On the Performance of an Indoor Open-Source 5G Standalone Deployment

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***Abstract*—5G, the latest generation of cellular technology, targets not only enhanced data rates but also new applications which require, e.g., ultra-reliable low latency communication. Verticals like industrial automation or automotive, which want to make use of this type of wireless services, need experimental deployments to test the performance of 5G in various modes and environments for their use cases. Due to the ongoing standardization process, experimental 5G networks based on open-source frameworks are especially well suited, as they provide the possibility to easily implement new features introduced by the yearly 5G standard releases. We thus present an experimental 5G standalone deployment, based on the OpenAirInterface, which is an open-source framework, that is being used both, commercially and for academic purposes. We evaluate coverage parameters including reference signal received power, reference signal received quality, and signal to interference and noise ratio both for single user and multiple user scenarios. The measured downlink data rate reaches up to $390\,\mathrm{Mbps}$ at a bandwidth of $60\,\mathrm{MHz}$, which is close to the achievable theoretical value. The average latency both for uplink and downlink was measured to be $19\,\mathrm{ms}$ for the round trip time, while the minimum latency value was $6\,\mathrm{ms}$, which is acceptable for many application.**

***Index Terms*—5G standalone (SA) network, OpenAirInterface (OAI), data rate (DR), Latency, Coverage**

I. INTRODUCTION

The 5G standard provides the possibility for both the so-called non-standalone (NSA) and the SA mode of operation. For network operators with an existing 4G network, the 5G NSA deployment allows for an evolutionary approach that relies on the existing 4G long-term evolution (LTE) infrastructure and offers a quick 5G network deployment solution for an enhanced communication experience as compared to LTE. New network operators without an already existing 4G network need a SA deployment in which all network components are 5G compliant, which has the advantage of delivering the full 5G flexibility (e.g., in terms of slot durations and sub-carrier spacing (SCS)) and performance without any limitation by the legacy 4G network components required for NSA. Thus, 5G in SA is much better suited for applications which require massive machine type communication (mMTC) or ultra-reliable low latency communication (URLLC).

The application areas for mMTC and URLLC have been added in the standardization process of 5G as compared to third and fourth generation cellular standards, which mainly focused on increasing the data rate for improved Internet access on mobile devices. Supporting a very high number of devices with a low data rate but very long battery life as in mMTC or providing wireless links with extreme reliability and lowest latency as in URLLC is achieved by the introduction of many new features in the PHY, MAC, and higher layers of the 5G communication stack. These new application areas offer many possibilities for verticals like industrial automation, automotive, health care, etc., to use 5G for improved or even new services to their customers. However, there is a large need to test and validate the use of 5G for those services in these new application areas before companies are able to commercialize them. Thus, experimental deployments are urgently needed to test the performance of 5G in various modes, environments, and use cases.

As the standardization of cellular systems is a continuous process with typically yearly releases, not all intended features are already defined in the standard, and even new features which are already standardized might not yet be implemented in currently available either hard- or software for 5G. This is another motivation for installing experimental deployments to test the performance of 5G with different hard- and software and with new features from new standard releases. Already several experimental studies have been reported, but most of them rely on a 5G NSA deployment and only a few studies report on the experimental analysis of a 5G SA version. A detailed overview of 5G deployments are given in Sect. II

Industrial networks being a vertical market for 5G have evolved from specific Fieldbus systems over Industrial Ethernet to industrial wireless networks. The connectivity requirements for industrial applications are very diverse regarding the spatial extent, mobility, energy consumption, DR, deterministic communication, reliability, and quality of service (QoS). As a consequence, currently several wired and wireless network technologies are combined to provide the required services [1].

Until a few years ago, the use of cellular technology has focused on the benefits of a nation- or world-wide availability of mobile internet access, while latency has only been considered in a best-effort manner. Especially with the deployment of 5G SA networks, the service customization capabilities of the network, the ability to flexibly, easily, and quickly deliver targeted connectivity services to the various vertical sectors based on their specified needs, extremely high DR (eMBB), extremely low latency (URLLC), or massive numbers of connected devices (mMTC) [2] is possible.

