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Design Considerations and Deployment Challenges for TurboRAN 5G and Beyond Testbed

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ABSTRACT Prior to standardization, new features, algorithms, and solutions have to be rigorously evaluated and verified using different methods. In this regard, testbeds are considered as one of the most important and effective experimental platforms for performing tests, thus paving the way towards the real-world implementation of many solutions, from the most basic to the most disruptive and innovative ones. Compared to computer simulators, testbeds provide near-realistic implementation and can obtain practical results while posing less risk to live networks. They are also cheaper compared to field trials. Given the crucial role of testbeds in the cellular network ecosystem, it is imperative to create awareness regarding the design challenges associated with constructing an effective and efficient testbed deployment. In this work, we discuss the design considerations and challenges we experienced while deploying an outdoor testbed that we call TurboRAN—a 5G and beyond network testbed facility. It is designed to facilitate the evaluation of early real-world use case algorithm implementations and deployments. We present the process and methodology used to select components, including antennas, amplifiers, base stations, and cabinets, to name a few, and describe the integration of the components to construct a fully operational testbed. Finally, we discuss a use case that demonstrates the TurboRAN's ability to conduct real-world experiments. The use case demonstrates the detrimental impact of sub-optimal handover parameter configuration on network performance—a big challenge in modern cellular communication. This work intends to inspire and guide the development of a cellular testbed by providing a generalized framework that describes step-by-step the efforts made for its construction.

INDEX TERMS TurboRAN, 5G and beyond testbed, testbed deployment consideration, testbed deployment challenges

I. INTRODUCTION

Every proposed solution towards the advancement of cellular technology such as 5G and beyond (5G&B) must go through rigorous testing using various methods before real-world deployment on the live network. For instance, the academic research community relies on analytical models to gain performance insights into proposed solutions under various network deployment scenarios [1]–[3]. To be able to be used, these models make a lot of assumptions, restrictions, and sometimes oversimplifications. To attain tractability, these models use numerous assumptions, restrictions, and oftentimes oversimplifications that limit the capability of these mathematical models to capture the holistic view of cellular network functions.

Due to these shortcomings, the investigation of complex systems, including cellular networks, is challenging to completely examine by tractable analytical analysis. Many network simulators have been developed to overcome the limits of analytical modeling methods. However, most of the existing simulators lack complete system realization or may require excessive computational power [4]. Meanwhile, the more practical cellular network experimentation in the form of field trials is reserved exclusively for the network operators with large research and development (R&D) funds

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as conducting field trials on a large scale is time-consuming and expensive. The same is true for high fidelity realistic network simulators such as Atoll [5], which come with hefty licensing fees that only large operators can afford. Therefore, historically, the academic research community in wireless networks has been more focused only on performing theoretical analysis.

Given the aforementioned challenges in evaluating novel solutions for emerging cellular networks, there is an increasing trend to leverage testbeds by the research community. Testbeds allow R&D before the actual network deployment, which is challenging to achieve using other methods identified above, such as analytical modeling, simulators, or experimentation on live commercial networks. Today, many companies offer off-the-shelve testbed solutions, e.g., 5G R&D Testbed by Keysight Technologies, Anritsu, and National Instrument, which enable accelerated R&D. However, these testbeds are experiment-specific and offer experimentation mostly on the physical layer and mac layer and, hence, do not offer enough flexibility for system-level R&D. To cope with this challenge, one option is to use software-defined radio (SDR) in conjunction with the readily available front-end hardware. In this way, most of the processing can be performed in software, while hardware limitations apply only to the front ends. In the literature, several types of testbeds have exercised this deployment approach while being used for different types of experiments [6]–[8]. These testbeds vary from single black boxes to complex distributed systems deployed over large areas. Regardless of the testbed type, the proper understanding of the design and deployment process is critical [9] for the testbed designers as well as the users. This is especially true while deploying or using large-scale testbeds which are more challenging than deploying small-scale indoor ones.

Large-scale testbed design and deployment involve complex steps such as network layout and site design (e.g., coverage and capacity planning), selecting the appropriate hardware components (e.g., antennas, cables, amplifiers, cabinets, etc.), and software application [10]–[12]. While literature on specific functions or capabilities designed in a testbed exists, such as [13], [14], no existing work offers a step-by-step guide for an over-the-air testbed implementation. The design and deployment of a virtualized testbed were presented in [13] while authors in [14] shared their experience developing a prototype virtualized 5G testbed. These papers are centered on the design architecture and prototyping of one feature, i.e., Network Function Virtualization (NFV) only. Furthermore, the focus of both [13], [14] is to highlight the testbeds' supported use cases, and not to provide insights into their design and deployment process.

Testbed deployment can be a complex and time-consuming process involving many cascaded design procedures, feasibility studies, and making multi-faceted trade-offs through datasheet-driven and budget-constrained equipment selection decisions. It requires proper planning and insights to guide the design and deployment. Some information on the inventory and final design of testbeds can be gained from the websites of the currently available testbeds such as those presented in [15]–[18]. However, because these websites are focused on highlighting the capabilities of respective testbeds, the information supplied by these sources has very limited utility in guiding the design and deployment of a new over-the-air testbed. To the best of the authors' knowledge, there is currently no paper that describes end-to-end over-the-air testbed deployment from planning, equipment selection, installation, and testing. This paper is the first attempt to bridge this gap.

In this work, we discuss the design considerations and challenges one might face while deploying an outdoor 5G&B system-level testbed. In particular, we present our hands-on experience of designing, planning, and deploying a 5G&B testbed called TurboRAN: Testbed for Ultra-Dense-Multi-Band Control and Data Plane Split Radio Access Networks of the Future. TurboRAN is built using SDR-based 5G base stations also known as gNodeB (gNB). Deploying such a testbed for indoor experimentation or a limited outdoor setup is relatively straightforward. However, configuring it in an outdoor setup to cover a wide area with continued over-the-air coverage to enable system-level solution testing is quite challenging [19], [20]. Therefore, this paper can be used as a reference for designing and deploying a practical 5G&B testbed and, at the same time, provide insights into the utility of such testbeds.

A. CONTRIBUTIONS AND ORGANIZATION

The contributions of this paper can be summarized as follows:

- First, we present a summary of the currently available 5G&B testbeds around the world. This summary provides key information about several testbeds, including the deployment and access type. Moreover, we provide a discussion and highlight their key features, capabilities, and the different experiments they support. Although non-exhaustive, the presentation of several testbeds creates awareness for the readers regarding the current and emerging platforms that can be leveraged for the specific field of research.
- We then discuss the planning and design considerations when deploying a system-level testbed based on our hands-on experience of working on the TurboRAN testbed installation. This detailed discussion is focused on the aspects of testbed deployment, including link-budget, cell planning, selection of base stations, antennas, feeders, amplifiers, enclosures, and cooling systems among others.
- Finally, we show some preliminary results from our deployed TurboRAN testbed. This use case highlights the capabilities of the TurboRAN to support experiments on system-level problems such as mobility management. In the absence of over-the-air system-level multi-cell testbeds, this type of experiment would not be possible. Such experiments cannot be performed in a real network

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without causing service degradation. Results from the use case also shed light on the detrimental impact of sub-optimal handover parameter configuration and thus highlight the potential of testbeds to assist in the development of system-level optimization solutions otherwise difficult to investigate problems such as mobility management.

The rest of this paper is organized as follows: In Section II we present some of the current and emerging 5G testbeds. In Section III we present a high-level overview of the TurboRAN testbed, followed by the discussion of the deployment design and planning considerations. Meanwhile, Section IV presents a case study regarding mobility-based inter-frequency handover, and Section V concludes the paper.

