Insights into the performance of 5GOpen@TheBeacon: a flexible and scalable 5G testbed based on open source solutions

João Francisco Nunes Pinheiro*, Andreas Gavrielides*, Miguel Camelo*, Johann Marquez-Barja*
*University of Antwerp - imec, Internet & Data Lab (IDLab), Antwerpen, Belgium
email: {joaofrancisco.nunespinheiro, andreas.gavrielides, miguel.camelo, johann.marquez-barja}@uantwerpen.be

***Abstract*—As 5G rollout keeps progressing, the need for experimentation platforms with different functionalities, like MEC deployments, flexible Core functions and multi-vendor compatibility, keeps growing. Existing testbeds have some commercial/closed source solutions integrated to a degree (in the Core, Radio Access Network (RAN) or both), limiting development of new and innovative functionalities, and experimentation that might require more fine grain control over the network. This paper provides valuable insights into the current 5G performance by using the 5GOpen@TheBeacon testbed, a flexible solution that utilizes multiple open-source solutions in both indoor and outdoor environments, working in real-world conditions. We leverage two architectures and combine the different software available which later can enable research across different use cases, such as eMBB, URLLC and V2X.**

***Index Terms*—5G, Testbed, open source, Smart Highway, OpenAirInterface, srsRAN, Open5gs, performance**

I. Introduction

Many platforms nowadays aim to demonstrate and allow researchers to perform experimentation in 5G networks, but most of them use solutions that do not allow for the level of flexibility predicted in 5G deployments[1], [2]. Although the use of emulators and simulators help in predicting the behaviour of networks [3], [4], real-life experimentation with deployments in different environments can behave in a complete different way then what is expected from the other methods.

In this paper we present the 5GOpen@TheBeacon testbed, a testbed based on open source software that targets real wold experimentation in indoor and outdoor environments. We show two different architectures, based on multiple open-source software combinations, that were tested, validated and can be leveraged in a range of use cases, such as enhanced Mobile Broad Band (eMBB), Ultra-Reliable Low Latency Communications (URLLC) and enhanced V2X (eV2X). To finalize, we present results collected in the platform and list the future targets to be developed and integrated in our testbed.

II. Background

Ghassemian et al., [5] showcase a test 5G non-SA (NSA) (with later plans for a Standalone (SA)) network with commercial equipment. They use 3GPP functional split Options 2 and 7 [6], with Virtual Centralized Unit (CU) and Distributed Unit (DU) and a hardware Radio Unit (RU), focusing on *mmWave* capabilities, aiming at the following experimentation

TABLE I: Comparison between existing solutions and 5GOpen@theBeacon

	[5]	[7]	[8]	Ours
Indoor	No	N/A	No	Yes
Outdoor	Yes	N/A	Yes	Yes
SA/NSA	NSA	N/A	SA	SA
CORE	4G	Open5GS, OAI, Free5GC	Commercial	Open5GS & OAI
RAN	Commercial	UERANSIM & Commercial	Commercial	OAI, srsRAN & UERANSIM
Cloud/Edge Support	N/A	Yes	N/A	Yes

possibilities: Cloud based gaming, Assisted Living Remote robotic control and immersive telepresence, Low-latency situation recognition and Dedicated Quality-of-service (QoS) Support outside broadcast media.

In [7], the authors deploy a cloud-native 5G experimental platform with end-to-end monitoring based on containers (Kubernetes with Helm Charts) with the addition of Multi-access edge computing (MEC) capabilities. They use Open5GS[1] as Core solution, with a commercial, closed source, gNB (Amarisoft Callbox[2]). Both support monitoring using Prometheus and Grafana dashboards to showcase Key Performance Indicators (KPIs) and metrics. The use-cases presented in this work focus on User Plane Function (UPF) reselection for MEC deployments and User Equipment (UE) mobility, which was emulated on their infrastructure.

In [8], the authors present preliminary performance tests an a live 5G network, on a 100 MHz channel with a commercial solution from a Telecom provider. The tests show latency varying between 9 and 15 ms and downlink throughput average of 869 Mbps, which is aligned with the targets from ETSI [9].

