Experience in Profiling and Optimizing A 5G StandAlone Radio Access Network (RAN) Based on an Open Source Testbed

Lusani Mamushiane*,†, Albert A. Lysko*,†, Joyce Mwangama*, Hlabishi Kobo†, Humphrey Owuor Otieno*,‡
†Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa
*University of Cape Town (UCT), Cape Town, South Africa
‡Strathmore University, Nairobi, Kenya
[1]RVHLUS001@myuct.ac.za, lmamushiane@csir.co.za

***Abstract*—The adoption of 5G technology in Africa has been increasing steadily, with initial emphasis on non-standalone (NSA) architecture to leverage existing 4G investments and accelerate return on investment. The uptake of standalone (SA) 5G has been slower due to technical complexity, handset interoperability, spectrum availability, infrastructure readiness, and other factors. Several institutions in South Africa have established 5G research and development (R&D) testbeds to foster innovation and develop local expertise in 5G and its enabling technologies. When setting up a 5G testbed, adhering to best practices and conducting a comprehensive profiling of the environment is crucial for optimizing network performance. This paper provides a guide for profiling and optimizing the Radio Access Network (RAN) segment within a 5G testbed. Experimental evaluations show that optimizing parameters such as antenna gain, CPU performance, and antenna configuration significantly improves air interface stability, underscoring the importance of RAN optimization for overall network performance in a 5G testbed environment.**

***Index Terms*—Radio Access Network, RAN, 5G Standalone, Testbed, Resource profiling,Network Performance, Optimization, srsRAN, Signal-to-Noise Ratio (SNR), Air Interface**

I. Introduction

The fifth generation (5G) of mobile network technologies is expected to provide unprecedented data speeds, reaching peak rates of around 20 Gbps for stationary or low-mobility environments. It also offers options of ultra-low latency to support mission-critical applications and enables connectivity for a massive number of Internet of Things (IoT) devices. In South Africa, several network operators, including MTN, Rain, Telkom, Liquid Telecom, and Vodacom, have launched 5G networks using the emergency temporary spectrum provided by the Independent Communications Authority of South Africa (ICASA) during the COVID-19 pandemic in 2020. This initiative was driven by the increased demand for network data during that time [1]. The proliferation of 5G-capable handsets and the emergence of data- and latency-intensive industrial use cases (such as autonomous tractors by John Deere [2], autonomous drilling systems for mines [3], remote learning, UHD video-based telehealth consultations, etc.), as well as consumer applications (such as UHD video streaming, conferencing, gaming, etc.), have played a significant role in driving the adoption of 5G technology in South Africa.

Similarly to previous generations of mobile networks, a 5G network comprises three key components: the Radio Access Network (RAN), the Transport Network (or backhaul), and the Core Network (CN). The RAN facilitates wireless connections between end user devices and the network, utilizing antennas, base stations, and fronthaul connections. The CN handles tasks such as user traffic routing, mobility, and session management. The connection between the RAN and CN is established through a backhaul network, which can be wired (e.g., fiber optics) or wireless. Although overall network performance depends on the collective performance of these network components, the RAN has a more direct and significant impact on data speeds, coverage, signal strength, and capacity. The performance of the CN and backhaul becomes more crucial for latency-sensitive use cases that require timely data transmission and efficient data processing at the CN. Additionally, the RAN accounts for the largest portion of capital expenditure (CAPEX) and operating expenditure (OPEX) in mobile networks [4], making it a critical component to optimize.

Equipment providers and network operators collaborate to design and deploy RAN solutions that ensure optimal resource utilization, wider coverage, higher capacity, and improved signal quality. These efforts help offset the substantial investments in CAPEX and OPEX while meeting customer expectations. Technological advances in 5G networks, such as massive Multiple Input Multiple Output (MIMO), beamforming, and network slicing, play a crucial role in improving network performance.

Ongoing research and development (R&D) in 5G technology has led to the establishment of various testbeds in South Africa. The Council for Scientific and Industrial Research (CSIR) has set up a 5G testbed focused on dynamic spectrum management, IoT, network slicing, and resource sharing [5], [6], [7]. The University of Cape Town has developed a testbed for telehealth applications, wildlife monitoring, and delivery drones [8], [9][10]. The University of Witwatersrand, in collaboration with Huawei and Rain, has launched a 5G Innovation Hub to help build human capacity and capability in 5G technology [11].