II. TESTBEDS FOR 5G AND BEYOND CELLULAR NETWORKS

The Third Generation Partnership Project (3GPP) has already completed the initial phase standardization of 5G and Phase I of 5G is already being deployed. The standard will keep evolving and the updates will be reflected in the new release. To support this evolution, it is important to investigate new features proposed by the research community and industrial partners. To avoid the risk of performance degradation when performing tests on real networks, testbeds are used as a practical solution. Testbeds are designed to function in the same manner as a real network but on a smaller scale. This means that, at least in theory, testbeds are capable of executing almost all the necessary functions of a real network such as downlink, uplink, handovers, resource allocation, and scheduling to name a few. Testbeds offer the freedom of experimenting with different scenarios and can also provide open access to the data generated from these experiments without privacy concerns. Given the importance of testbeds, it is imperative to create awareness regarding the existing testbeds the research community can utilize. In this section, we discuss different types of 5G testbeds that are available for different purposes.

There exist several ways to classify testbeds including the size of deployment (e.g., indoor, outdoor small-scale, city-scale) and type of access (e.g., open or proprietary). Another way of classification is by using the different layers of the OSI model. Based on these classifications, the research community divides the testing of wireless systems into two main levels: link-level and system-level. The link-level testing is related to the physical layer (PHY) as well as some functionalities of the medium access control layer (MAC) and involves channel estimation, channel coding, rate matching, multicarrier modulation, and feedback techniques, to name a few [21], [22]. In contrast, system-level testing takes care of upper layers and focuses on system-level multi-cell operations such as handover, interference management, admission control, link adaptation, power control, and resource scheduling and allocation among others [23].

Several wireless testbeds have recently been established around the world to aid research on future cellular networks. Most prominent among these include the 5GIC [24], Ericsson's 5G Testbed [25], 5TONIC [26], FOKUS [27], NITOS [28] and SK Telecom 5G Playground [29]. Table 1 summarizes the present and emerging 5G and beyond network testbeds around the world. Among these, testbeds that are truly focused on system-level research aspects of the next-generation mobile networks primarily exist in Europe and Asia (i.e., [24]–[33]). The 5GIC testbed at the University of Surrey in the United Kingdom is one of the deployed testbeds closest to a real network. It is comprised of a full-fledged Long-Term Evolution (LTE)-based cellular network spread over four square kilometers. However, the utility of this testbed is bounded by two factors: 1) Cost—platinum level access is required to conduct the proposed research which is advertised at a membership fee of £600K per year or over $1M per year [34]; and 2) A commercial vendor administers and manages the testbed equipment with proprietary application programming interfaces (APIs) limiting its flexibility and programmability. As a result, academic researchers are unable to experiment on network characteristics directly and readily. Instead, they must rely on the equipment manufacturer to configure experimental parameters.

In the United States, there is a small number of open-access 5G testbeds. These include Cognitive Radio Network Test (CORNET) at Virginia Tech [15], AERPAW deployed in North Carolina State University [16], and 2 testbeds namely POWDER and PhantomNet located at the University of Utah [17], [18]. CORNET, as the name suggests, is mainly aimed to conduct experiments related to opportunistic spectrum access in the context of cognitive radio networks. The nodes in CORNET can be linked through a sophisticated channel emulator RFnest. Notably, the CORNET community wireless testbeds primarily feature programmable PHY and MAC layers and do not have the end-to-end, multi-cell programmable cellular network capabilities needed to conduct research on the themes identified in Table 2.

PhantomNet is a testbed dedicated to support 3GPP-compliant cellular network research [17]. This testbed offers emulation capabilities of eNodeB and user equipment (UE). It also has the ability to support software defined network (SDN)-related studies, making it a good platform for LTE core network exploration. It also includes Access Points and UEs based on Universal Software Radio Peripheral (USRP) to facilitate PHY layer research. However, PhantomNet is not based on actual cellular deployment. Instead of using a true air interface, PhantomNet connects RF devices (UEs and eNodeBs) using a custom-built RF attenuation matrix. On the other hand, POWDER [18], a city-wide testbed based at the University of Utah, is designed to do large-scale evaluations on SDNs and massive MIMO. Finally, AERPAW [16] is a one-of-a-kind testbed designed to investigate 5G network applications related to unmanned aerial vehicle (UAV).

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TABLE 1: 5G network testbeds around the world.

5G Network Testbed	Location	Scale of Deployment	Access	Key Features and Supported Experiments
5GIC [24]	ICS, University of Surrey, Guildford, UK	University-wide	Close	IoT, broadband mobile radio, mmWave, satellite backhauling
5GUK Test Network [30]	University of Bristol, UK	City-scale	Not Specified	mmWave, network function virtualization (NFV), massive MIMO, massive IoT, network slicing
5TONIC [26]	Madrid, Spain	Indoor	Open	Network function virtualization (NFV)
Aalto 5G network [31]	Otaniemi, Espoo, Finland	University-wide	Open	NB-IoT, network slicing, mobile and edge computing, VR/AR, gaming, industrial Internet
AERPAW [16]	North Carolina State University, USA	City-scale	Open	UAV, mobility
CORNET [15]	Virginia Tech University, USA	Indoor	Open	Cognitive radio techniques, software-defined radio (SDR), dynamic spectrum access technologies
COSMOS [10]	West Harlem (New York City), USA	City-scale	Open	mmWave, distributed edge cloud, backhaul research
Ericsson 5G [25]	Ericsson, Stockholm, Sweden	City-scale	Close	5G-LTE dual connectivity, distributed MIMO, mmWave, massive MIMO
FOKUS [27]	Fraunhofer FOKUS and TU Berlin campus, Germany	University-wide	Open	Network slicing, URLLC, IoT
LuMaMi [32]	Lund University, Sweden	Mobile Base Station	Open	Massive MIMO
NITOS [28]	University of Thessaly (UTH), Volos, Greece	City-scale	Open	Mobility, mmWave, cloud computing
PhantomNet [17]	University of Utah, USA	University-wide	Open	Mobility, D2D, eMBB, URLLC, NB-IoT
POWDER [18]	University of Utah Campus, USA	City-scale	Open	Software-defined networks (SDN), massive MIMO
SK Telecom 5G Playground [29]	SK Telecom R&D Center, Bundang, Korea	Not Specified	Close	3D beamforming, massive MIMO, 4K live broadcast system and AR/VR
TitanMIMO-6 [33]	Nutaq, Québec, Canada	Indoor	Not Specified	Massive MIMO
TurboRAN	**University of Oklahoma, Tulsa, USA**	**University-wide & Indoor**	**Open***	**Refer to Table 2**

* TurboRAN testbed does not have a remote access interface at the moment. However, it is open to be used by community via physical visit or remote collaborative experimentation.

TABLE 2: A summary of cellular system research areas supported by TurboRAN.

Ultra-Dense Multi-Tier, Multi-Band Networks (UDMN)	
1	User centric RRM, advanced interference management schemes*
2	Advanced Small Cells/ Multi-tier Heterogeneous networks*
Highly Flexible Architectures: Network Orchestration	
3	Artificial Intelligence (AI)-based System-level Automation*
4	Context Aware RAN/ Proactive-SON (P-SON)*
5	Software RAN/Control and Data Plane Split Architecture*
6	Database-Aided Control and Data Split Architecture (D-MUD)*
7	Operation on Unlicensed Bands*
8	Radio Access Network (RAN) Sharing*
9	Network Function Virtualization**
10	Moving Networks**
Large Scale Machine-to-Machine (M2M) Communications	
11	Advanced Multiple Access Schemes*
12	Device-to-Device Communication (D2D)*
13	Very low power consumption operation modes (IoT)*
PHY Focused Technologies	
14	System-level performance (capacity, EE, QoS) evaluation of mmWave**
15	System-level performance evaluation with new waveforms**

* Indicates a research topic that is fully supported.
** Indicates partially supported research areas but will eventually be captured with future upgrades and expansions.