Tab. I compares our Testbed with the existing works, with notable distinction lying in the versatility across various environments (outdoor and indoor) and its complete support for Open Source Over-the-Air (OTA) RAN, which allows for tailor made solutions and/or functions to be integrated and tested in our Testbed.

The next sections present our platform that combines some of the features from aforementioned works, like virtualization, MEC deployments, and adds flexibility of multiple architectures, deployment styles, and allows users to further develop,

[1]https://open5gs.org
[2]https://amarisoft.com/products/test-measurements/amari-lte-callbox/

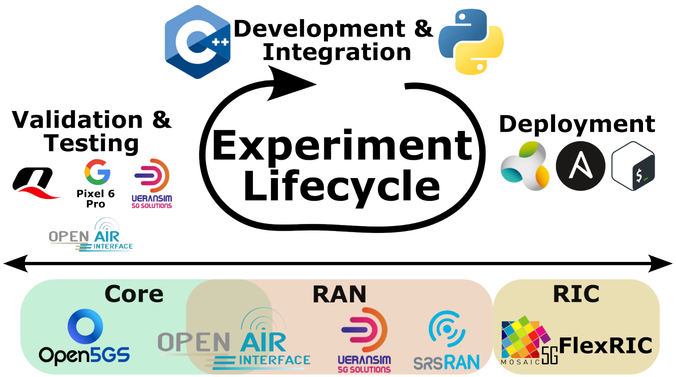


Fig. 1: 5GOpen@TheBeacon experiment lifecycle

integrate, and test functionalities on top of pre-tested open source solutions in indoor and outdoor environments.

III. Testbed Description

5GOpen@TheBeacon is a 5G testbed based on Open-source solutions that are Open RAN (O-RAN) compliant. It aims to perform 5G development, deployment, integration, validation, and testing in both indoor (office) and outdoor environments by making use of solutions such as OpenAirInterface (OAI)[3], Open5GS, UERANSIM[4], srsRAN[5] and FlexRIC[6], to deploy full End-to-End 5G networks, enabling experimentation in a 5G SA chain, from the core network to the RAN, and RAN Intelligent Controller (RIC), bridging the gap to current test setups that aim at one type of environment at a time.

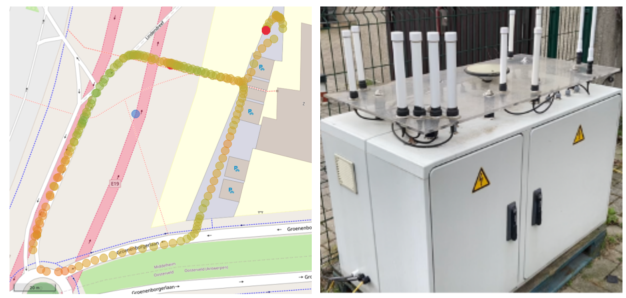
Fig. 1 shows the experiment lifecycle from 5GOpen@TheBeacon and illustrates the corresponding software solutions used in each lifecycle stage. Within the Development & Integration stage, we engage with different software using Python and/or C++, and go beyond the main code base, encompassing additional functions that will be properly integrated and tested in our stack, including not only the source code, but configuration of the different software ensuring seamless interaction. Next, in the Deployment stage, we leverage Bash and Ansible scripts that contain all necessary steps to automatically setup the software into the testbed. Furthermore, we Validate & Test the 5G setup by connecting UEs to the deployment, ensuring that the End-to-End (E2E) 5G chain is operational while collecting data and extracting insights that substantiate the conducted experiments.

For the office environment we currently have 3 distributed gNBs (similar to the one shown in Fig. 2) to provide 5G coverage to one floor with Universal Software Radio Peripherals (USRPs) B210 as RUs. Alongside with that, we have a separate setup for configuration validation, smaller scale experimentation and to verify the E2E performance of the network (in terms of Round Trip Time (RTT), Jitter and Throughput). This small scale setup is connected using SubMiniature version A (SMA) cables instead of OTA connectivity, allowing for lossless transmissions and presenting us the maximum performance that we can expect in a near-perfect environment.