In a testbed environment, profiling and optimizing the deployment of the Radio Access Network (RAN) are important. This process involves evaluating network performance, optimizing parameters, testing protocols, validating use cases, and facilitating network planning. RAN profiling quantifies radio conditions and network capacity based on current configurations, such as antenna orientation, channel bandwidth, power settings, and hardware resources. Profiling provides empirical data for designing and optimizing the 5G network, enabling researchers to apply appropriate optimization solutions to enhance functionality, efficiency, and effectiveness.

To the best of our knowledge, there have only been a handful of studies that have focused on RAN profiling on 5G networks. For instance, Lin et al. [12] proposed techniques to profile the performance of cloud RAN systems, specifically focusing on the software architecture of the baseband processing software. Their study aimed to identify performance improvement points at the kernel-level to enhance network speeds and compute resource usage. However, their profiling and optimization work did not consider the air interface, focusing solely on the computing platform hosting the RAN stack. Dongzhu et al. [13] conducted a study on a commercial 5G network, measuring network coverage, throughput, and latency. They also profiled the energy consumption of 5G applications, identified network performance bottlenecks, and proposed power management techniques for the RAN stack. While their work provided valuable insights into energy consumption and baseline performance evaluation, it was limited to proprietary and closed RAN and CN solutions. Additionally, their optimization efforts focused primarily on energy efficiency rather than other important metrics such as throughput, signal strength, and coverage. Wei et al. [14] performed a network performance analysis and CPU profiling to analyze the computing cost breakdown in different RAN architectures: monolithic RAN and disaggregated RAN stack with Centralized Unit (CU) and Distributed Unit (DU) functional splits. They provided insights into the overheads incurred at each RAN protocol layer and deployment architecture, which can guide 5G base station design and optimization. Their experiments were conducted using an open-source software stack for the RAN and CN. However, they did not conduct optimization experiments to demonstrate which parameters should be tuned for maximum RAN performance.

Our study has three (3) main contributions. First, we introduce a profiling technique to measure the resource allocation of a 5G testbed, specifically targeting the RAN domain. This can provide researchers and developers with insight into their network's resource pool, capacity, and coverage. Secondly, we propose a framework for optimizing the testbed's performance. This framework identifies adjustable parameters in the air interface, radio head, and baseband processing unit, enabling researchers and developers to enhance the testbed's performance. Lastly, we present results based on our profiling and optimization efforts, demonstrating the effectiveness of our proposed techniques.

A. *Organisation of Paper*

The paper is organized as follows: Section II provides an overview of the key building blocks of our 5G testbed. Section III describes the RAN profiling technique followed by the RAN optimization framework in Section IV. Section V presents and discusses the results. Finally, Section VI concludes the paper and provides a direction for future research.

II. Testbed Overview

Figure 1 illustrates our testbed setup, consisting of two open source implementations of 5G RAN stacks: srsRAN [15] and OpenAirInterface (OAI) [16]. These are deployed on a Linux-based compute node (Intel x86 PC architecture) along with software-defined radios (SDRs), specifically universal software radio peripherals (USRPs). The srsRAN and OpenAirInterface serve as the baseband processing units (BBUs) or gNBs, while the SDRs function as the remote radio heads (RRUs) responsible for RF signal reception, transmission, filtering, and amplification. We chose SDRs for their reconfigurability and programmability, allowing us to adapt radio protocols, operating frequencies, modulation methods, and antenna gain based on specific conditions such as interference, noise, and traffic volume. In our configuration, we operated the SDRs in Single Input Single Output (SISO) mode without beamforming, resulting in moderate throughput for the 5G network.

For the fronthaul connection between the BBU/gNB and SDR, we use a 10GB PCIe connector for X series SDRs and USB3.0 for B series SDRs. This choice ensures lower latency and higher data transfer rates. Our Core Networks (CN) consist of a combination of open source and commercial implementations. They are deployed in an OpenStack virtual environment on our commodity data center infrastructure. Each CN runs on Docker containers and is connected to the RAN through a private 1GBE backhaul. The CN ecosystem in the data center includes Magma [17], Open5Gs [18], Free5GC [19], OAI 5GC[20], Open5GCore [21], and Cumucore [22]. Internet breakout occurs through a local area network connected to a fiber-based last-mile network.

In terms of user equipment (UE), we utilize consumer-grade 5G-capable devices such as smartphones and modems. Currently, only a few UEs compatible with 5G SA are available on the market, as most UEs only work with 5G NSA networks. In our experiments, we successfully connected the Huawei P40 Pro and Samsung S22 to the 5G testbed. The UE establishes an internet connection via a core network function called User Plane Function (UPF), over a masqueraded GTP tunnel.