5G is currently being deployed around the world, providing mobile users with an enhanced service compared to previous generations of cellular networks. At the same time, several 5G trial networks are being deployed that allow the industry to leverage the enhanced capabilities of the new networks, beyond simply a “faster version of 4G” [3]. Therefore, in this work, we describe the steps to deploy an experimental private 5G SA network and evaluate its performance in an indoor environment. Private 5G refers to a mobile network that is technically the same as a public 5G network, however, access to the network infrastructure is exclusive to authorized devices. This is beneficial in several terms including network availability, reliability, security, self-customization, and service adaptability to the application requirements. In our deployment, another benefit is its compactness. We set up the core and gNodeB (gNB) on the same server machine, allowing easy mobility of the system. We evaluated our system in terms of DR, latency, and coverage. The measured results show that the current system performance is suitable for many applications with moderate latency requirements, while further improvements are expected with future enhancements.

The remainder of the paper is structured as follows. Section II presents related works. Section III explains the system setup and the components used. The measurement results are described and interpreted in Section IV and finally, Section V concludes the paper.

II. Related Works

In this section, we summarize the open-source platforms for a 5G network. As discussed in [4], there are variant open-source platforms, like OAI, srsRAN, and free5GC. These are ongoing projects providing testbeds for 5G networks. In addition to the projects which are developing the Radio Access Network (RAN) and core network of 5G, there are other projects like O-RAN, Open Network Automation Platform (ONAP), SD-RAN, and MOSAIC5G that are helping the 5G community to enhance by enabling other features of 5G. In Table I, a summary of the ongoing 5G open-source projects is presented. As a result of the review of the related works on the testbeds [4], however in [5] the latency in uplink (UL) and downlink (DL) are measured, but there is no discussion about the coverage and stability of the network. Besides that, the used testbed is not an open-source testbed, while in our case the core network and the RAN both are open-source. In [6] mostly the latency and the methods of deployment of a 4G and 5G networks are presented and compared. However, in the provided uses cases the DR of the network, which is a parameter of interest in 5G industrial applications like URLLC, has not been considered. [7]–[9] present studies about the application of 5G in industry 4.0 use cases and the tools how to measure the performance of the testbeds. In this work, we present an open-source 5G testbed developed by OAI and we evaluate the basic measurements such as latency, DR, and coverage parameters we have implemented for the specific scenarios.

TABLE I
Ongoing 5G open-source projects [4]

open-source platforms and frameworks	
Framework Title	Summary
OAI	Developing RAN and Core based on 3GPP standards Rel.16
MOSAIC5G	OAI sub-project to develop platforms like RAN Inteligent Controller (RIC) and integration of O-RAN with OAI
srsRAN	has a stable LTE RAN and EPC toward a future 5GC
SD-RAN	Compatible RAN components for O-RAN project
ONAP	Orchestration Platform with build-in management network slicing
O-RAN	Disagrregated RAN with Software Defined (SD) control over Radio Resource Control (RRC)
Free5GC	Implementation of most service based Virtualized Network Functions (VNF)s with RAN simulators

III. Overview of OAI Configuration

The OpenAirInteface (OAI) is an open-source software suite developed by Eurecom to support mobile telecommunication systems including 4G and 5G. Eurecom deployed a cloud radio access network (C-RAN) network using OpenAirInterface software and inexpensive commodity hardware [9]. We have deployed a similar setup to what exists in Eurecom located in Silicon Austria Labs (SAL) in Linz, Austria. The implementation is based on 3GPP Rel. 15 and Rel. 16 and operates in SA with an SCS of $30\,\mathrm{kHz}$ and a bandwidth of $20\,\mathrm{MHz}$ in the frequency band 77 at $3.45\,\mathrm{GHz}$. In Fig. 1 and Table II the summary of the setup is presented. We aim to evaluate the possibilities of using this deployment for industrial applications like controlling robots and tracking. For such applications, it is crucial to know the achievable performance in terms of latency and DR. In the following section we describe the experimental setup in detail.

The configuration consists of one server for the core and gNB, a Universal Software Radio Peripheral (USRP) which is configured as a radio head (RH), and a server which runs the user equipment (UE). We explored different hardware for running the UE: a Windows notebook, a Raspberry Pi (RP) and a UP mini computer[1] to check the influence of the different hardware and its associated Operating System (OS) on the performance of the setup. In the following part of the paper, technical details of the setup, the used RHs, and setup of the UE are explained.

