmission. Some parameters in the OAI configuration file are important to adapt to the quality of the wireless channel. These are Radio Unit (RU) specific settings like attenuation and gain, but also more general aspects like power levels for different uplink (UL) and DL procedures or retransmission thresholds. Moreover, the configuration includes the parameters for the channel itself, cell visibility to the UE and the initial access procedures. These parameters have to be configured accordingly to the 3GPP specifications, the capabilities of the UEs and statutory regulations. The following Section IV illuminates these aspects in detail.

B. 5G New Radio

This section reviews some basics about 5G NR regarding the radio transmission that are necessary to understand the RAN configuration. At the fundamental level the transmission is based on orthogonal frequency division multiplexing (OFDM) and therefore divided into different subcarriers. The subcarrier spacing (SCS) is flexible in NR allowing to adapt the setting to different total channel bandwidths. Groups of 12 consecutive subcarriers form a ressource block (RB), which is a unit for the frequency-domain resource allocation. The first block, indexed

with 0, is also referred to as reference RB including the definition of its lowest subcarrier as *"Point A"*. This is used as common reference point for the RB grid and different settings regarding the channel bandwidth. A contiguous set of RBs with the same SCS form a BWP [13]. Hence it is defined by its first RB and the number of used RBs. This concept was introduced in NR to allow a wider variety of UEs; some low-cost devices might only support a small bandwidth while other high-end devices are able to utilize higher bandwidths. Inherently, the BWP is smaller or equal than the total channel bandwidth of the cell. There are different types of BWPs, e.g. the initial BWP that is part of the initial attach procedure.

The cell search and initial attach of an UE require several other concepts. Initially, a UE has to acquire synchronization with network by receiving a SSB. This block contains a primary and secondary synchronization signal as well as the Master Information Block (MIB). The MIB is the first Radio Resource Control (RRC) message and contains information about the physical resources of the CORESET0. After the reception of this control message, an UE is able to receive and decode the first comprehensive RRC message, the System Information Block (SIB)1. The decoded SIB1 contains the necessary control information about the initial BWP, where all of the dedicated data and control channels are located till the end of the initial access procedure. Now, the UE can receive the RRC setup, exchange the Non-Access Stratum (NAS) setup messages and subsequently RRC reconfiguration messages, which conclude the attach process. The article "5G/NR - Initial Attach" in [17] provides more details about every step of the initial attach procedure.

IV. RAN CONFIGURATION

This section draws the link between the OAI configuration and the corresponding theoretical details about the cell search and initial access procedures as presented in Section III-B. During this process, an UE first discovers the SSB transmitted by the gNB allowing the UE to search for the SIB1. Second, the UE receives the initial BWP and common configurations via the SIB1. Afterwards, the UE and the network can exchange RRC messages. Fig. 2 depicts the information blocks, the RAN transmits throughout the initial attach procedure of an UE. The horizontal axis shows the time and the vertical axis indicates the frequency, representing a time-frequency grid. All elements in *italic* are OAI parameters, while the non-italic terms represent the NR related notion of specific parts. Grey arrows show the size of particular components and the relationships between them, in contrast to the magenta arrows indicating the impact of one aspect upon another. Dotted and dashed lines represent the interpretation of the combination of different points.

As mentioned in Section III-A the main motivation to change the frequency range of the transmission are statutory regulations. This holds true for scientific as well as industrial applications, a license for the utilized frequencies is required to operate a 5G network within the licensed spectrum. Hence, the starting point of configuring the RAN is to determine the
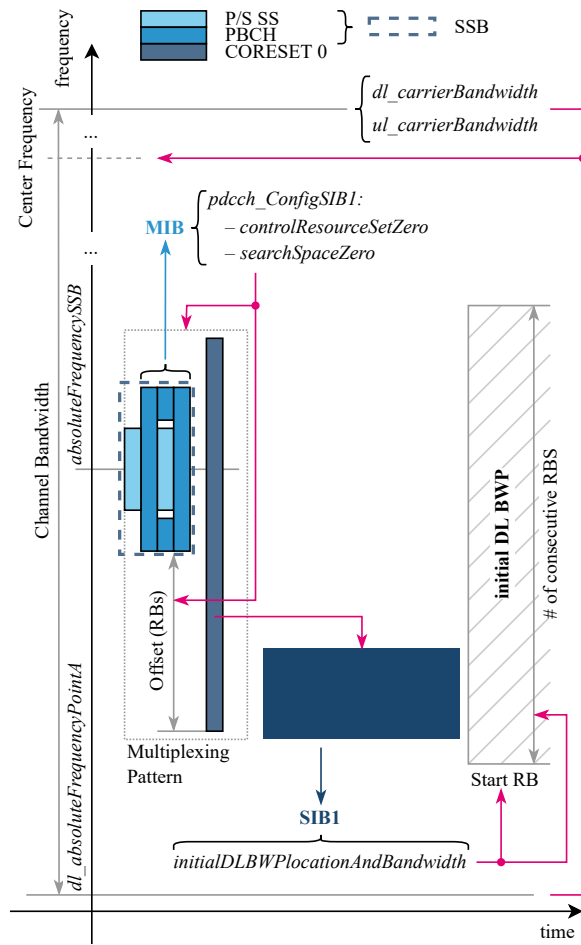
Fig. 2. The messages of the initial access procedure with their corresponding OAI configuration parameter as well as their interrelations.

