2022 Seventh International Conference On Mobile And Secure Services (MobiSecServ) | 978-1-7281-8837-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/MobiSecServ50855.2022.9727204

Investigating Handover Behavior with 5G and Beyond TurboRAN Testbed

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***Abstract*—With a recent roll out of Fifth Generation (5G), the focus of cellular industry and research community is now turned towards Sixth Generation (6G). The aim of 6G is to provide substantially higher capacity, seamless connectivity, better energy efficiency, spectral efficiency, reliability, and latency among others. To achieve this goal, new technologies and concepts are being proposed, however, to demonstrate their actual performance, it is important to integrate them in practical networks and then analyze the performance. Nowadays, testbeds are considered as an essential tool to evaluate realistic performance of cellular networks. Nevertheless, deploying a large-scale testbed often involves complex steps including network, site planning and choosing the appropriate hardware. In this work, we present our newly deployed TurboRAN testbed, and report all the findings, that are indispensable for evaluating different concepts of next generation cellular networks. The TurboRAN testbed is a complete integrated mobile cellular network deployed over 300 000 m^2 area with the combination of indoor and outdoor cell deployment. It supports a variety of essential cellular networks features and aims to offer free access to the community for conducting experiments. In order to illustrate some of the capabilities of TurboRAN, in this work, we also investigate handover procedure and mobility management in different settings. In a nutshell, this work serves as a guide for readers who are planning to deploy a testbed for 5G and Beyond testing networks.**

I. INTRODUCTION

The standardization of Fifth Generation (5G) has recently been completed by the Third Generation Partnership Project (3GPP) in their latest release providing the research community an opportunity to focus towards the Sixth Generation (6G). The 5G overcomes several shortcomings encountered by the previous generations of mobile networks and relies on trade-offs (e.g., between energy efficiency, spectral efficiency, throughput, reliability, and latency) to support enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra Reliable Low Latency Communications (URLLC) applications [1]. On one hand, similar to its previous generations, the 5G will continue to evolve with time to enhance the existing features and to support new verticals as well as deployment scenarios. On the other hand, unlike 5G, the main aim of 6G will be to jointly meet the stringent network demands instead of relying on the aforementioned trade-offs [2].

Regardless of the generation and technology, any new introduced features are needed to be rigorously verified before the standardization and commercializing them to the general public. A common way to demonstrate new concepts and algorithms is by performing mathematical analysis followed by the computer simulations [3]. This provides an adequate overview of the theoretical and baseline performance. However, in case of complex systems such as cellular networks, it is comparatively difficult to fully traverse by merely tractable theoretical analysis or even with the reliable simulations due to the inherent system complexity. Therefore, to investigate the practical performance of the cellular networks, network operators rely on field trials in the actual deployment area. Even though field trials are helpful in realizing the realistic performance of the cellular networks, conducting such field trials is often difficult, time-consuming, expensive, or not always possible [4]. To address this challenge, deploying dedicated testbeds for experimentation has gained immense attention in the recent times. Testbeds are now being deployed by not only network operators and industrial players, but also by academics to strengthen their research so that they could play an active role in the standardization of the next generation of cellular networks [5], [6], [7], [8].

In general, testbeds can be of many types ranging from a simple black box to a sophisticated testbed deployed outdoors. Moreover, these testbeds can be used to investigate all layers of the OSI model or merely the physical layer performance in some cases, however, regardless of its features, testbeds are able to demonstrate the performance of a technology that is more close to the reality. The complexity of deploying a testbed varies according to the testbed type and features it offers. Deploying a large-scale testbed to evaluate new concepts in cellular networking domain involves complex steps including network and site planning, choosing right equipment for the network nodes, etc. Therefore, in this work, we present a newly developed TurboRAN testbed and discuss challenges one might face in deploying such a testbed for evaluating different concepts of next generation cellular networks.