[3]https://openairinterface.org
[4]https://github.com/aligungr/UERANSIM
[5]https://www.srslte.com/
[6]https://gitlab.eurecom.fr/mosaic5g/flexric

(a) (b)

Fig. 2: (a) gNB and (b) UE (OTA) Equipments



(a) (b)

Fig. 3: Groenenborger Campus test location (a) and RSU (b)

Scaling up from the office environment, we use IDLab's Smart Highway testbed[7][10] as our outdoor environment. It consists of 7 Distributed Nodes (Road-side Units (RSUs)) alongside 4 Km of Antwerp's E313 Highway and one node at the Groenenborger Campus of the University of Antwerp. We used one of the Smart Highway nodes as a proof of concept that our deployment methods and network configuration would perform properly in a larger open environment (shown in Fig. 9) and the node at the campus for smaller scale performance tests, but still in an outdoor OTA environment (map and node presented on Fig. 3)

The combination of indoor (office) and outdoor (Smart Highway) environments has the potential to cover a variety of 5G targeted use cases such as eMBB, massive MTC (mMTC), URLLC and eV2X communications.

Regarding equipment, the following is used in each environment: 1) Office: a) Core: Dedicated host with i7-8700K CPU and 16 GB RAM b) gNB: Dedicated host with i7-11700K CPU, 64 GB RAM and 10 Gbps SPF networking for use with the RUs. c) RUs: USRP X310 over 10 Gbps link and/or USRP B210 over USB3.0 2) Outdoor (Smart Highway): a) Core and gNB: Shared host with an Intel Xeon E5-2620 CPU and 32 GB RAM. b) RUs: USRP N310 over 10 Gbps link

For both environments, we used Intel NUCs (NUC10FNH, i7-10710U processor and 32 GB RAM) with Quectel RM500Q

[7]https://www.uantwerpen.be/en/research-groups/idlab/infrastructure/smart-highway/

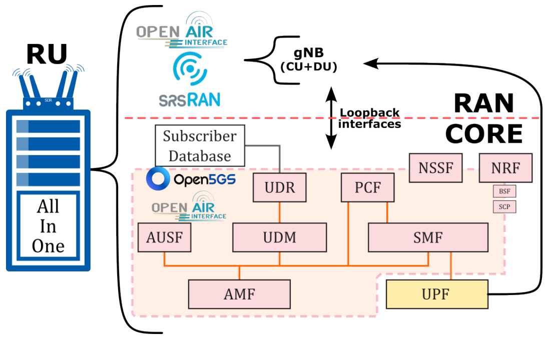


Fig. 4: All-In-One architecture

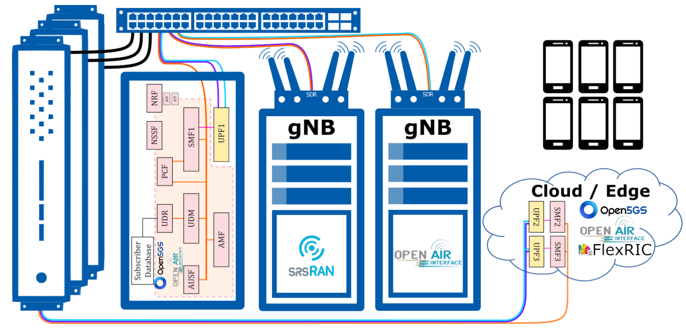


Fig. 5: Core-RAN disaggregation

5G modems as UEs. Although they are Commercial off-the-shelf (COTS) units, they provide us with more granular control over some UE characteristics, such as band selection, operation mode (SA vs NSA) and even the antenna models we can use, thanks to its external connectors.

To provide a more End-User like experience, we have added a Google Pixel 6 Pro phone to our list of UEs, showing that our testbed can be used with both Experimental and COTS equipment.

IV. Architecture

Our Testbed is based on 2 main architectures, each with different objectives and targeting different use cases.

A. All-in-one Architecture

For demonstration and portability purposes, our All-in-One setup hosts all core functions on the same machine where the gNB is deployed. Although this allows for better performance network wise, it does require a more powerful machine to run all network functions.

All 5G interfaces shown in Fig. 4 are passed over a loopback interface internal to the host, thus the network latency from gNB to Core is negligible. Since all networking is done internally, no external access is possible to any O-RAN interfaces, and no additional gNBs can be connected to the Core network.