A. Technical features

The core is Docker-based deployment on a server where the gNB is also deployed. The server hosts the network

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[1] https://up-board.org

TABLE II
SPECIFICATIONS OF HARD- AND SOFTWARE

OAI Hardware	
Component	Specification
CPU	Intel(R) Core(TM) i7-10750H CPU @ 2.60 GHz
Hard Disk	1024 GB
USB Ports	USB 3.0
Radio device	
Component	Specification
gNB	USRPB210
Antenna	Omnidirectional Monopole
UE	Quectel RM500Q
OAI software	
Component	Specification
Operating System	Ubuntu 18.04
Linux Kernel	Low Latency
OAI Branch	Develop

Fig. 1. Components used for the setup.

elements Access and Mobility Management Function (AMF), Session Management Function (SMF), Unified Data Management (UDM), Unified Data Repository (UDR), Network Function Repository Function (NRF), and Serving and Packet Data Network Gateway (SPGW) [2].

A technical issue to consider is the use of the correct USRP Hard Driver (UHD) version for the setup. It is highly recommended to follow the minimum server specification provided by OAI[3] for a smooth deployment of the setup. In most cases, the Core Network (CN) and RAN are deployed on separate servers. However, we chose to deploy both on the same server. This largely simplified the installation of a mobile setup for measurements across our office area.

B. Universal software radio peripheral setup

Multiple options are available on the selection of RH since Ettus Research provides a wide range of USRPs. In our setup, we used USRP B210 and N310, with the main difference being the maximum supported bandwidths (56 MHz for USRP B210 and 100 MHz for USRP N310). These series of USRPs can load the configuration in their Field Programmable Gate Array (FPGA) at the time of execution. All signal processing functions on the I/Q samples are performed in the FPGA. The USRP Hardware Driver UHD provides an application programming interface (API) to conveniently program the FPGA. However, we noted that it is important to use the proper UHD version for successful usage in combination with the OAI. We used v3.15.0.0 and v4.0.0.0 for deploying the setup which are compatible with both B210 and N310 USRPs.

C. User equipment

The Quectel RM500Q-GL modules are used as UEs in our setup as is also suggested by OAI guidelines. These modules are mounted using USB 3.0 carrier boards to connect as a client either with Windows or Linux OS. The UE is controlled via AT commands which are a series of serial commands for controlling the Quectel module. In our setup, we have connected the Quectel modules to different devices such as a PC, a RaspberryPi, or a UP mini-computer to evaluate the performance of the setup with the different devices and OSs. The point to consider is the correct configuration [4] of the module to enable connection to the gNB. As we will discuss in the following part of the paper, Quectel RM500Q-GL is one of the candidate devices that can be used with OAI, but we show in the later section that this version is not suitable to support URLLC service. However, at the time of writing, Quectel RM500Q-GL is the latest commercially available product.

As per the Subscriber Identity Module (SIM), we used and configured blank SIM cards from the Open Cells Project with the UICC application [5]. The data of the SIM cards are entered in the respective pre-defined database in OAI, which is required to authenticate the UE.

IV. MEASUREMENT RESULTS

In this section, we describe the measurement procedure for latency, DR and coverage, we present the environment in whcih we conducted the measurements and we analyze the measurement results. Therefore, for analyzing the latency and DR, the UEs and the gNB are placed as it is shown in Fig. 2.

A. Latency

1) UL and DL Round Trip Time (RTT) latency analysis with a single UE: In the first scenario with USRP B210 we measured the latency from one UE to the other UE as well as the latency in the UL and DL. To measure the latency we used the Ping command, which gives the RTT, with a time intervals of 1 ms, and a packet size of 1000 bytes, and we

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[2] https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/develop/doc

[3] https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/OpenAirSystemRequirements

[4] https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/ci/quectel-at-commands