The TurboRAN testbed, deployed at the Tulsa campus of University of Oklahoma, funded by a million dollars grant, is a university-wide testbed covering a huge area incorporating all the essential network nodes including evolved NodeB (eNB) for Long-Term Evolution (LTE), gNodeB (gNB) for 5G, as well as other core network entities. Each network node is a computer with Software Defined Radio (SDR) cards and having AMARISOFT software which offers a complete support for LTE, 5G New Radio, Narrowband Internet of Things (NB-IoT), and Long-Term Evolution for Machines (LTE-M). Moreover, it supports a variety of features necessary for the evaluation of the emerging cellular networks. Furthermore, contrary to other available testbeds that do not have an open access to everyone and accessing them from outside the network to conduct experiments can be very expensive, TurboRAN is targeted for 5G and Beyond (5G&B) and aims to offer free access to everyone for research. In a nutshell, this work serves as a guide for readers who are planning to deploy a testbed for 5G&B testing. Finally, to showcase the capabilities of TurboRAN, we investigate handover procedure in different settings. We focus on handover and mobility management as they are considered as essential enabling features for the uninterrupted connectivity in ultra-dense cellular networks, and cannot be demonstrated simply with a testbed of limited capabilities.

Our main contributions are summarized as follows:

- We summarize relevant testbeds that are available worldwide for cellular network testing and discuss their capabilities (Section II).
- We present an overview of our deployed TurboRAN testbed and highlight important factors that need to be taken care of when deploying a cellular network testbed outdoors (Section III).
- Finally, we investigate the handover procedure with the TurboRAN to showcase its capabilities and functionality (Section IV).

II. RELEVANT TESTBEDS

To facilitate research on future cellular networks, several wireless testbeds have recently been set up across the globe. Summary of the existing and emerging 5G&B network testbeds worldwide is shown in Table I. The 5GIC testbed [5] located at the University of Surrey in UK comes closest to real network. It is composed of LTE-based, albeit upgradeable not programmable cellular network spread over 4 km^2. Access to this testbed is limited as to conduct proposed research, a membership cost of 600K GBP/year (i.e., over \$1 million/year) is required. Moreover, flexibility and programmability of testbed is provided and managed by a commercial vendor with proprietary APIs. As such, academic investigators are not able to tune network parameters as desired. Instead experimental parameters have to be configured by the equipment vendor.

A limited number of relevant, open access testbeds are also located in the USA. These include PhantomNet and POWDER at the University of Utah [6], [7], and AERPAW which is located in the North Carolina State University [8]. PhantomNet [6] is a community testbed capable to enable research on cellular networks in 3GPP-compliant settings. This testbed provides an excellent platform for Evolved Packet Core (EPC) experimentation by offering emulation of eNB, and User Equipment (UE) components with sufficient functionality to allow Software Defined Network (SDN)-focused research. It also includes Universal Software Radio Peripheral (USRP)-based Access Points (APs) and UEs to enable physical layer research as well. However, unlike 5GIC and other 5G testbeds in Europe and Asia, PhantomNet is not based on real cellular deployment. In PhantomNet, RF devices (UEs and eNBs) are connected via a custom-built RF attenuator matrix instead of a real air interface. Another testbed located at the University of Utah known as POWDER [7] is a city-wide testbed built to perform large scale testing on SDN and massive Multiple-Input Multiple-Output (MIMO). Lastly, AERPAW [8] is a unique testbed built specifically to study Unmanned Aerial Vehicle (UAV) related use cases in a 5G network.

TABLE I: Distinctive features of 5G and Beyond testbeds.

5G Testbed	**Deployment Type**	**Key Attributes**			
		Mobility	**mmWave**	**MIMO**	**IoT**
5GIC, UK [5]	University-wide	✓	✓	-	✓
PhantomNet, USA [6]	University-wide	✓	-	-	✓
POWDER, USA [7]	City-scale	-	-	✓	-
AERPAW, USA [8]	City-scale	✓	-	-	-
5GUK Test Network, UK [9]	City-scale	-	✓	✓	✓
Aalto 5G network, Finland [10]	University-wide	✓	-	-	✓
Ericsson 5G, Sweden [11]	City-scale	-	✓	✓	-
FOKUS, Germany [12]	University-wide	-	-	-	✓
LuMaMi, Sweden [13]	Mobile Base Station	-	-	✓	-
NITOS, Greece [14]	City-scale	✓	✓	-	-
TurboRAN	University-wide	✓	✓	✓	✓

III. TURBORAN TESTBED

This section provides details of the TurboRAN testbed. First, we present an overview of the TurboRAN. We then discuss the approach we followed to design and plan the underlying network. Finally, we present our strategy in selecting and installing the appropriate equipment before explaining the details of AMARISOFT software and its capabilities.