The 5G testbed is specifically configured to operate in 5G Standalone (SA) mode. However, it is worth noting that our testbed has also demonstrated the capability to operate in 5G Non-Standalone (NSA) mode, as described

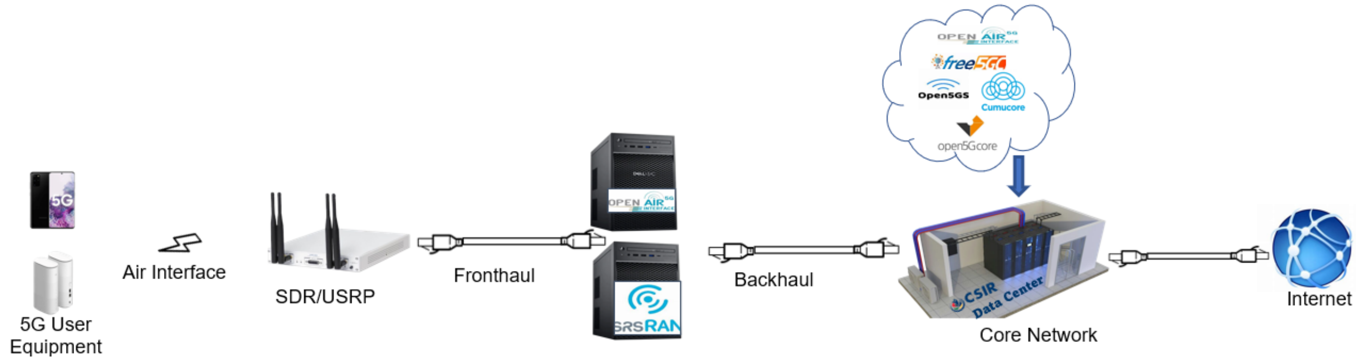

Fig. 1: Testbed Overview

in references [6] and [23]. In NSA mode, a combination of 4G Core Network (CN) and Radio Access Network (RAN) infrastructure is utilized alongside the 5G New Radio (NR) to achieve 5G network speeds. NSA mode is typically chosen when a network operator has a substantial 4G infrastructure and wants to leverage existing assets while gradually transitioning to 5G SA. However, 5G SA is essential to unlocking the full potential of 5G, particularly through advanced features such as network slicing, ultra-reliable low-latency connectivity (URLLC), and massive machine-type communications (mMTC).

III. Profiling the RAN Performance

Our 5G RAN profiling is divided into two categories: Air Interface profiling and gNB Compute Resource profiling. Air Interface profiling focuses on evaluating radio conditions for capacity planning, coverage optimization, resource allocation efficiency, quality of service assessment, and cost optimization. gNB Compute Resource profiling involves quantifying computing and networking resources such as CPU power, memory, storage, and NIC speed to determine the processing capacity of the gNB. This section provides an overview of the various parameters that need to be considered during RAN profiling.

A. Physical Site Survey

Site survey involves assessing the physical attributes of the testbed location. The following parameters are proposed for profiling:

- **Geographic location**: the location of the testbed, whether rural, peri-urban, or urban, is significant. Rural areas have minimal RF activity, resulting in less interference from existing wireless networks. This cleaner radio spectrum reduces the likelihood of interference, enabling improved network performance and more accurate testing of 5G technologies. In contrast, urban areas have a substantial presence of commercial 4G and 5G networks, making them susceptible to mutual interference.
- **Obstacles**: whether or not the RAN is deployed in an indoor or outdoor setting, it is important to note if there are any obstacles or radio equipment in the area that could impact signal propagation.
- **Network cable and connection condition**: it is important to assess the quality and integrity of the cables used, including weather-resistant cables for outdoor deployments, to maintain signal integrity and reliability.
- **Operating Temperature**: research grade SDR platforms typically have stringent temperature requirements (typically between 0° C and 25° C), which, if violated, could potentially lead to performance variation or even device malfunction.

Our 5G testbed is situated in an urban area with a significant presence of commercial 4G and 5G networks. It is located indoors, and we have assessed the condition of our network cables using an RF network analyzer. The testbed room is free of obstacles, which helps to improve signal strength by minimizing signal reflections, diffractions, and absorption. The temperature in the room is maintained at a fixed 24° C.