[5] https://open-cells.com

TABLE III
CONFIGURATION PARAMETERS FOR THE GNB WITH USRP B210

Common parameters		
Description	Acronym	Value
Mobile Country Code	MCC	208
Mobile Network Code	MNC	95
Tracking Area code	TAC	1
Number of Antennas	nb_tx,nb_rx	2
Resource Blocks	dl_carrierBandwidth	106
Gain	max_rxgain	114
IP address of AMF	amf_ip_address	192.168.70.132
Band of frequencies	absoluteFrequencySSB dl_absoluteFrequencyPointA dl_frequencyBand ul_frequencyBand	630048 628776 77 77
SCS	subcarrierSpacing	30 kHz
Networks Interface	ADDRESS_FOR_NG_AMF ADDRESS_FOR_NGU	192.168.70.129/24 192.168.70.129/24
TDD period	TransmissionPeriodicity	2.5 ms
Downlink slot Duration	nrofDownlinkSlots	1 ms
Uplink slot Duration	nrofUplinkSlots	1 ms

TABLE IV
CONFIGURATION PARAMETERS FOR THE GNB WITH USRP N310

Common parameters		
Description	Acronym	Value
Mobile Country Code	MCC	208
Mobile Network Code	MNC	95
Tracking Area code	TAC	1
Number of Antennas	nb_tx,nb_rx	4
Resource Blocks	dl_carrierBandwidth	162
Gain	max_rxgain	114
IP address of AMF	amf_ip_address	192.168.70.132
Band of frequencies	absoluteFrequencySSB dl_absoluteFrequencyPointA dl_frequencyBand ul_frequencyBand	630048 628776 77 77
SCS	subcarrierSpacing	30 kHz
Networks Interface	ADDRESS_FOR_NG_AMF ADDRESS_FOR_NGU	192.168.70.129/24 192.168.70.129/24
TDD period	TransmissionPeriodicity	2.5 ms
Downlink slot Duration	nrofDownlinkSlots	1 ms
Uplink slot Duration	nrofUplinkSlots	1 ms

performed the experiments for 1 minute 100 times, and the average latency which is measured in Table V is the RTT either between the UEs or among the CN and a UE. As it is shown in Fig. 3, we measured the latency of the UL once when the UEs are both connected to the RPs. In the same setup, we connected our UE to a mini UP computer which is operating via Windows10 OS, and we did the UL and DL RTT latency measurements. The purpose of doing the measurements with two variant OS, was to clarify weather the OS of the client where UE is running has influence on delay performance.The result which is quite interesting is that the latency is dependent on the OS on which the UE is operating, and at the moment of writing this paper, to the knowledge of the author, it is not clear what are the possible reasons for this difference, but we know is that the measurements shows that RPs have a better performance in comparison with the UP mini computers. The UL RTT latency with the UEs that are connected to the RPs is on average around 8 ms, while the average UL RTT latency with the UE connected to the windows client is around 12 ms. However, based on the future application both could be applicable, moreover in the course of these experiments the differences between the OSs were investigated. As can be seen from Table V, the average, minimum and maximum RTT values for both USRP types are almost the same since the UL and DL slot allocation for the both are the same.

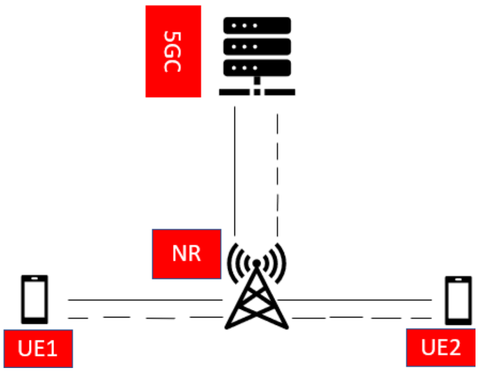

Fig. 2. Multi UE scenario.

2) Multi UE latency analysis: One of the features of our deployment is to simultaneously support with multiple UEs. Therefore, we have connected our UEs to two RPs due to their better performance as described above. As can be seen from Fig. 3, the RTT between two UEs is on average around 19ms which is acceptable for a application such as intelligent transport systems, and low latency enhanced mobile broadband (eMBB) applications like augmented reality assuming the reliability conditions are fulfilled [10]. As it is shown in Fig. 3, the RTT shows distinct, almost periodic patterns. The reason for that is a buffer in the Quectel module which causes this periodic pattern. We can conclude, that this version of the Quectel module is not suitable for URLLC applications due to its hardware limitations.