III. TURBORAN OVERVIEW, DESIGN, AND PLANNING CONSIDERATIONS

In this section, we present the TurboRAN testbed by providing an overview of its deployment design, key components, and architecture. We present a summary of the steps considered for equipment related design choices and considerations as shown in Fig. 1. We then discuss in detail the design strategy, planning considerations, as well as the challenges we encountered during the deployment phase of TurboRAN.

A. TURBORAN OVERVIEW

TurboRAN is an end-to-end 5G&B network testbed facility designed to facilitate the evaluation of early real-world use case deployment. Unlike many 5G testbeds that allow experiments on the physical, link, and MAC layers only TurboRAN is designed to enable system-level research on the next-generation mobile network as identified in Table 2. Located at the University of Oklahoma (OU)-Tulsa campus and managed by AI4Networks Research Center [35], TurboRAN is a university-wide mobile cellular network with a combined indoor and outdoor cell deployment that covers a 300,000 m^2 area. TurboRAN's BS density deployment translates to roughly 57 BS/km^2 with 17 distinct cell sectors, which is in line with the predicted 5G BS density of 40-50 BS/km^2 [36]. Fig. 2 provides a schematic of the TurboRAN

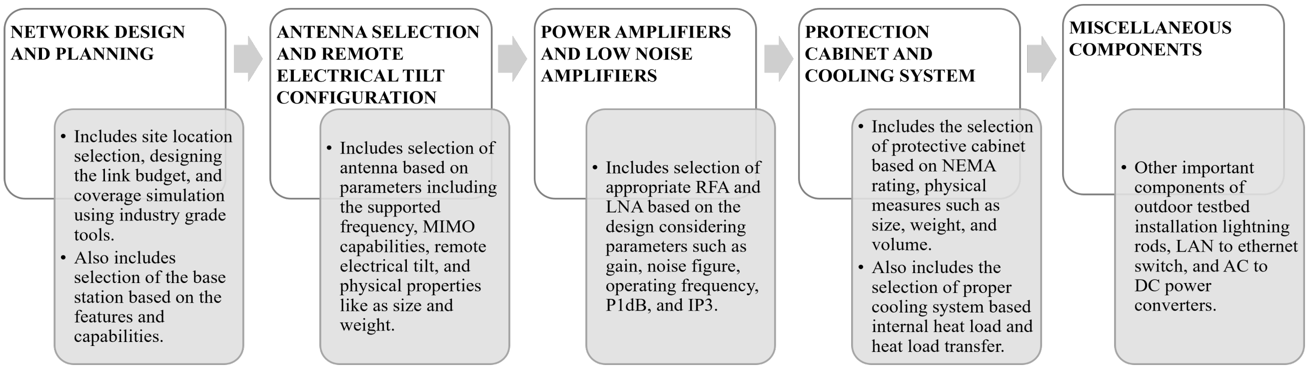

FIGURE 1: Summary of the steps considered for equipment related design choices and considerations.

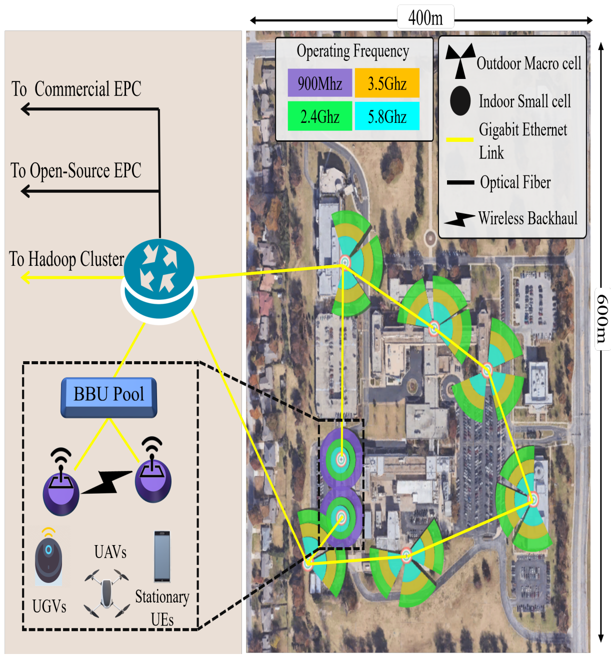

FIGURE 2: TurboRAN deployment illustration.

network design. The outdoor environment contains roads, pedestrian areas, lawns, trees, and parking lots, representing a typical suburban area. The outdoor cell deployment has 6 microcells, each covering the portions of the campus outdoor area. TurboRAN cells operate in the unlicensed bands below 6 GHz — including ISM – 915.0 ± 13 MHz, ISM – 2450.0 ± 50 MHz, and ISM – 5.8 ± 0.075 GHz, as summarized in Table 3. Since these bands lie close to the cellular bands of 800 MHz, 2500 MHZ, and the 5G bands in 5 GHz, results generated by TurboRAN can be applicable to commercial bands. In the near future, TurboRAN will also operate in Citizens Broadband Radio Service (CBRS) 3.5 GHz, upon obtaining an experimental license, in addition to planned mmWave band operation.

Each cell of the TurboRAN has 4 antenna elements forming an array for MIMO and 3D beamforming capabilities. Cell radii in all cells are adjustable through adaptation of the transmit power and antenna tilts. Precisely controlled mobility in the indoor and outdoor can be achieved using unmanned ground vehicles (UGVs) and UAVs, respectively. The TurboRAN testbed has commercial and open source 5G Core (5GCs)/EPCs. As another distinct feature, the testbed incorporates a Hadoop cluster for big data processing. This cluster is connected to 5GCs and EPCs, as well as access points (APs) for applying machine-learning algorithms, allowing for zero-touch automation and proactive self-organizing network (P-SON) functionalities. High-capacity optical fiber cables connect the cells to the 5GCs/EPCs and large data processing cluster, allowing for data rates of up to 10 Gbps.

TABLE 3: ISM frequency bands supported by TurboRAN.

Frequency Range	Bandwidth	Center Frequency
902 - 928 MHz	26 MHz	915 MHz
2400 - 2500 MHz	100 MHz	2450 MHz
5725 - 5875 MHz	150 MHz	5800 MHz

B. NETWORK DESIGN AND PLANNING

In each of the TurboRAN outdoor and indoor tiers, an AP consists of three main components: antennas, a software-defined radio (SDR), and a computer node to host the open source LTE and 5G protocol stack. An extensive survey of a large number of the SDRs, compute nodes, antennas, chassis, connecting mediums, and open source stacks have been conducted to select the optimal available components to build the APs that meet TurboRAN requirements for each of its planned tiers. While selecting hardware for APs, we also conducted a survey of all potential vendors (e.g., Ettus, NI, Texas Instrument, PRISMTECH, Nuand, AVENET, EPIQ, Sidekiq, Hack RF blue, Nutaq, BeeCube) with the following considerations: 1) cost; 2) bandwidth of the channel; 3) frequency range; 4) MIMO support; 5) clock speed; 6) GPS-based precise clock synchronization; 7) ease of programmability; 8) maximum output power; 9) 10 Gbps high-speed connectivity, and; 10) compatibility with programming languages of the open source stacks.