This architecture was used to validate the Smart Highway environment, where we tested only one node due to its location and easiness of access (roundabout with different accesses and strategic locations that allowed us to properly stop a car, debug and benchmark the network).

B. Core-RAN disaggregation

Here we have a more flexible architecture that achieves better performance overall (between compute resource management and network performance), by disaggregating core functions from the RAN. This is the base for MEC deployments, where multiple core functions can be placed in different locations, e.g. cloud and/or edge, improving performance, stability and adding redundancy to the network.

The RAN in this case is still represented by a monolithic deployment of CU + DU + RU in the same host (which can be replicated to improve coverage), while Core functions can be distributed across multiple domains.

With the separation of RAN and Core, additional computing resources can be allocated to each component, but there is a trade-off in terms of E2E network performance since we need to add at least one new network link between gNB and Core. If more than one gNB is deployed we have to add a network switch, resulting in increased latency.

This architecture is used in the indoor environment, allowing for distributed gNBs to ensure coverage of the full office area.

```
-- AMF --
[amf] InitialUEMessage
[amf] [Added] Number of gNB-UEs is now 1
[gmm] Registration request
[gmm] [imsi-001010000008640] Registration complete
[amf] [imsi-001010000008640] Configuration update command
[amf] [Added] Number of AMF-Sessions is now 1
-- SMF --
[smf] [Added] Number of SMF-UEs is now 1
[smf] [Added] Number of SMF-Sessions is now 1
[smf] UE SUPI[imsi-001010000008640] DNN[oai] IPv4[10.45.0.6] IPv6[]
-- UPF --
[upf] [Added] Number of UPF-Sessions is now 1
[upf] UE F-SEID[UP:0x576 CP:0xfb3] APN[oai] PDN-Type[1] IPv4[10.45.0.7] IPv6[]
```

Fig. 6: Example logs from Open5GS Core (AMF, SMF and UPF) while attaching a new UE

V. Testing methodology and Results

Given the hardware and software presented in Sec. III, we tested and evaluated the interaction between the different software and the subsequent impact of each combination in the architectures shown in Sec. IV. This enables users to choose the best possible combination of software and architecture for their own experiment, which can aim at performance testing and/or stability of the network. For each combination of software, we test and evaluate 2 main aspects of the network, which are covered over the following subsections.

A. Basic connectivity

The first aspect of the network that we evaluate is basic connectivity, including UE attachment procedures, address assignment by the core and Protocol Data Unit (PDU) session establishment. One example of logs shown in parts of the Core network (specifically from Open5GS) is represented in Fig. 6.

In the example, we can observe the attachment procedure of the UE from the Core perspective, beginning on the Access and Mobility Management Function (AMF) side, where we can see the Initial UE message, registration request and completion messages. On the UPF logs we can also observe the Fully qualified Session Endpoint Identifier (SEID), with the ID of the User and control planes, as well as the allocated IP address of the UE.

```
[NR_MAC] Frame.Slot 256.0
UE RNTI fe0f (1) PH 43 dB PCMAX 21 dBm, average RSRP -88 (16 meas)
UE fe0f: dlsch_rounds 14080/3/1/1, dlsch_errors 1, pucch0_DTX 6, BLER 0.00000 MCS 9
UE fe0f: ulsch_rounds 385317/5/2/2, ulsch_DTX 7, ulsch_errors 1, BLER 0.00000 MCS 28
```

Fig. 7: Example logs from the OAI gNB

B. Performance

The performance of the network is evaluated based on the following metrics: 1) Channel metrics: a) Received Signal Received Power (RSRP): indicates the quality of the 5G reception by the UE and allow operators to evaluate their network coverage (ranges from -140 to -44 dBm [11]) 2) Network metrics (Downlink, from UE to UPF): a) Round Trip Time (RTT): commonly used to diagnose connectivity problems but it also indicates how fast a UE can reach different endpoints b) Network jitter (ms): show how stable the network is by examining irregularities in the arrival of packages at the UE c) Throughput (Mbps) from in UDP transmissions: evaluate the speed of content delivery to the UE

We chose this specific set of metrics because they can provide us with valuable insights into the end-user experience in a network, showing us how strong the network signal is (and if we need to reevaluate the network deployment to cover more area), how fast and reliably users can access different endpoints and finally, how fast a user can consume different types of data, based on their size.