B. Data rate

A very important communication parameter is the throughput of the network. In 3GPP 38.306 chapter 4.1.2 [11], the approximate DR is computed as follows

$$\mathrm{DR} = v_{\mathrm{L}}\, Q_m\, f\, R_{\max} \frac{N_{\mathrm{PRB}}^{\mathrm{BW},\mu}\, 12}{T_s^{\mu}} (1 - \mathrm{OH}) \tag{1}$$

wherein $R_{max} = 984/1024$, v_{L} is the maximum number of supported layers transmission, Q_m is the maximum supported modulation order, f is the scaling factor, μ is the numerology, T_s^{μ} is the orthogonal frequency division multiplexing (OFDM) symbol duration, $N_{\mathrm{PRB}}^{\mathrm{BW},\mu}$ is the maximum possible resource block (RB) allocation in bandwidth (BW), and OH is the overhead [11].

To measure the DR we placed our setup in our laboratory with a distance of 1 m between UEs and USRPB210. To

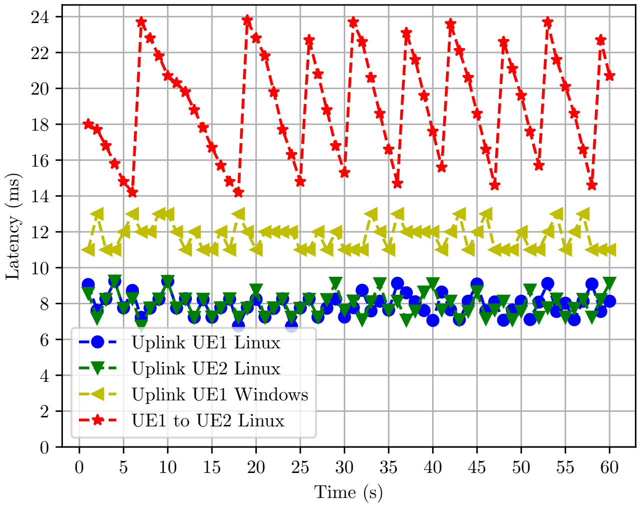

Fig. 3. Measured RTTs with two UEs operating simultaneously.

evaluate the effect of different OSs on the DR, we first measured the DR with a Quectel module connected to a RP, repeated the same measurement with another Quectel module connected to an UP computer and performed the same measurements with the USRP N310. For all measurements we used the Iperf command for 3 minutes with a data rate of $100\,\mathrm{Mbit/s}$ and pushed User Datagram Protocol (UDP) packets as traffic. For the DL DR measurement, we set the CN as server and the RP as client and exchanged their roles for the UL measurement. According to Eq. (1), the maximum theoretical DR we achieved in DL via our configuration is $131\,\mathrm{Mbps}$ and $40\,\mathrm{Mbps}$ for UL with $40\,\mathrm{MHz}$ of BW and $402\,\mathrm{Mbps}$ for DL and $120\,\mathrm{Mbps}$ for UL with $60\,\mathrm{MHz}$ of BW. The DR that we achieved with USRP B210 was $127\,\mathrm{Mbps}$ in the DL and $18\,\mathrm{Mbps}$ in the UL with $40\,\mathrm{MHz}$ of BW. On the other hand, we achieved a maximum DR of $390\,\mathrm{Mbps}$ with the USRP N310 and a BW of $60\,\mathrm{MHz}$ in the DL and $28\,\mathrm{Mbps}$ in the UL. The summary of the results is shown in Table VI. In the DL we achieved a DR very close to the theoretical value, while in the UL we found a large gap between theory and measurement. We assume that this gap in performance is due to the fact that the UL part of OAI is still not yet fully developed.