Fig. 3 shows the high-level block diagram used for TurboRAN deployment. This block diagram shows the main components of TurboRAN including base stations, amplifiers, Remote Electrical Tilt (RET) controller, switch, cabin, cooling, and antenna system. Additionally, this block diagram

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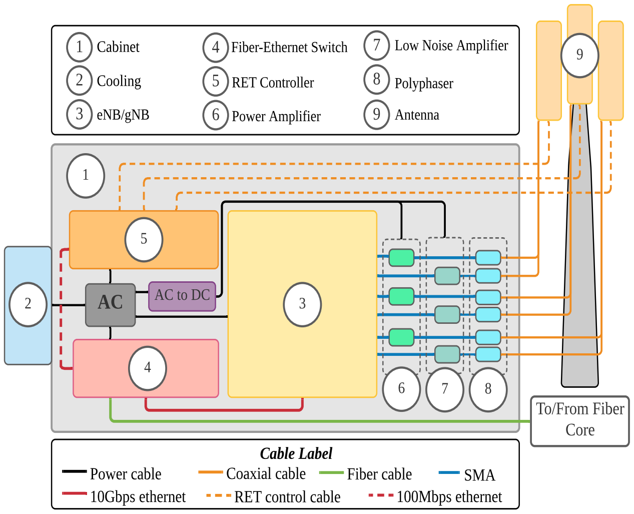

FIGURE 3: Block diagram representation of the TurboRAN testbed deployment.

shows the connection between the different components as well as the types of cables used in the deployment. The protective cabin shown in 1 encloses the majority of the equipment. To maintain the temperature inside this cabinet, a cooling system shown as 2 is used. Labeled 3 in the figure is the main equipment composed of SDRs and 3GPP compliant software to act as the base station. To connect it to the Internet and other base stations via fiber, a fiber-ethernet switch is exploited as shown in 4. The SDRs of the callbox are connected to the amplifiers using SMA cables. More specifically, the transmitter is connected to RF power amplifiers (PA) 6 while the receive side is connected to low noise amplifiers (LNA) 7. Before terminating the coaxial cables to the antenna 9, a surge protector is inserted to protect the base stations against lightning strikes. Finally, Finally, to regulate the tilt adjustment remotely, a RET controller 5 is attached to the antenna through a RET controller cable. Most of the components use an AC power supply except for the amplifiers which need DC. For amplifiers, we use AC to DC converter.

1) Network Planning

Network planning is one of the most critical parts of testbed deployment. At a high-level viewpoint, network planning involves processes such as base station location selection, link-budget analysis, and coverage simulation including transmit power, tilt, and azimuth optimization.

In selecting the base station location, we considered several factors. First, the location should be easily accessible not only to avoid any problem during the installation and maintenance but also for manual reconfiguration of the site if needed for future experiments. Second, the availability of facilities such as power source and fiber connectivity has certain merits like reduced efforts for setup, and cost-effectiveness. We identify 6 outdoor and 2 indoor locations that are ideal to deploy TurboRAN core sites as shown in Fig 2. After determining the site locations, the next logical step is to conduct a link-budget analysis, which entails determining the gains and losses experienced by the communication signal as it travels from the transmitter to the receiver. The link-budget ensures that data is transmitted intelligibly with a reasonable signal-to-noise ratio. Finally, the validation process is performed by leveraging tools such as network simulators that are built for coverage calculations. We use Atoll [5], a ray-tracing based industry leading radio network planning software, to generate a practical coverage map for TurboRAN deployment. TurboRAN's coverage simulations take into account important environmental characteristics as geography, clutter type, building heights, and vegetation. Moreover, we leverage the automatic cell planning (ACP) feature of Atoll to optimize the critical base station parameters (tilt and azimuth). Fig. 4 shows the Reference Signal Received Power (RSRP) plot after performing the tilt and azimuth optimization process.

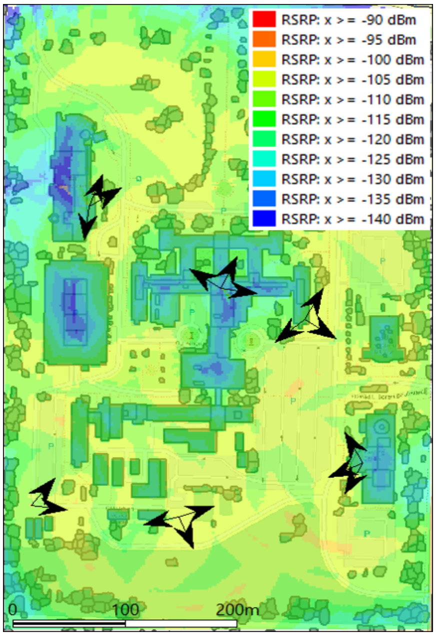

FIGURE 4: Optimized RSRP simulations using Atoll.

2) Base Stations

Though the core network and antenna system are vital components, the base station is still considered as the heart of the testbed. This is primarily because of the base station software support and the hardware capabilities that dictate the use-cases we can perform in our deployed testbed. In choosing a base station for TurboRAN, the availability, affordability, and functionality of software that supports 4G and 5G protocol stacks are among the most important factors to take into account. Often time, open source software provides more freedom compared to close source or proprietary software with regards to configuring different test scenarios. Similarly, the intended coverage of the network (i.e., indoor or outdoor) and the type of base station (i.e., macro cell or micro cell), are also integral parts of the selection process. Support for 3GPP standard features including MIMO, carrier

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aggregation, multi-technology connection, and mobility or handover should also be considered. The feature selection of the SDR that comes along with the base station is also another key consideration aspect for the base station selection. Features including downlink (DL) and uplink (UL) antenna ports count, maximum radiated power, maximum allowable bandwidth, and operating frequencies, should be considered. Lastly, software support, troubleshooting, and upgrades are also important. Table 4 shows the comparison between some of the 5G base stations we considered for TurboRAN. Among other solution providers, we shortlisted the three most suitable options including Anritsu MT8000A [37], Ixia Keysight [38], and Amarisoft Callbox [39]. Anritsu MT8000A offers a wide range of features such as 5G standalone (SA) RAN, 5G core, and support for mmWave. However, most of these functions and features need to be purchased individually which makes this option uneconomical and complicated to handle. Furthermore, MT8000A only supports tests and analysis of Layers 1 and 2, limiting the experimentation that can be performed. Meanwhile, Ixia Keysight has most of the vital features already included in the standard package. However, it does not support mmWave and does not include 5GC implementation.

For a testbed capable of testing various innovative AI-based zero-touch automation solutions and Self-Organizing Network (SON) solutions, there is a need for a base station with flexible software support. For this reason, we chose the Amarisoft CallBox series equipment for TurboRAN [40]. Amarisoft Callbox is a 3GPP-compliant base station and core network that can be used for functional and performance testing. It is powered by a deployment-ready software suite that allows modification for additional flexibility and experimentation. We determine Amarisoft Callbox to be the best solution for TurboRAN because of its vast range of supported technologies and functions.

We use two different series of the Amarisot Callbox namely Amarisoft Callbox Pro and Callbox Classic. Table 5 summarizes the key features of Amarisoft Callbox Pro and Classic. Amarisoft Callbox works with a variety of networks, including 5G Standalone (SA), 5G Non-Standalone (NSA), LTE, and NB-IoT. The 4G and 5G implementations are compliant with 3GPP-release 14 and 15, respectively. In comparison to other alternatives, EPC implementation is combined with 3GPP-compliant 5GC. It supports both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) modes of transmission, with a supported frequency band of 500 MHz to 6 GHz along with the bandwidth of 200 kHz to 56 MHz, and the maximum downlink and uplink throughput reported are 1200 Mbps and 150 Mbps, respectively. Further, it can support up to 6 SDRs for Amarisoft Callbox Pro and 3 SDRs for Amarisoft Callbox Classic, offering support for up to 1000 active UEs distributed within one cell.