B. Signal-to-Noise-Plus-Interference Ratio (SNIR) Profiling

signal-to-noise-plus-interference ratio (SNIR) is a measure that compares the level of a desired signal to the level of unwanted background noise (such as the “noise floor”). SNR measurements in a 5G testbed environment are crucial for the following reasons:

- **Baseline assessment of RF conditions**: which helps in determining the noise floor and interference levels at the deployment location of the testbed. This assessment helps evaluate the severity and properties of the interference, enabling the development of potential strategies to mitigate it. These strategies may include adaptive power control, interference cancellation, or frequency hopping. It is important to note that a low (SNIR) can negatively impact network performance and result in higher error rates, leading to packet drops.
- **Frequency planning**: measuring the noise floor of the testbed radio environment helps in identifying and strategically selecting frequency bands with the least amount of interference, enabling the allocation of resources that reduce the risk of co-channel interference. In practice, this must also consider the spectrum

license obtained as this would define the choice of the frequency bands available for experimentation (unless the experiments are performed in a shielded environment, e.g. in a shielded box/Faraday cage or in an anechoic chamber).

- **Accurate benchmarking**: measuring the noise floor provides a reference point for accurate benchmarking and comparison of the testbed's performance against industry standards or other similar deployments. It helps in assessing the testbed under real-world conditions by considering the noise and interference levels that are typically present in commercial networks.

In our 5G testbed, we continuously monitor and measure RF parameters, including the noise floor, due to the generally unpredictable RF environment. To measure the noise floor, we used two methods: a spectrum analyzer and SNR reports from User Equipment (a 5G smartphone in our case). To calculate SNR, we relied on the Channel Quality Indicator (CQI) reported by the phone while connected to our 5G network, following the guidance of Abitha et al. [24]. We employed this dual approach to cross-validate the figures. Additionally, open-source software-based spectrum analyzers like gr-fosphor[25] can be used to analyze transmitted RF signals. It is crucial to perform SNR measurements at different times of the day and week, such as during business hours with high RF activity and off-peak hours with minimal RF activity. This helps capture variations in RF noise, identify interference sources, and understand occupancy changes.

C. Modulation and Coding Scheme (MCS)

The Modulation and Coding Scheme (MCS) determines the number of useful bits that can be transmitted per resource element in a 5G system. It depends on the signal-to-noise ratio (SNR) and its code ranges from 0 to 28, with a higher value indicating better radio conditions for transmitting more data. To estimate the radio channel quality, the gNB utilizes techniques such as pilot signals and feedback from the User Equipment (UE), such as Channel Quality Indicator (CQI) reports. Based on the estimated channel quality, the gNB refers to a predefined MCS table (specified in TS 138 214 [26]), which maps different modulation schemes (e.g., QPSK, 16-QAM, 64-QAM) and coding rates to various radio conditions. The gNB selects an appropriate MCS value based on the measured radio conditions and sends it to the UE. The UE adjusts its receiver parameters accordingly to align with the chosen MCS value. During a data transmission session, the gNB initiates communication using the selected MCS. The gNB continuously monitors the radio conditions and dynamically adjusts the MCS value based on the current radio conditions. This adaptive approach ensures optimal data transmission performance at any given time.

The OpenAirInterface RAN stack supports the adaptive Modulation and Coding Scheme (MCS) based on changing radio conditions. However, srsRAN lacks this capability and requires a manual configuration of the MCS by the network administrator. To select an appropriate MCS in srsRAN, the user needs to estimate the noise floor using a spectrum analyzer or CQI reports and consider the desired data rate and error rate. In our testbed, we used an MCS value of 10 (equivalent to 16QAM) for srsRAN during peak hours. In contrast, we relied on dynamic MCS adaptation for the OpenAirInterface testbed implementation. It is important to note that the volatility of the radio environment may result in a fixed MCS value being too low or too high for different times of the day.

D. Compute Resources

In the context of 5G, Network Function Virtualization (NFV) [27] and Software Defined Networking (SDN) [28] enable the deployment of the gNB (BBU) on Linux-based commodity servers, allowing it to run as a process. Due to the real-time nature of data transmission, it is crucial to have comprehensive visibility into the computing server that hosts the gNB logic. This involves analyzing and noting key compute resources such as CPU usage, memory (RAM) utilization, and disk I/O operations. Profiling these computing resources offers several benefits:

- **Performance optimization**: By profiling compute resources, areas within the gNB software architecture that require improvement can be identified based on resource consumption patterns.
- **Capacity planning**: Computing resource profiling enables estimation of the maximum number of concurrent UE connections and traffic volume that a gNB server can handle. This information aids in extrapolating the scalability and capacity of the gNB server to accommodate large traffic volumes.