TABLE V
MEASURED LATENCY

RTT Measurements			
USRP B210	Min. RTT (ms)	Avg. RTT (ms)	Max. RTT (ms)
UE to CN	6.394	8.510	9.234
CN to UE	6.806	9.206	12.928
UE to UE	14.156	19.320	23.952
USRP N310	Min. RTT (ms)	Avg. RTT (ms)	Max. RTT (ms)
UE to CN	6.717	8.256	9.314
CN to UE	7.126	9.189	12.191
UE to UE	15.731	21.748	26.236

TABLE VI
MEASURED VS. THEORETICAL DATA RATE

Theoretical DR		
USRP B210	UL TP Mbit/s	DL TP Mbit/s
UE to CN	40	131
USRP N310	UL TP Mbit/s	DL TP Mbit/s
UE to CN	120	402
Measured DR		
USRP B210	UL TP Mbit/s	DL TP Mbit/s
UE to CN	18	126
UE to UE	18	-
USRP N310	UL TP Mbit/s	DL TP Mbit/s
UE to CN	28	390
UE to UE	28	-

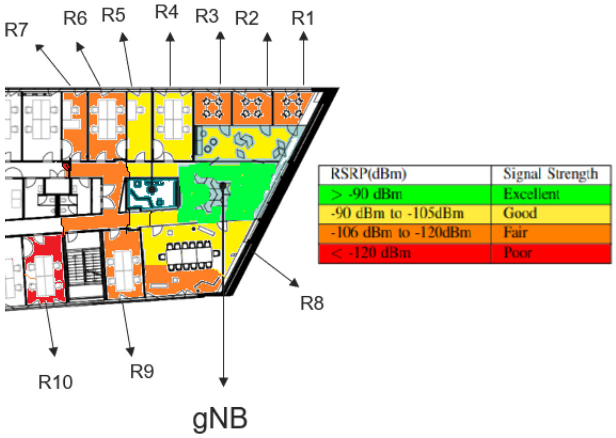

Fig. 4. Coverage Map based on Reference Signal Received Power (RSRP).

C. Coverage evaluation

To analyze the coverage of our setup, we implemented the measurement of the parameters RSRP, Reference Signal Received Quality (RSRQ), and Signal to Interference and Noise Ratio (SINR) in the OAI develop branch and gathered measured values of these parameters from different points in ten rooms of an office area at SAL Linz premises. The layout of the office area can be seen in Fig. 4. The gNB was located in the center of the hall and transmitted with the maximum available transmit power of $23\,\mathrm{dB}$ of the used USRP B210. Using the UE we performed the measurements in the rooms marked in Fig. 4. In rooms which are coloured white we did

TABLE VII
COVERAGE

	RSRP(dBm)	RSRQ(dB)	SINR(dB)
R1	-116, -108	-13.5, -11.5	1.0, 9.5
R2	-106, -104	-11.5, -11	10.5, 13.5
R3	-107, -101	-11.5, -11	10.5, 14.5
R4	-106, -100	-11.5, -11	14.5, 18
R5	-104, -102	-11.5, -11	13.5, 16
R6	-111, -107	-11.5, -11	6.5, 10.5
R7	-117, -116	-13.5, -12.5	1.5, 3.5
R8	-116, -104	-16, -11	1.0, 9.0
R9	-111, -108	-11.5, -11	7.0, 11.0
R10	-121, -120	-11.5, -11	1.5, 5

not perform measurements. We conducted two measurements in each room, one at the door and one in the back of the room. The results are summarized in Table VII and displayed in Fig. 4, in which we used the model from [12] for coloring . The SINR varies between $1\,\mathrm{dB}$ and $14.5\,\mathrm{dB}$. As expected, the lowest SINR were measured at the largest distances to the gNB and with the most walls and othe obstacle in between. The low coverage resulted from the low maximum transmit power delivered by the USRP B210.

V. CONCLUSION

In this paper we presented an indoor open-source 5G standalone deployment base on OAI. We used inexpensive commodity hardware for the RF and baseband signal processing part of the deployment. We have performed first measurements to determine latency in terms of RTT, data rate, and coverage in an office environment. The results indicate that with the used hardware we are able to come close to the theoretically reachable DL data rates and achieve sufficient coverage. The UL data rate stayed well below the theoretical possible values, which can probably be attributed to the fact that the UL is not yet fully implemented in OAI. In terms of latency we could achieve average values around 19 ms for the RTT, which is acceptable for many applications, however, still far from values required for URLLC applications. Future work will concentrate on the reduction of latency and on the increase of the UL DR.

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