A. *TurboRAN Overview*

TurboRAN is a fully functional cellular network testbed deployed over an area of 300 000 m^2 in the Tulsa campus of University of Oklahoma. It is funded by National Science Foundation (NSF) with an initial grant of one million dollars. The main aim is to investigate system-level performance of 5G&B cellular networks. The overall network design of TurboRAN testbed deployed in the university campus which resembles a typical suburban area is shown in Figure 1. It consists of two indoor small cells and six outdoor macro-cells, each macro-cell having three sectors for improved coverage, and each sector having an antenna with four elements for MIMO and beamforming. Radius of each cell is adjustable through antenna tilts and controllable transmit power, whereas the mobility of UEs in the network is achieved by using UAVs and Unmanned Ground Vehicles (UGVs). Moreover, the TurboRAN operates in various unlicensed frequency bands below 6 GHz as shown in the figure, and will operate in the licensed band of 3.5 GHz once experimental license is obtained in the near future in addition to operation in mmWave bands. The TurboRAN also includes two separate 5G Core

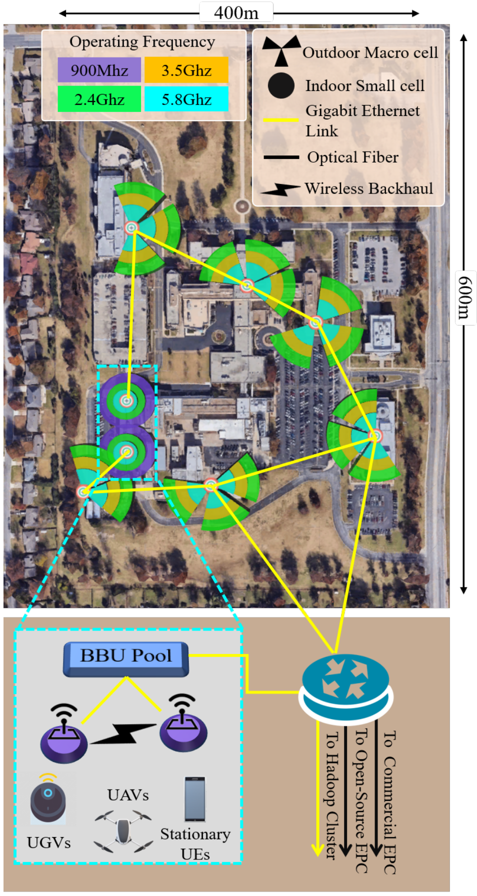


Figure 1: TurboRAN deployment overview.

(5GC)/EPC, i.e., commercial and open source, and incorporates a big data processing Hadoop cluster integrated to 5GC/EPC, and the APs for implementing machine-learning algorithms to enable proactive self-organizing network (P-SON) functions. The cells are connected to the 5GC/EPC and the big data processing cluster via high capacity optical fiber links that are able to support a data rate of up to 10 Gbit/s.

B. Network Planning and Design

Selecting appropriate location of the base stations, link-budget analysis, and analyzing the coverage area before actual deployment of a testbed are all part of network planning and design. On the one hand, base stations should be placed where installation and maintenance are easily possible. On the other hand, it is also important to consider the availability of other facilities in the chosen locations such as power source, fiber connection, etc. so that the installation could be performed with minimal efforts in cost-effective and time-efficient manner. The base station locations of TurboRAN shown in Figure 1 are selected using the aforementioned pointers. Once site locations are identified, the next step is to perform link-budget analysis, i.e., the investigation of all gains and losses in the network. The link-budget analysis helps in ensuring intelligible transmission of the data with sufficient Signal-to-Noise Ratio (SNR). Finally, to validate the overall coverage area of the network, we used a ray-tracing based industry standard radio network planning and optimization platform called ATOLL to first create a realistic coverage map. The coverage simulations are then performed by taking into account the vital environmental factors such as buildings, clutter type, terrain, and vegetation etc.

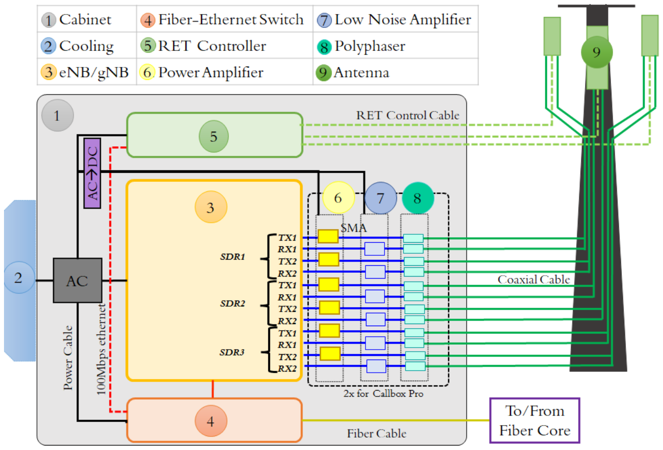


Figure 2: Block diagram of TurboRAN site deployment.