channel bandwidth and frequency range. In NR and especially OAI, this is adjusted by the *dl_absoluteFrequencyPointA* and the *dl_carrierBandwidth* and *ul_carrierBandwidth*. The first parameter describes the frequency-location of Point A as in Absolute Radio Frequency Channel Number (ARFCN) [22]. The latter two specify the channel bandwidth of the carrier in terms of RBs. Fig. 2 shows that in combination, these three parameters implicitly define the center frequency of the channel. In addition to the bandwidth, there are also some more parameters that impact the overall transmission. *dl_offstToCarrier* and *ul_offstToCarrier* describe the frequency offset between Point A and the lowest usable subcarrier in terms of RBs for DL and UL. The *dl_frequencyBand* and *ul_frequencyBand* indicate to the RAN which frequency band is used. Depending on the deployed frequency band, there is a frequency raster and resulting possible NR-ARFCN values as defined in Table 5.4.2.3-1 of [23]. Hence, the ARFCN of Point A has to match with this raster which is checked by the OAI upon starting the gNB. The *dl_subcarrierSpacing* and *ul_subcarrierSpacing* configure the default SCS of the cell. The actual SCS of the transmission is not static, since different elements in NR can define their own SCS overriding

the default value.

The second present ARFCN parameter is the *absoluteFrequencySSB* determining the frequency-domain position of the SSB. Due to the flexible nature of NR, the UE monitors multiple predefined positions, the Global Synchronization Channel Number (GSCN), to detect the SSB and thus see the cell. Hence, there is a synchronization raster containing these predefined locations specified in Table 5.4.3.3-1 of [23]. Fig. 2 shows the SSB with its different components in light blue. The Physical Broadcast Channel (PBCH) transmits the MIB containing the *pdcch_ConfigSIB1* necessary to decode the SIB1. This parameter consists of two parts, the *controlResourceSetZero* and the *searchSpaceZero*. The *searchSpaceZero* determines the monitoring occasion for the Physical Downlink Control Channel (PDCCH) while the *controlResourceSetZero* determines the physical resources of the CORESET0. Hence, the parameters depend on the desired positioning of the SSB and the CORESET0. Each of both parameters is four bits in size. There are tables, how these values are interpreted by the RAN, depending on several factors like SCS or frequency range. Table 13-1 to Table 13-14 of [24] show the possible combinations and the resulting values for the parameters. Fig. 2 visualizes the influence of the *pdcch_ConfigSIB1* parameter on the physical parameters of the CORESET0.

It is important to ensure that the arrangement of the SSB and the CORESET0 remains within the boundaries of the channel bandwidth. Especially in the case of smaller bandwidths (e.g. 20 MHz), this can become difficult. Nevertheless, a larger CORESET0 is beneficial since this results in a higher possible aggregation level and therefore a more robust PDCCH. By adjusting the Offset (RBs) via the *controlResourceSetZero* parameter as shown in Fig. 2, there is a higher degree of freedom in configuring the SSB. In addition, with a larger Offset (RBs) a larger CORESET0 is possible in case the SSB is close to the end of the channel bandwidth.

The CORESET0 contains the control information scheduling the SIB1 transmission. The SIB1 includes the parameters setting the initial DL/UL BWP and common configurations that allows the UE to receive the RRC setup. As described in Section III-B, the first RB and the number of consecutively used RB describe a BWP. The *initialDLBWPlocationAndBandwidth* parameter specifies both in one value. The RAN interprets this value according to Section 5.1.2.2.2 of [25]. The parameter *initialDLBWPsubcarrierSpacing* configures the SCS in this BWP, unless an other element explicitly configures this. In each case, this overrides the default cell configuration. These two OAI parameters also have an corresponding UL counterpart. In contrast to this, the parameters *initialDLBWPsearchSpaceZero* and *initialDLBWPcontrolResourceSetZero* exist only for the DL. The initial DL BWP has to contain the full CORESET0 in the frequency-domain [13]. The initial DL/UL BWP contains all NR channels that are necessary to conclude the initial access procedure. Thus all control and higher layer messages regarding the UE attach are transmitted within this BWP.