Other metrics, like Modulation and Coding Scheme (MCS), Power Headroom (PH) and UE Maximum Tx Power (P_{CMAX}), are available on the gNB (see Fig. 7), but to properly assess the end-user experience, we chose to evaluate the performance directly from the UE perspective, collecting all metrics directly on the user's equipment and later consolidating them in a centralized database for evaluation.

Based on the data collected from the experiments, we can have a better insight on the performance of the different software combinations, to select the best combination to achieve the desired outcomes in each use-case.

C. Network setup

The simplest network we have tested is composed of a minimal set of Core functions necessary to make a 5G SA functional (AMF, NRF, SCP, SMF, UPF, AUSF, UDM, UDR, PCF, NSSF and BSF), 1 monolithic gNB and 1 UE (Quectel modem)[8]. From here, we executed the tests depicted in Fig. **??**.

D. Results

From the list of tests presented in the previous section, items 1-3 were tested in a controlled environment, to make sure that all software combinations were properly working. Then, items 4-6 were tested both in the office environment (extensively) and at the Smart Highway testbed (less extensively). The results are presented in Tables II and III.

Although Tab. III only covers a fraction of the tests we performed, it is worth mentioning some specific cases: 1) We performed a set of tests in the Smart Highway (see Figures 9 and 10), where the environment is not controlled. Between natural variables (like the rain) and the presence of obstacles

[8]All tests with the UERANSIM gNB had to use its own software UE.

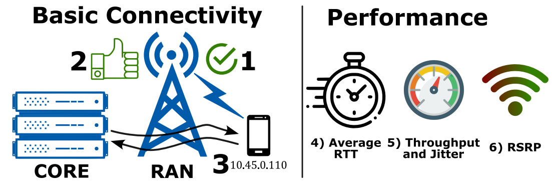


Fig. 8: Connectivity and performance tests: 1) UE managed to detect the network (checked on the UE itself) and request registration at the core 2) UE is assigned a proper IP address based on the network slice 3) UE can ping Core network and access the internet 4) Ping-based average RTT over 10s 5) Throughput (Mbps) and Jitter (ms) average over 10s based on *iperf3* 6) RSRP value extracted from the modem over AT Commands

TABLE II: Basic Connectivity tests

Core	GNB	#1	#2	#3
OAI	OAI	PASS	PASS	PASS
OAI	srsRAN	PASS	PASS	PASS
OAI	UERANSIM	PASS	PASS	PASS
Open5GS	OAI	PASS	PASS	PASS
Open5GS	srsRAN	PASS	PASS	PASS
Open5GS	UERANSIM	PASS	PASS	PASS

TABLE III: Tests #4, #5 and #6 in an OTA office environment

Core	GNB	#4	#5 (T/J)	#6
OAI	OAI	10.829 ms	99.4 / 0.102	-87 dBm
OAI	srsRAN	29.048 ms	41.4 / 0.586	-81 dBm
Open5GS	OAI	12.077 ms	96.3 / 0.128	-87 dBm
Open5GS	srsRAN	29.656 ms	40.7 / 0.423	-80 dBm

(like traffic signs, viaducts and passing cars and trucks), the results were satisfactory but with room for improvement (see Sec. VI for future works and improvements). 2) In our office environment we had more consistent performance (see Fig. 11 for the Throughput results) in comparison to the one mentioned above. This can be associated with the lower number of variables impacting the overall system. Although we had better performance overall, it is worth mentioning that in some points we had difficulties establishing proper connectivity due to double fireproof glass that attenuated our transmission [12]. But even with those difficulties and considering that this is an active office space (tests were performed between 9am and 5pm), we still achieved good results. 3) Although srsRAN provided a more stable network, it could not reach the same level of performance from OAI (in terms of throughput). This is mainly due to the configuration of the gNB, which was not optimized for our trials at the time of testing.