C. ANTENNA SELECTION AND REMOTE ELECTRICAL TILT CONFIGURATION

In addition to base station selection, one of the most challenging tasks for an over-the-air testbed deployment is the choice of the best antenna. Although the Amarisoft Callbox includes antennas, they are simple dipole low-gain antennas with a limited range meant for indoor use. Clearly, these antennas do not meet the requirement of the outdoor deployment required in TurboRAN. More appropriate outdoor antennas are required to provide wider coverage. Based on the anticipated deployment, we determine the appropriate antenna with the required properties. Antenna selection for TurboRAN is influenced by factors such as support for ISM bands, MIMO, remote electrical tilt, and physical properties like weight and size.

TurboRAN is designed to initially operate on the ISM band with configurable SDRs. To maximize the SDR capabilities, the antenna should complement the SDRs and support a variety of ISM frequency bands. Due to the space and tower loading constraints, we focused on antennas that can support the frequency range shown in Table 3. Although, indoor antennas provided with Amarisoft Callbox support multiple frequencies, finding suitable commercial antennas with higher gain that can support the target frequency is not a straightforward task. Most of the current commercially available antennas operate on commercial bands such as 3.3 GHz to 4.2 GHz. Other antennas that provide support for the ISM band, support only one or two frequency bands at max. There exist antennas that support at least 3 frequency bands such as [41]. However, with the increase of the number of supported frequency bands, there is an increase of antenna elements, that ultimately increase the total weight of the antenna. To utilize the existing poles on the campus without any retrofitting, and avoid installation of the 5m poles, the antennas should weigh light.

Most commercial cellular networks and testbeds incorporate MIMO in their deployment, as MIMO has proven to have several advantages. In the industry, MIMO is used to increase the throughput of the base station by using multiple antennas transmitting at the same time. For testbeds, having MIMO capability can open more alleys in terms of experimentation. In addition to MIMO, modern cellular networks are equipped with functionality to remotely control the antenna tilt settings, known as RET. RET has become an indispensable part of the cellular network due to the convenience as well the savings in the operational cost it brings to the network operators. Hence, RET eliminates the need to physically visit the site for tilt adjustments. Therefore, RET and MIMO support were two other criteria considered in the antenna selection for TurboRAN.

After evaluating various antennas that fitted the above-mentioned desirable attributes, we chose the AW3639 antenna from Alpha Wireless [42]. This antenna has 12-ports and can operate on 1695 to 1995 MHz / 1920 to 2170 MHz / 2170 to 2500 MHz / 2500 to 2690 MHz / 3400 to 3800 MHz / 5150 to 5925 MHz frequencies. It can also support

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TABLE 4: Comparison between select 5G network testbed solutions.

5G Solution Provider	Supported Technology	Core	Frequency	MIMO	Carrier Agg.	Supported Layers for Analysis	Possible Test Scenarios	Limitations	Ref.
Anritsu MT8000A	5G SA with option of 4G	EPC and 5GC for additional cost	All FDD and TDD bands in sub-6 GHz and mmWave	4x4	8 CA	L1 and L2	-Dynamic Spectrum Sharing (DSS) -Throughput Tests - Handover Tests	-Most functions and features need to be purchased individually. -Supports only L1 and L2.	[37]
Ixia Keysight	5G SA, 5G NSA	EPC	All FDD and TDD bands in sub-6 GHz	4x4	4 CA	All Layers	-Capacity Tests -Throughput Tests -Voice and video quality tests -Mobility Tests	Support for 5GC and mmWave are not available.	[38]
Amarisoft Callbox	5G SA, 5G NSA, and 4G	EPC and 5GC inclusive	All FDD and TDD bands in sub-6 GHz	4x4	8 CA	All Layers	-Throughput Tests -Handover Tests -VoLTE Tests -NB-IoT Tests -Capacity Tests	Support for mmWave is not available.	[39]

TABLE 5: Key features of Amarisoft CallBox.

Feature	Callbox Pro	Callbox Classic
RAN	4G, 5G (NSA, SA)	
LTE-M/NB-IoT	✓	
Core	EPC/5GC	
Duplex	FDD/TDD	
#SDRs	6	3
#Cells	6	3
IMS Server	✓	
eMBMS Server	✓	
GPS synchronizer	✓	
OS	Linux	
CPU	Inter Core i9	Inter Core i7
3GPP Release No.	Release 14 for 4G / Release 15 for 5G	
Supported Frequency	500 MHz - 6 GHz	
Supported Bandwidth	200 kHz - 56 MHz	
Indoor Wireless Range	10 m	
#UEs	1000	
UE Category	0 - 12	0 - 10
Maximum DL Throughput	1200 Mbps	600Mbps
DL Modulation	256QAM	
Maximum UL Throughput	150 Mbps	150 Mbps
UL Modulation	64QAM	
CA	8 CA	
MIMO	4x4	2x2
Handover	Intra Base Station & Inter Base Station	

TABLE 6: Selected antenna specification.

Parameters	Values		
Frequency (MHz)	1695-2690	3400-3800	5150-5925
Port Configuration	4 ports	2 ports	2 ports
Gain (dBi)	14	10	6
Beamwidth (degrees)	65		
Tilt	RET		
Impedance (Ω)	50		
Voltage Standing Wave Ratio	1.5		

up to 4x4 MIMO. It has a compact design, only 0.61 m in length, and lightweight weighing only 5.9 kg. Table 6 shows the configuration of the antenna chosen for the TurboRAN deployment.

Alpha Wireless AW3639 antenna is also AISG 2.0 compatible, i.e., it can support RET controller from other manufacturers abiding AISG 2.0 standard with a range of 2° to 10°, as for TurboRAN, we have incorporated RET. Several

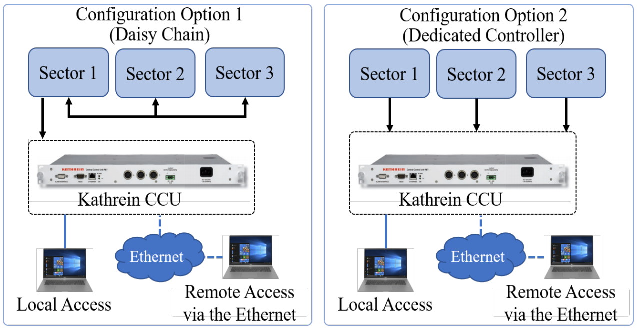

FIGURE 5: Two options for RET configurations.

RET controllers that are available in the market are considered including the solutions offered by Comba [43] and Commscope [44]. Consequently, Kathrien Central Control Unit (CCU) [45] is chosen as the preferred solution considering various advantages over other options. These advantages include interoperability with most antenna and support for a dual power supply. The CCU acts as an interface between the antennas' remote-control unit (RCU) and the control system, and can be operated both locally and remotely. Fig. 5 shows the two RET configuration options, we have considered in TurboRAN deployment. The first option we have considered is deploying the RET using the daisy chain method. In this method, RET ports of the antenna are cascaded and only one cable is terminated at the RET controller. Even though this method is more cost-efficient, it is prone to complete RET failure due to the existence of a single point of failure. Therefore, for TurboRAN, we decide to use the second approach which is to use a dedicated RET controller cable for each antenna. Although this approach needs more cables, it is more robust against total RET failures.