In our testbed, we have deployed the gNB on a high-end server based on Intel® Core™ i9 with 18 cores, 64GB RAM, and 1TB storage. The 5G gNB requires more CPU, RAM, and storage resources compared to previous cellular technologies such as 4G. This is due to factors such as the complex signal processing algorithms involved in massive MIMO and the introduction of new protocols and network interfaces to support features like ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC).

Although this paper does not specifically assess the compute resource usage patterns of the gNB, we acknowledge the importance of such an analysis. Evaluating CPU and memory usage under various workloads and analyzing metrics like system calls made by the gNB process would provide insights into software design efficiency and compute bottlenecks. This aspect is considered for future work. However, we have already performed a load testing of 5G core networks to measure the usage patterns of compute resources [29].

E. Theoretical Throughput

We consider the theoretical throughput or channel capacity to represent the maximum achievable data rate in the uplink and downlink under ideal radio channel conditions, typically with a high signal-to-noise ratio (SNR) and the utilization of specific modulation and coding schemes (MCS). It hence serves as an upper limit for the data transmission capacity of a given network configuration. Various factors are considered when determining the theoretical throughput, including the channel bandwidth (such as options ranging from 5 MHz to 100 MHz in 5G), the selected MCS, the antenna configuration (Multiple Input Multiple Output (MIMO) or Single Input Single Output (SISO)), the number and distribution of cells, and other parameters. The theoretical throughput can be determined using 3GPP TS 38.306 or manually using this New Radio calculator [30].

To determine the theoretical throughput of our testbed, we selected an MCS value of 20. To determine this value, we monitored noise variation over a 24-hour period and calculated the average value. Our testbed is configured to SISO mode, and the channel bandwidth was set to 20 MHz, equivalent to 100 physical resource blocks. With this configuration, the theoretical throughput for the uplink and downlink was estimated to be 163.72 Mbps and 87.57 Mbps, respectively.

IV. Optimising the RAN Performance

This section delves into the optimization of various parameters to enhance the performance of the Radio Access Network (RAN). These parameters include sampling rates, signal-to-noise ratio (SNR), sleep modes and hibernation, CPU performance, antenna placement and orientation, gain settings, signal power, duplex modes, channel bandwidth, and more. However, it is important to note that optimization can only be carried out effectively after conducting a thorough profiling of the RAN system. Profiling provides accurate visibility into the baseline resource pool and physical parameters, enabling informed decision-making during the optimization process.

A. Site Planning

During the planning phase, the careful selection of the RAN site plays a crucial role in minimizing interference sources and optimizing coverage. Several factors should be taken into account, including line-of-sight obstructions, proximity to other transmitters, and potential interference-prone environments. In the case of a testbed scenario, it is recommended to deploy the RAN at a remote rural site. This choice offers certain advantages, as such locations often provide a shielded and stable radio environment. Such stable radio environment is particularly conducive for testing bandwidth-intensive use cases like Ultra High-Definition (UHD) video streaming, telehealth applications, and more. By selecting a remote rural site, a wider choice of bands may be available and he potential interference from other transmitters and environmental factors can be minimized, allowing for a more controlled testing environment.

B. Antenna Placement and Orientation

Proper antenna placement and orientation can significantly reduce interference and improve signal quality. To achieve this, antenna placement and orientation should be in such a way that obstructions and interference sources are minimized and that the signal strength and coverage radius are maximized. Beamforming and antenna tilting techniques can be employed to improve signal directivity and mitigate unwanted noise and interference. In our testbed, we placed the antennas perpendicular to each other to minimize cross-leakage from TX to RX, which can degrade signal quality. This arrangement is known as cross-polarization. When antennas are placed perpendicular to each other, they have orthogonal polarizations, helping to increase signal isolation and reduce self-interference.

C. Antenna Gain Settings

Different antennas (such as dipole antennas, patch antennas, or parabolic reflectors) have different gain characteristics. Antenna gain is specified for the transmitter (TX) and receiver (RX). Optimizing the gain settings is crucial for all networks, including testbeds. A higher antenna gain results in focusing the fields carrying the signals, which increases the signal strength. However, this happens at the expense of radiation in other directions and is most suitable in cases where the User Equipment is fixed at a certain location. Setting the gain too low can result in a weak or noisy received signal and, thus, errors and potential loss of connection. Setting the gain too high can lead to signal distortion or saturation. There is thus a need to select an antenna gain that provides adequate signal strength and coverage. It is important to note that optimizing the gain for a 5G testbed can be an iterative process that can require occasional adjustments based on factors such as test objectives, radio conditions, link budgets, and network load. Therefore, continuous monitoring, performance analysis, and fine-tuning of gain settings are necessary to ensure optimal RAN performance under varying network conditions.