VI. Conclusions and Future Work

In this paper, We presented initial performance results from 5GOpen@TheBeacon and the extension to the Smart Highway testbed. We showed the flexibility of deployment with different architectures that have distinct objectives, like portability, performance and reliability, and that this setup can scale up and down from a lab-sized environment for small scale experiments, to an office space and finally to a large open environment that targets mobility and Vehicle-to-Everything (V2X) use cases.

We also show that within our testbed we can combine and match different vendors, such as Open5Gs, OAI, srsRAN

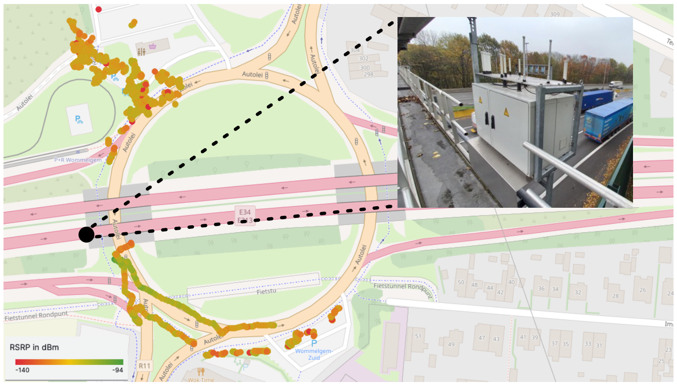


Fig. 9: Smart Highway RSRP measurements

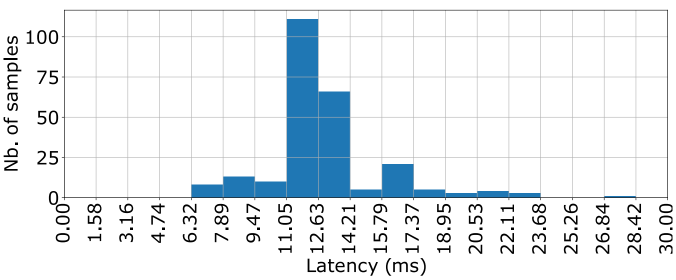


Fig. 10: Smart Highway Latency distribution

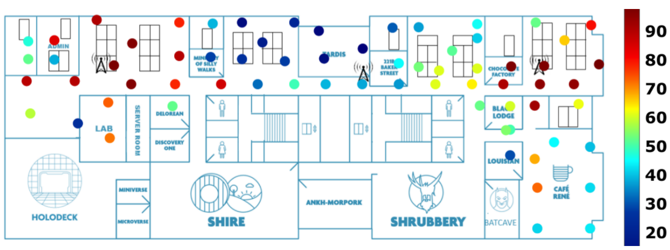


Fig. 11: Office environment throughput (Mbps) results

and UERANSIM which allow experimenters to use different functionalities from each vendor in order to find the best combination for their experiments.

Currently we are pursuing multiple paths to expand the functionalities of this testbed, which firstly include further automation of the testbed by using jFed[9] and rspec configurations to standardize the deployment and setup of the different architectures. Additionally, we will further validate and optimize MEC depoyments in the Smart Highway testbed to enhance flexibility and optimize resource allocation, which will lead to exploring additional use cases related to V2X [13], while also influencing performance improvements in user mobility studies. Another aspect involves the seamless integration of FlexRIC across various testbed use cases, such as Dynamic Slicing and automatic resource allocation. This integration is expected to facilitate research in ML and AI-based solutions for data analytics and function placement. Furthermore, ongoing efforts will include a thorough examination of open interfaces within both the Core and RAN, aiming to enhance overall interoperability and to introduce centralized monitoring capabilities for both the Core and RAN components, ensuring comprehensive oversight and management.

[9]https://jfed.ilabt.imec.be/

ACKNOWLEDGEMENT

The imec.icon project 5GECO is a research project bringing together academic researchers and industry partners. It is co-financed by imec and receives financial support from Flanders Innovation & Entrepreneurship (project nr. HBC.2021.0673) and/or Innoviris. This work has received funding from the European Union's Horizon-JU-SNS-2022 Research and Innovation Programme under Grant Agreement No. 101095871 (TrialsNet)

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