D. POWER AMPLIFIERS AND LOW NOISE AMPLIFIERS

The Amarisoft Callbox SDRs can only output 5dBm of signal power at their maximum. This presents a challenge because such a small amount of power can only adequately cover

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TABLE 7: Power amplifiers and low noise amplifiers requirements.

Parameter	RFA and LNA Requirements
Connector	SMA
Gain	>20 dB
Noise Figure	<6 dB
Operating Frequency	(2.4, 3.5, 5.8) GHz
P1dB	>5 dBm
IP3	>15 dBm
Impedance	50

limited indoor regions. Furthermore, this amount of power is insufficient to fuel the external antennas. To address this problem, we use radio frequency amplifiers (RFAs) on the transmit side to increase the signal power originating from the SDRs.

Amplifiers measure the amount of boosting or amplification by the parameter called gain. According to the simulations using Atoll as shown in Fig. 4, at least 20dB gain is necessary to ensure coverage for TurboRAN. Another important RFA parameter is the linearity measured by the 1 dB compression point (P1dB). The output power level gain deviates 1 dB less than the linear constant value at the P1dB point. Since the maximum power from the SDRs is 5 dBm, amplifiers with more than 5 dB P1dB can work effectively. Upon reaching P1dB, the amplifier losses linearity and starts producing byproducts such as distortion and harmonics. These harmonics, especially the third-order product, can cause interference to the first-order or fundamental power. Thus, another critical parameter to consider in amplifier selection is known as the third-order intercept or IP3. This parameter is an imaginary point wherein the fundamental power and the third-order power both have the same value. Practically, this point can never be reached as the amplifiers saturate before reaching this point. Usually, IP3 is 10 dB greater than P1dB. Therefore, for TurboRAN deployment, we require an amplifier with IP3 of at least 15 dBm. Table 7 shows the RFA requirements for TurboRAN.

The extremely weak signal received by the base station antennas, similar to the transmit side, requires amplification before being analyzed by the SDRs. While providing amplification to the received signal is straightforward, the real challenge, in this case, is the introduction of noise from the amplifier which can compromise the noise level in the extremely weak signal. To address this issue, a specific type of amplifier called Low Noise Amplifier (LNA) is used to minimize the added noise from the amplifier by utilizing components and topologies that generate less noise. Similar to RFA, the critical parameters for consideration while selecting LNAs are gain, P1dB, and IP3. Noise figure or the sensitivity of the amplifiers to noise is another crucial parameter for LNA. Table 7 also summarizes the LNA requirements for TurboRAN.

E. PROTECTION CABINET AND COOLING SYSTEM

As previously mentioned, one major limitation of Amarisoft Callbox is not having the support of outdoor deployment. However, we can counter this shortcoming by installing the equipment inside a protective cabinet having the optimal weather control and rain/sleet cover. To allow the TurboRAN to operate in an outdoor scenario, a protection cabinet is another aspect that needs attention. Since Tulsa, Oklahoma features both sub-zero as well as fairly hot days maintaining acceptable temperature in the outdoor cabinet sheltering the equipment is another challenge for outdoor deployment. In deploying TurboRAN, we have considered several cabinets which can provide the needed weather protection for the base station equipment. However, choosing the right cabin for this fragile equipment requires consideration of different factors. In this subsection, we discuss the factors we have considered in choosing the protection cage for the base stations.

1) Protection Cabinet

NEMA rating is perhaps the most important and first factor to consider in choosing the right enclosure. NEMA which stands for National Electrical Manufacturers Association, is an organization that oversees the crafting of technical standards and specifications for electrical and medical imaging device manufacturing in the United States. The NEMA rating system is a classification system for the types of environmental conditions in which a given enclosure can be employed. NEMA ratings for non-hazardous, outdoor locations are shown in Table 8. For TurboRAN deployment, we have selected a cabinet that conforms to NEMA rating Type 4. In summary, Type 4 enclosures can be used for both indoor and outdoor locations. It is watertight and dust-tight providing protection against rain, snow, sleet, windblown dust, splashing water, and hose-directed water. However, when the deployment area is near the bodies of water such as sea which can cause corrosion, one should go for Type 4X, while 6 and 6P are recommended if there are chances of flooding and water submersion.

Another factor to consider is the physical measures of the outdoor cabinet such as its size, weight, and volume. First, weight should be considered especially when the cabinet is wall or tower mounted. It should be light enough to be anchored on the walls or pole. In TurboRAN deployment, we have designed our cabinets to be floor mounted wherein a pad is built on the ground and the cabinet is placed on top. With this regard, weight is not the main factor we considered in choosing the cabinet. The more crucial factor to consider is the cabinet size and volume. The cabinet should be able to enclose not only the Amarisoft callbox but also the other equipment that are needed to make the TurboRAN up and running (i.e., amplifiers, switch, RET controller, etc.). In addition, future expansion should also be considered in choosing the best size of the outdoor enclosure.

After consideration of the above-mentioned criteria (i.e., NEMA rating, weight, size, and volume), we shortlisted two potential candidates for further evaluation. First is the OD-30DXC, a 15 Rack Unit (RU) enclosure used in industrial applications in the field of telecommunications, fiber optics, military, and public safety. It would have been a perfect fit for TurboRAN deployment. However, if future expansion is

TABLE 8: Comparison of specific applications of enclosures for outdoor nonhazardous locations (from NEMA 250-2003).

Provides a Degree of Protection Against the Following Conditions	Types of Enclosures									
	3	3X	3R*	3RX*	3S	3SX	4	4X	6	6P
Access to hazardous parts	X	X	X	X	X	X	X	X	X	X
Ingress of water (Rain, snow, and sleet**)	X	X	X	X	X	X	X	X	X	X
Sleet***	-	-	-	-	X	X	-	-	-	-
Ingress of solid foreign objects (Windblown dust, link, fibers, and flyings)	X	X	-	-	X	X	X	X	X	X
Ingress of water (Hosedown)	-	-	-	-	-	-	X	X	X	X
Corrosive agents	-	X	-	X	-	X	-	X		X
Ingress of Water (Occasional temporary submersion)	-	-	-	-	-	-	-	-	X	X
Ingress of Water (Occasional prolonged submersion)	-	-	-	-	-	-	-	-		X

* These enclosures may be ventilated.
** External operating mechanisms are not required to be operable when the enclosure is ice covered.
*** External operating mechanisms are operable when the enclosure is ice covered.

TABLE 9: Outdoor enclosure specification.

NEMA Rating	NEMA 4 and 4X configurable
Exterior Enclosure Dimensions	51"H x 28"W x 30"D
Approximate Shipping Weight	73 kg
Size in RU	26 RU
Mounting Type	Floor Mounted

considered, this particular design does not have room for the installation of any further equipment beyond what is already needed for TurboRAN's current deployment. Thus, we made a decision to use a larger enclosure called OD-50DXC. This 26 RU outdoor enclosure is almost double the size of the OD-30DXC giving enough room for future expansion and equipment addition. This cabinet, which supports NEMA Type 4 and 4R configurations, is utilized in applications similar to the OD-30DXC. It also includes a side spool-up cabinet for cable entry and an electrical panel with internal outlets, both of which are missing from the OD-30DXC. Table 9 provides the specification summary of OD-50DXC.

2) Cooling System

The temperature in Oklahoma can easily cross $37.5°C$ in summer. Inside a metallic enclosure the temperature can easily rise above the outdoor temperature. This can lead to temperature high enough that can cause severe damage to the base station equipment despite the protection offered by the OD-50DXC cabinet. That is why TurboRAN outdoor enclosures must have a cooling system to keep the temperature within the equipment's operating range. Due to the harsh summer conditions in Oklahoma and the delicateness of the equipment, cooling using the built-in enclosure fan would not suffice. To address this challenge, we have added an air conditioning system to the TurboRAN outdoor deployment unit designs to maintain the temperature inside the cabinet.