C. Hardware Components

Each outdoor site in TurboRAN consists of several components. Figure 2 shows the high-level block diagram of all these components. In the following, we briefly go through details of each of these components and reasoning behind choosing the selected component type. The first and foremost component, i.e., cabinet, encloses the majority of other components and is required especially for outdoor sites to provide a protection against bad weather and potential flooding. National Electrical Manufacturers Association (NEMA) which oversees the manufacturing of devices such as cabinets offers a standard rating system which is used to categorize the types of environment conditions where a particular enclosure can be used. We select Type 4 enclosure that is dust tight and watertight, and provides protection against rain, windblown dust, sleet, snow, splashing water, and hose-directed water. By considering other important factors such as weight, size, and volume of the cabinet along with the NEMA rating, we decided to go with enclosure model called OD-50DXC that has 26 Rack Units and is used in industrial applications. This type of cabinet can be configured as either NEMA Type 4 or 4R, and has a side spool-up cabinet for cable entry and electrical panel with internal outlets.

The second component in Figure 2 is a cooling system which is required to maintain the temperature inside the cabinet and avoid causing potential damage to the components due to overheating. The two important factors when choosing a right Air Conditioner (AC) are the internal heat load generated by the equipment components inside the cabinet and the heat load transfer, i.e., the heat loss or gain that penetrates the enclosure though its walls from the ambient air. After carefully calculating the internal heat load and the heat load transfer, we decided to choose a 3000 British Thermal Unit per Hour (BTU/H) AC system.

TABLE II: Characteristics of the AMARISOFT Callbox series.

Features	**Callbox Classic & Callbox Pro**
3GPP Release	4G: Release 14 & 5G: Release 15
Downlink Throughput	600 Mbps & 1200 Mbps
Downlink Modulation	256 QAM
Uplink Throughput	150 Mbps
Uplink Modulation	64 QAM
RAN	4G, 5G (NSA, SA)
Handover supported	Intra and Inter frequency
Operating System	Linux
Core	EPC/5GC
Number of SDR cards	3 & 6
Number of supported UEs	1000
MIMO	2x2 & 4x4
RF Coverage	500 MHz to 6 GHz
RF Bandwidth	200 kHz to 56 MHz
Carrier Aggregation	8 CA

Next, we discuss about one of the most important components, i.e., eNB/gNB or base station in general. While selecting a base station, it is important to focus on both software and hardware, as they jointly describe the overall capabilities of a base station. Here, we present details regarding the hardware only as the software part is discussed in the next subsection. Hardware used for base stations in testbeds is generally made up of computers that directly contribute towards the overall processing and storage capabilities, and SDR cards. Features that need to be taken care of regarding SDR cards include number of downlink and uplink antenna ports, supported frequency bands, maximum allowable bandwidth, and maximum radiated power. Among other solutions, we opt for AMARISOFT Callbox series solution, i.e., Callbox Pro and Callbox Classic. Key specifications of Callbox Pro and Classic are summarized in Table II. The Callbox Pro supports up to 6 SDRs cards, whereas the Callbox Classic supports a maximum of 3 SDR cards. Each SDR card has a maximum output power of up to 5 dBm, offers two input and two output ports for MIMO functionalities, and can operate in sub-6 GHz band with a maximum bandwidth support of 56 MHz. The Callbox is powered by a deployment quality software suite that allows modifications, for added flexibility and meeting the aforementioned demands. Due to its wide variety of supported features, we found AMARISOFT Callbox as an ideal solution for TurboRAN.

The fourth component is simply a fiber-ethernet switch to connect a base station to the internet as well as other base stations. Next, a Remote Electrical Tilt (RET) controller is connected to antennas via RET control cable to manage the antenna tilt settings remotely. In TurboRAN, we have used Kathrien Central Central Control Unit (CCU) due to its several advantages over the other solutions, such as proven quality, compatibility with most antennas, and dual power supply option (AC or DC). The CCU provides a site interface between several Remote Control Units (RCU) on the antennas and the control system, and can be accessed both locally and remotely.