V. Connection Setup

Table I.
Utilized hardware and software components with their version

Component	Version
OpenAirInterface RAN	develop 2022.42
OpenAirInterface CN	1.4.0
USRP N310 FPGA iamge	XG
UHD	3.15 LTS
Quectel RM500Q-GL	RM500QGLABR11A06M4G

Table II.
Parameters describing the frequency range of the 5G NR transmission

Parameter	n40	n78
NR-ARFCN Point A	464000	650760
Frequency in MHz Point A	2320	3761.4
NR-ARFCN SSB	467810	652032
Frequency in MHz SSB	2339.05	3780.48
CORESET0	12	12

In this section we present the performance of a working connection between an UE and a RAN, which configuration is based on the previous Section III-A and Section IV. We show 3GPP configurations in two different frequency bands, *n40* and *n78*, to provide practical examples for our explanations. Moreover, we describe the physical setup and the utilized software components to provide a reference setup, that is as reproducible and comprehensible as possible.

The architecture of the OAI-based 5G network corresponds to Section III-A, consisting of the OAI RAN and the OAI CN. We deploy the RAN and the CN on the same physical host, to simplify the overall structure, and avoid additional overhead or potential sources of errors. The RU is an Ettus Research USRP N310, that is connected to the host machine via two 10G cable links. There is also an Global Positioning System (GPS) antenna connected to the device, for time synchronization purposes. On the SDR must be the same version of the UHD as on the RAN host machine. Additionally, the SDR needs the correct FPGA image, to enable the dual 10G connectivity. To show that the RAN configuration is compliant with the specifications, we use a *Quectel RM500Q-GL* CotS modem as an UE. Table I gives an overview about the mentioned components as well as their respective software or firmware version.

In both frequency bands we use the same channel bandwidth of 40 MHz corresponding to 106 RBs. Likewise, the 30 kHz SCS is also the same in both configurations. Most of the remaining parameters are similar to the configuration templates. We have only adjusted the parameters affecting the transmission frequency range, by configuring Point A, the SSB and the MIB. Table II shows the values of these parameters for each frequency band configuration.

To show that the customized configurations work correctly, we measure the latency and the throughput of the network. To assess the end-to-end connectivity in general and the Round Trip Time (RTT) in the 5G network, we use *ping* with a standard packet rate of 1 packet per second. We start the tool with the command `ping <UE IP-Address>` in the DN container of the CN, after the modem has been successfully connected to network. The packets are transmitted via the DL to the UE, where they are echoed and sent back to the RAN and subsequently the CN in the UL direction. Hence, the resulting time delay shows the RTT in the network. To evaluate the maximum achievable throughput, we use *iperf* in the DL direction to send User Datagram Protocol (UDP) packets with a throughput of 130 Mbps. We choose a UDP based connection instead a Transmission Control Protocol (TCP) based connection, in order to not influence the achievable rate by congestion control mechanisms of these layer 4 protocols. That way, also packet losses are handled only in the NR transmission between the RAN and the UE. We start the client application on the UE side with the command `iperf -s -u -i 1 -B <UE IP address>` and the corresponding server in the DN container with the command `iperf -u -c <UE IP address> -i1 - t10 -b130M`. On the client side, we can measure the actual possible throughput of network, hence the 130 Mbps are larger than the maximum achievable throughput of the 5G network. We perform these measurements for both of the two frequency range configurations.
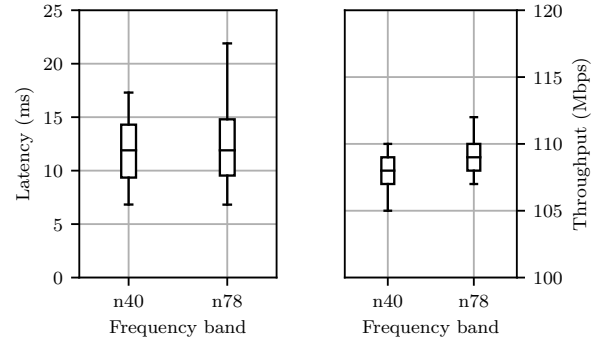

Fig. 3. OAI 5G network latency (round-trip time) and throughput (DL) in two different frequency bands with an Quectel RM500Q-GL: 40 MHz channel bandwidth, 30 kHz SCS

Fig. 3 shows boxplots of the results. The boxplots of the latency measurements are on the left side and the bobxplots of the throughput measurements are on the right side. In general, this shows that both of the network configurations are 3GPP compliant, because the CotS modem can connect to the network. Fig. 3 depicts, that the performance of the network is nearly the same in both frequency bands. The deviations are due to noise and interference. The *n40* band is close to WiFi, while the *n78* band is also used by other nearby 5G research setups. Fig. 3 shows a larger deviation of the outliers for the latency in the *n78* band compared to the latency in the *n40* band. These outliers are caused by a higher number of occurring retransmissions, which are reported by the RAN logs.

VI. Conclusion

In this work we presented physical layer configuration details of a 5G RAN in detail. We gave an overview of the general structure of the network with CotS hardware and subsequently explained the necessary parameters in the configuration. Using the OAI RAN configuration, this paper presents a novel link between theoretical aspects of NR and their practical application in a real-world system. We concluded the explanation with two configuration examples, demonstrating the 3GPP compliant operation of the network in two different frequency bands. This work presents the necessary information, to configure an OAI RAN according to specific frequency requirements.

Acknowledgment

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