To select the proper size of the air conditioning to be used, worst-case conditions need to be considered. Internal heat load and heat load transfer are two elements to consider while selecting the appropriate cooling system for the enclosure. The former refers to the heat load generated by the equipment components inside the cabinet, while the latter refers to the heat loss or gain from the ambient air that enters the enclosure through its walls. Internal heat load expressed in British thermal unit per hour (BTU/H) can be calculated using

TABLE 10: Maximum heat output of the equipment inside the cabinet.

Equipment	Maximum heat output
Amarisoft Callbox	200 Watts
RET Controller	50 Watts
Switch	250 Watts
Amplifiers	1.5 Watts (x 12)
Total	518 Watts

the maximum heat output specifications of the equipment expressed in Watts. Conversion of Watts to BTU per Hour is given as:

$$\phi = \omega \times 3.413 \tag{1}$$

where ϕ is the internal heat load (IHL) in BTU/H and ω is the maximum heat output specifications of the equipment expressed in Watts. The sum of all the internal heat loads of all the components inside the cabinet is the total internal heat load. For TurboRAN deployment, Table 10 shows the maximum heat output of all the equipment inside the cabinet equating to a total of 518 W. Assuming that around 99% will be converted into heat (i.e., 512 W), gives an IHL of 1,747 BTU/H. Meanwhile, heat load transfer (HLT) can be calculated using:

$$\vartheta = 1.25 \times S \times (\tau_a - \tau_i) \tag{2}$$

where ϑ is the HLT in BTU/H, S is the enclosure surface area in ft^2, τ_a is the maximum outside ambient air temperature in $°F$ and τ_i is the maximum allowable internal enclosure temperature in $°F$. The constant value of 1.25 is an industry standard for metal enclosures. We calculate HLT based on S of $4.46m^2$ $(48ft^2)$, τ_a of $37.5°C$ $(100°F)$ and τ_i of $26.5°C$ $(80°F)$ to be 1,200 BTU/H. The total cooling capacity (CC) of the air conditioning system is the sum of IHL and HLT. IHL of 1,747 BTU/H and HLT of 1200 BTU/H brings the total CC to 2,947 BTU/H. Thus, we have decided to use a 3,000 BTU/H cooling system to meet this requirement.

F. MISCELLANEOUS TURBORAN COMPONENTS

Other important components of TurboRAN's outdoor installation include a surge protector or lightning surge suppressor

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to protect the equipment from electromagnetic pulse (EMP) caused by lightning strikes or other strong electrical changes. Additionally, lightning rods are installed on the antenna poles to protect the antenna from lightning strikes. The lightning rods as well as the surge protector are terminated to a copper bus bar which goes directly to the ground. Meanwhile, LAN to ethernet switch is used to connect the Amarisoft Callbox to the LAN of the campus and the internet. Lastly, to provide DC power to the amplifiers, multi-port AC to DC power converters are utilized.

IV. CASE STUDY: MOBILITY-BASED INTER-FREQUENCY HANDOVER

After the successful deployment of a testbed, it is important to verify its operation functionality. One approach to achieve this is to design and test common network scenarios, then evaluate the results. We consider the following criteria in selecting the suitable use case to present: 1) the use case should require and validate over-the-air capabilities of the testbed; 2) the use case should address a problem that is not yet covered in literature; 3) the use case should address a practical problem that is relevant for industry; and 4) the use case should be simple to understand for researchers with no prior experience of testbed. Out of plethora of use cases TurboRAN can support, we include a mobility management-related use case since it fits all of aforementioned criteria. Additionally, we chose this use case since mobility management is one of the most challenging tasks in cellular networks, and few testbeds support mobility functions.

In 5G cellular networks, to cater to the increasing data rate requirements, dense networks are deployed. For the provision of uninterrupted and efficient communication services to mobile users in emerging dense networks, handover is an essential enabling feature. In addition, to improve the coverage range, Quality of Service (QoS), and overall data rate, generally heterogeneous networks are deployed. However, despite the auspicious aspects of such networks, the small cells in a dense network increase the handover attempts for a mobile user. Hence, the issues related to mobility such as ping-pong, early and late handovers, and handover failures become more challenging problems in the emerging ultra-dense multi-band multi-tier networks such as 5G [46]. These issues, if not taken care of in a timely manner, can lead to degradation in Key Performance Indicators (KPIs) including data rates, latency, user Quality of Experience (QoE), power consumption of communication devices, and signaling overhead. Thus, the cellular networks must be equipped with efficient mobility management systems to avoid degradation in the aforementioned KPIs. Not many simulators model HO and mobility with realistic details. Analytical models on the other hand often omit mobility altogether to have tractable results and are asymptotic. Testbeds are the platforms that offer the most resource capabilities to test mobility management capabilities and algorithms. Therefore, in this section, study TurboRAN's potential to investigate mobility management realistically. In the process, we demonstrate how improper configuration of the handover-related parameters can have a detrimental effect on ping pong and performance in a real network. We demonstrate the significant influence especially to inter-frequency handovers, which occur between the cells of various frequency layers.

Fig. 6 shows the setup for the experiment using the TurboRAN base station (Amarisoft Callbox). The SDRs are programmed to act as base stations that operate on various frequencies. We considered the default frequency settings of the TurboRAN base station, i. e., the first SDR is set to operate in Band 7 with 2655 MHz center frequency while the second SDR is set to operate in Band 4 with 2130 MHz center frequency. The maximum transmit power of both SDRs is 5 dBm. The summary of base station parameters is shown in Tables (ii) and (iii) of Fig. 6. To analyze the effect of handover under different configuration settings, a mobile user moves out of the coverage of one base station towards the coverage region of another base station, thus causing a handover (HO).

We perform several experiments using different settings of HO-related parameters such as events A1, A2, and A3. These events that are used to trigger handovers are also summarized in Table 11. For these experiments, we use RSRP-based HO triggering. When the serving base station's RSRP falls below a threshold, event A2 is triggered. This event is used to start the measurement gap or time, during which the user measures the signal condition of other frequency layers. When the RSRP of the neighboring base station exceeds that of the serving base station, Event A3 is triggered, and the handover is performed. Meanwhile, event A1 is communicated to the serving base station to cancel the measurement gap if no appropriate cell is detected during this period and the serving base station's RSRP improves above a threshold. These events are triggered if the condition is sustained for the duration specified by the time-to-trigger (TTT) parameter.