In many RAN implementations, there is a need to maintain a balanced correlation between RX and TX gains to avoid imbalances that may cause performance issues. This means that the same adjustment made on the TX gain should also be made for the RX gain for consistent signal quality. In certain scenarios, independent gain control may be employed. This allows more flexibility in optimizing each signal flow direction independently. For example, RX gain can be adjusted to maximise the sensitivity of the RX channel to improve the received signal quality, while TX gain can be adjusted to optimise transmit power and coverage.

In our case, we chose to implement independent gain control and conducted iterative testing and measurement cycles due to the challenges we faced in establishing network connectivity with our 5G smartphones. In some instances, the UE was able to see the network, but experienced a weak signal strength. Through our iterative approach, we determined the optimal TX gain setting to be 32-35 dB, which improved coverage and transmit power. On the RX side, we encountered difficulties with mobile phone registration, as we were unable to trace the registration requests from the mobile phones on the network. To address this, we fine-tuned the RX gain until we successfully detected the registration requests. The suitable RX gain setting for our network was found to be between 36.5-37 dB. Ideally, it would be more efficient if our testbed incorporated feedback mechanisms and control loops to dynamically adjust the RX and TX gains based on the prevailing radio conditions. However, such capabilities are commonly found in certain RAN architectures, primarily in commercial systems, but were not available in the RAN software stack we implemented for our testbed. In the near future, we have plans to incorporate dynamic gain control into our testbed implementation. It is crucial to note that gain adjustments must adhere to the limit on the maximum allowed equivalent isotropic radiated power (EIRP) and/or other limits defined by regulatory requirements and standards in each jurisdiction. These guidelines effectively impose constraints on the maximum gain levels to ensure compliance and prevent interference with other systems. In practical scenarios, when utilizing USRP (which typically has an output of approximately 6-10 dBm), it is highly unlikely to approach the regulatory limit, which typically ranges from 54-64 dBm.

D. Signal Boosters/ Amplifiers

In a testbed deployment utilizing SDR (such as a USRP) radio heads, there are situations where the inclusion of an amplifier can be advantageous. For instance, when aiming for wider coverage in scenarios such as trials conducted in rural areas with a USRP, an amplifier can amplify the transmitter signal power, compensating for the typically low power output of a USRP. This enables longer-range transmission and improved coverage. Moreover, integrating an amplifier can help counteract cable losses that may occur when using long cables to connect external antennas, leading to improved overall performance. It is worth noting that amplifiers offer an extra level of customization, enabling system designers to fine-tune signal levels and tailor the testbed to specific application requirements or specialized use cases. It is essential to adhere to the regulatory limits when using an amplifier. At present, our indoor testbed does not incorporate a signal amplifier. However, we have designated this functionality for implementation on our outdoor testbed.

E. Frequency Planning

The next critical step involves measuring the noise floor to identify frequency bands with minimal interference. The goal is to select clean frequency bands that minimize the risk of co-channel interference. By choosing these clean bands, a 5G testbed can operate in a spectrum environment with reduced interference, resulting in enhanced signal quality and overall performance. This careful selection of frequency bands helps optimize the utilization of available resources and ensures optimal communication in the testbed.

F. Sampling rates

The sampling rate is the rate at which analog signals are sampled and transformed into digital values. A higher sampling rate means that more samples are taken per second, resulting in a more precise representation of the original analog signal. In our testbed, we configured the sampling rate at 23.04 for the B series USRPs and 30.72 for the X series USRPs. It is important to note that the chosen sampling rate depends on factors like the processing power of the gNB's server, software configuration, and the specific application in use.

G. CPU Performance Tuning

Running a gNB software for 5G involves handling intensive computational tasks, such as real-time signal processing, decoding, encoding, and scheduling, that require a responsive computing environment. To achieve this, the CPU's operating frequency and power management settings are adjusted in a way that prioritizes performance over power efficiency. In other words, in performance mode, the CPU clock speed is set to run at a higher frequency, allowing the processor to execute instructions and complete tasks more quickly. Power management settings such as CPU scaling and throttling, sleep states, and hibernation are disabled to meet the real-time computing requirements of the RAN. It is important to note that setting the CPU to performance mode can lead to higher heat generation. Thus, in performance mode, thermal management mechanisms such as dynamic voltage and frequency scaling (DVFS) and thermal throttling may be adjusted to provide adequate cooling and prevent the CPU from overheating. For a multi-core server, it is recommended to work with the cores and not Hyper-Threading. Enabling Hyper-Threading can lead to resource contention and increased scheduling overhead, which may negatively impact the performance of these compute-intensive tasks.

Unless absolutely needed, it is not recommended to run the gNB/BBU software in debug mode, especially during use case testing, as the debug mode generates a lot of disk I/O operations, impairing network performance. Instead, the debug mode can be activated when unknown errors are encountered. Last but not least, we recommend "optimising" the Linux server environment by uninstalling applications not needed to run the gNB/BBU software and disabling auto-updates.

H. Other Optimisation Strategies

- **Channel Bandwidth**: 5G allows for channel bandwidth up to 100 MHz and flexible subcarrier spacing up to 12 kHz. Utilizing higher bandwidth and subcarrier spacing can optimize network performance and capacity depending on the uplink and downlink frequencies and the USRP model used.
- **Antenna configurations**: deploying advanced antenna systems like MIMO or beamforming can enhance signal quality, increase capacity, and mitigate interference.
- **Signal Filtering and Equalization**: implementing signal filtering and equalization techniques can help mitigate noise and interference. These techniques involve using filters and equalizers to suppress unwanted signals.

- **Cooling Systems**: maintaining an acceptable operating temperature in the deployed RAN area is important to ensure optimal performance and reliability.
- **RF enclosures**: using shielded RF enclosures, such as Faraday cages, can create a controlled and noise-free radio environment. This is particularly useful for testing scenarios involving the Core Network or when a 5G R&D spectrum license is not available.

V. Results and Discussion

Figure 2, 3, 4, and 5 provide a visual representation of the measured results for different measurement cycles, highlighting the impact of antenna gain optimization, antenna orientation, and streaming scenarios on channel quality and other relevant metrics. In particular, Figure 2 illustrates the results obtained when no gain optimization was applied, and the antennas were parallel to each other. In this configuration, the Channel Quality Indicator (CQI) reported by the User Equipment (UE) was mostly 9, but in some instances, it was reported as "N/A." The "N/A CQI" indicates that the UE could not accurately determine the channel quality due to weak, corrupted, or severely interfered received signals, making it challenging to provide a reliable CQI measurement. Figure 3 demonstrates a slight improvement in channel quality when the orientation of the antennas was adjusted to be at 90 degrees to each other and placed 2 meters apart. Figure 4 showcases the excellent signal quality achieved when both gain optimization and antenna orientation were optimized. Lastly, Figure 5 displays the results obtained during the streaming of UHD video from YouTube. The metrics shown on the signal trace include the Signal-to-Interference-plus-Noise Ratio (SNR) on the uplink channel (PUSCH), bit rate (brate) in bits per second, percentage packet drops (%), buffer status report (bsr) indicating the amount of data waiting to be transmitted as reported by the UE (in bytes), the number of packets successfully sent (ok), the number of packets dropped (nok), the physical cell identifier (pci), and the identifier used to identify the UE (rnti). In all of our tests, the UE remained stationary at a distance of 5 meters from the RAN.

```
             -------------DL----------------|-------------------UL---------------------
pci rnti  cqi  mcs  brate   ok  nok  (%) | pusch  mcs  brate   ok  nok  (%)     bsr
  1 4601    9    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601    9    0      0    0    0   0% | -22.6    0    16k    0    5   0%     0.0
  1 4601    9    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601    9    0      0    0    0   0% | -22.9    0    31k    0   10   0%     0.0
  1 4601    9    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601    9    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601  n/a    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601  n/a    0      0    0    0   0% | -23.8    0    16k    0    5   0%     0.0
  1 4601  n/a    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601  n/a    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601  n/a    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
```

Fig. 2: Signal trace under low TX/RX gain and parallel antenna orientation

```
             -------------DL----------------|-------------------UL---------------------
pci rnti  cqi  mcs  brate   ok  nok  (%) | pusch  mcs  brate   ok  nok  (%)     bsr
  1 4601   12   22   6.5k    0    1 100% |   n/a    0      0    0    0   0%     0.0
  1 4601   12    0      0    0    0   0% | -22.1    0    16k    0    5   0%     0.0
  1 4601   12    0      0    0    0   0% | -21.9    0    16k    0    5   0%     0.0
  1 4601   12    0      0    0    0   0% | -21.0    0    16k    0    5   0%     0.0
  1 4601   12    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601   12    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601   12    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601   12   22   2.2k    0    0   0% |   n/a    0      0    0    0   0%     0.0
  1 4601    5   22   2.2k    0    0   0% | -21.6    0    16k    0    5   0%     0.0
  1 4601   11    6   1.9k    0    5 100% | -24.6    0    16k    0    5   0%     0.0
  1 4601   11    0      0    0    0   0% |   n/a    0      0    0    0   0%     0.0
```