For experiment 1, a set of parameters are configured in the TurboRAN base station (Amarisoft software terminal), such that the handover from one base station to the other becomes very easy. To trigger the measurement gap quickly, we set A2-threshold and A2-TTT to -80 dB and 128 ms, respectively. Furthermore, A3-offset is adjusted to a negative value (-2 dB), causing handovers to occur even if the RSRP of the target base station is lower than that of the source. Additionally, A3-TTT is set to a small value (128 ms) for faster triggering. Meanwhile, parameter settings in experiment 2 make the handover moderately difficult compared to the parameter set for experiment 1. For the second experiment, we use 0 dB for A3-offset to force the handovers to happen when the source and target base station RSRPs are equal. Additionally, compared to experiment 1, we use a longer A3-TTT of 256 ms to delay the handover triggering. Lastly, for the third experiment, the set of parameters are configured such that the handover between base station 1 and 2 are avoided. To do this, we set A2-threshold to a low value equal to -110 dB to minimize measurement gaps. Then, we set the parameter A3 offset to a high value of 6 dB, in addition to

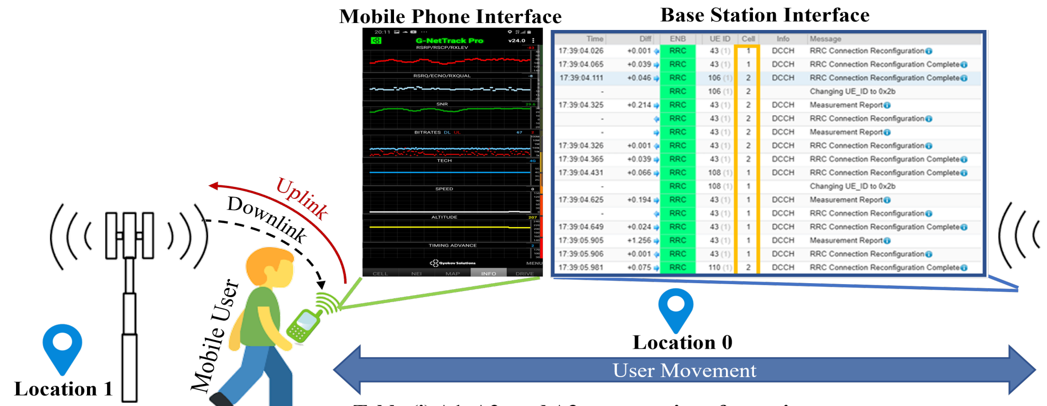

Table (ii) TurboRAN Base Station

Base Station # 1 Parameters	Values
Operating Frequency Band	Band 7
Tx Power	5 dBm
Cell ID	0x01
DL center Frequency	2655 MHz

Table (i) A1, A2, and A3 event settings for various user locations

Handover Parameters	Experiment 1	Experiment 2	Experiment 3
A1 RSRP (dBm)	-80	-80	-105
A1 TTT (ms)	128	256	640
A2 RSRP (dBm)	-80	-80	-110
A2 TTT (ms)	128	256	640
A3 offset (dB)	-2	0	6
A3 TTT (ms)	128	256	640

Table (iii) TurboRAN Base Station

Base Station # 2 Parameters	Values
Operating Frequency Band	Band 4
Tx Power	5 dBm
Cell ID	0x02
DL center Frequency	2130 MHz

FIGURE 6: Inter-frequency handover use case experimental setup.

TABLE 11: Summary of intra-RAT measurement events for LTE and 5G NR.

Event	Event Description	Function
A1	Serving base station becomes better than threshold	Cancel measurement gap
A2	Serving base station becomes worse than threshold	Start measurement gap
A3	Neighboring base station becomes offset better than serving base station	Initiate handover

setting a longer TTT of 640 ms. For this final experiment, we set the event A1 threshold to a low value (-105 dBm) so that the measurement gaps are canceled easily, hence, making sure the handover will not happen. The summary of the events settings for different experiments is given in Table (i) of Fig. 6.

Fig. 7 demonstrates the HO results for the three experimental settings in the TurboRAN and the serving time for different duration of times (i.e., 180, 360, and 540 seconds). A mobile user moves within the coverage region of the two TurboRAN base stations for the three aforementioned time durations. A mobile application (G-NetTrack Pro), shown at the top of Fig. 6, is used to track the number of handovers and serving time. On one hand, it can be observed through Fig. 7 that many handovers are also deteriorating for the stable service provision, causing ping-pong effect. On the other hand, if we make the parameter set to be highly stringent, handovers are suppressed even in cases where the user's RSRP value is very low and the desired data rates are not delivered. This captures the fact that late handovers also have a negative impact on the network performance. While

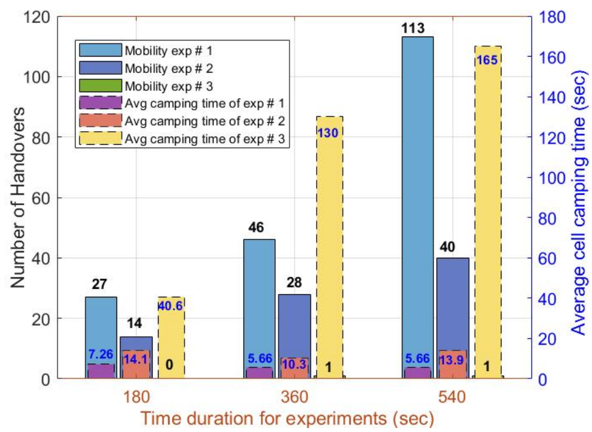

FIGURE 7: Number of handovers under mobile user settings.

observing the serving time for the three experiments, this time is much higher for the third experiment with stringent parameter settings.

Due to factors such as shadowing, different events configurations can cause the HOs even if the user is stationary, lead to ping-pong effect. The number of HOs while a user is static and its impact on the average RSRP is depicted in Fig. 8. For this use case, we investigated three scenarios: 1) the mobile is in the center of the two TurboRAN base stations, 2) the mobile is near the TurboRAN base station 1, and 3) the mobile is near the TurboRAN base station 2. The settings for experiment 1 (default settings) generate ping-pong effect with the maximum number of handovers,

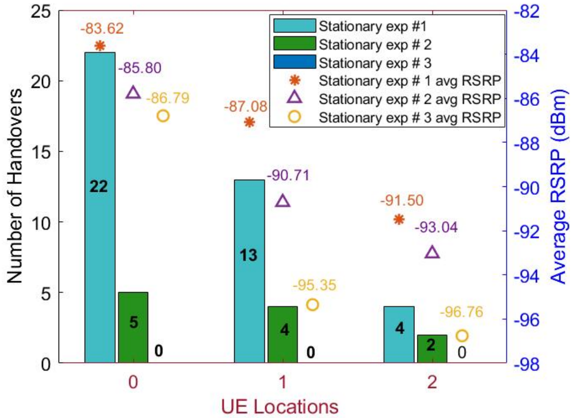

FIGURE 8: Number of handovers under static user settings.

even when the user is not moving. For the static case in experiment 3, no handover is detected. In addition, as the setting for experiment 2 are the best suited for the given scenario, i.e., the occurrence of handover happens only when the serving RSRP is not satisfactory, hence, keeping the data rates consistent for the user and providing satisfactory QoS.

V. CONCLUSION AND FUTURE WORK

Given the complexity of cellular networks and the number of components involved in an end-to-end network, designing and deploying a system-level cellular testbed can be challenging and overwhelming. To address this issue, leveraging insights from our hands-on experience of deploying the TurboRAN testbed, we present in detail the design considerations and deployment challenges one might face when implementing a 5G and beyond network testbed. We discuss the challenges and approach taken in the selection of all main components of the testbed. We also present the rationale behind using the selected hardware and software solutions for the base station as well as their limitations such as limited indoor coverage offered by most testbed base station vendors. We then explain how these limitations can be addressed by using outdoor antennas and amplifiers, to boost the transmit and receive power. Additionally, we elaborate the important features of the protective enclosure and the cooling system to enable the effective outdoor deployment of the base station. Finally, we demonstrate TurboRAN's functionality through a case study involving the influence of sub-optimal mobility parameter setup on user experience. This case study shows a typical experiment through which TurboRAN testbed can be used to gather realistic insights on system-level performance aspects (e.g., mobility/handover management in multi-cell environment) that are not possible with most existing simulation or analytical models.

Other use cases of TurboRAN include AI-based zero-touch optimization of parameters such as tilt and transmit power, resource allocation and scheduling, propagation model validation, and development of sophisticated multiple access techniques, among others. Validation and evaluation of these use cases through different validation setups, experiments, and results are beyond the scope of this paper and will be the topic of future dedicated experimental studies.

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