Fig. 3: Signal trace under low TX/RX gain and perpendicular antenna orientation

```
             -------------DL----------------|-------------------UL---------------------
pci rnti  cqi  mcs  brate   ok  nok  (%) | pusch  mcs  brate   ok  nok  (%)     bsr
  1 4602   15   28    27k    6    1  14% |  27.6   28   419k   15    0   0%     0.0
  1 4602   15   28   5.9k    4    1  20% |  24.5   28   1.1M   28    0   0%     0.0
  1 4602   15   28   2.4k    1    1  50% |  32.6   28   8.7k    2    0   0%     0.0
  1 4602   15   28   1.2k    1    0   0% |  32.0   28   4.4k    1    0   0%     0.0
  1 4602   15   28   3.0k    2    1  33% |  31.5   28   8.7k    2    0   0%     0.0
  1 4602   15   28   2.4k    1    1  50% |  31.7   28   4.4k    1    0   0%     0.0
  1 4602   15   28   2.4k    1    1  50% |  31.3   28   4.4k    1    0   0%     0.0
  1 4602   15   28   1.2k    1    0   0% |  33.1   28   4.4k    1    0   0%     0.0
  1 4602   15   28   2.4k    1    1  50% |  31.2   28   4.4k    1    0   0%     0.0
```

Fig. 4: Signal trace under optimal TX/RX gain and perpendicular antenna orientation

```
             -------------DL----------------|-------------------UL---------------------
 pci rnti  cqi  mcs  brate   ok  nok  (%) | pusch  mcs  brate   ok  nok  (%)     bsr
   1 4602   15   26    37M  924    9   0% |  33.4   27   774k  173    2   1%   1.04k
Late: 26; Underflow: 1; Overflow: 0;
   1 4602   15   28    30M  920   13   1% |  33.3   27   743k  163    2   1%     535
Late: 26; Underflow: 1; Overflow: 0;
   1 4602   15   25    23M  897   16   1% |  33.5   27   625k  172    4   2%     384
Late: 26; Underflow: 1; Overflow: 0;
   1 4602   15   28    17M  485   13   2% |  32.9   27   594k  126    2   1%     142
Late: 39; Underflow: 1; Overflow: 0;
   1 4602   15   28    14M  309    7   2% |  33.8   27   459k  148    0   0%     745
Late: 13; Underflow: 1; Overflow: 0;
   1 4602   15   28    13M  364    9   2% |  33.5   27   526k  160    0   0%     535
Late: 0; Underflow: 1; Overflow: 0;
   1 4602   15   26    19M  856   24   2% |  33.7   27   543k  163    0   0%     535
Late: 13; Underflow: 1; Overflow: 0;
   1 4602   15   28    20M  808   16   1% |  32.1   26   572k  232    6   2%     384
Late: 52; Underflow: 1; Overflow: 0;
   1 4602   15   25    20M  869   12   1% |  32.4   27   575k  143    3   2%     745
Late: 39; Underflow: 1; Overflow: 0;
   1 4602   15   28    21M  774   19   2% |  33.5   28   599k  133    0   0%     535
   1 4602   15   28    21M  790    9   1% |  33.0   28   603k  120    0   0%     745
```

Fig. 5: Signal trace under optimal TX/RX gain and perpendicular antenna orientation (UHD Youtube video streaming use case)

VI. Conclusion

When setting up a 5G testbed, it is essential to follow best practices similar to those used in commercial networks. This involves conducting a comprehensive profiling of the Radio Access Network (RAN) environment to understand internal and external factors and resources. The profiling process includes evaluating sources of interference, obstacles, RF device placement, orientation, and computing resources. The insights gained from this profiling are crucial to optimize network performance. This paper serves as a guide, outlining the essential elements of the 5G RAN in the context of a testbed, which should be considered during profiling and optimization. Our experimental results demonstrate that optimizing parameters such as gain, CPU performance, and antenna configuration can greatly enhance the stability and fidelity of the air interface.

Moving forward, our future plans involve integrating and evaluating the impact of RF signal amplifiers on network performance in an outdoor setup. Additionally, we intend to utilize signal filtering and equalization techniques to effectively manage the Signal-to-Noise Ratio (SNR).

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