The fifth and sixth components in Figure 2 are the Power Amplifier (PA) and Low-Noise Amplifier (LNA). At maximum, the signal power level emitted from the Callbox SDRs is only 5 dBm. This poses a challenge, since this much power can only effectively cover small indoor areas. Moreover, this level of power is not enough to drive the transmission power of the outdoor antennas. To address this challenge, we exploit PA on the transmit side to boost the signal power coming out of the SDRs. Our link-budget analysis showed that at least 20 dB gain is required to provide the required coverage for TurboRAN. There are several other important parameters such as P1dB and IP3 to consider when choosing a PA. The P1dB is a point at which the output power level gain deviates 1 dB lesser than the linear constant value, whereas IP3 is an imaginary point wherein the same values of the fundamental power and the third order power can be observed. Similar to the transmit side, the extremely weak signal received by the antennas also needs amplification before going into the SDRs. To amplify the received signal with minimal introduction of noise, LNAs are required. The important parameters to consider when selecting LNAs are similar to PA such as gain, P1dB, and IP3.

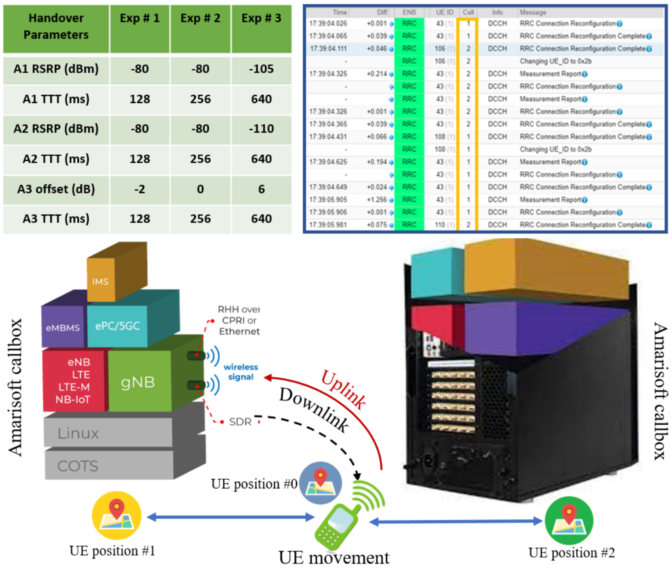
The final components in the site are simple polyphaser and the antennas. The AMARISOFT Callbox comes with antennas, however, these antennas are designed for the indoor use and have a limited range. Therefore, we require to select the appropriate antenna that has the required characteristics based on the planned deployment. These criteria include support for wide range of ISM bands, MIMO capabilities, RET features, and physical attributes such as size and weight. After considering several antennas that meet the above mentioned desired criteria, we selected Alpha Wireless AW3639 antenna. It is a compactly designed 12 port antenna that supports low-band, mid-band as well as 3.5 GHz and 5.5 GHz frequency, and can also support 4×4 MIMO.

D. *Amarisoft Software*

One major consideration in selecting a software for TurboRAN is a support of 5G protocol stacks. Moreover, support for 3GPP standard functions such as MIMO, carrier aggregation, dual connectivity, and handover should also be taken into account. As mentioned earlier, we have selected AMARISOFT Callbox as a base station for TurboRAN as it comes with the industry grade AMARISOFT software that supports different technologies such as 5G Non-Stand-Alone (NSA) and Stand-Alone (SA), LTE, LTE-M, and NB-IoT. The implementation is complaint with the 3GPP Release 14 and Release 15. Summary of features provided by the AMARISOFT software is provided in Table II. Compared to other solutions, 3GPP-compliant 5GC is also implemented along with EPC implementation. Additionally, AMARISOFT software offers extended support of up to 1000 UEs and allows to investigate different parameters on the UE side as well.

IV. HANDOVER PROCEDURE AND MOBILITY MANAGEMENT WITH TURBORAN

Once the task of testbed deployment is completed, it is required to authenticate its functionality and operation. To verify and evaluate our testbed, we leverage common network scenarios, and analyze the performance. In emerging 5G dense



Handover Parameters	Exp # 1	Exp # 2	Exp # 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

```
        Time      Diff   ENB   UE ID    Cell  Info  Message
17:39:04.026    +0.001   RRC   43 (1)   1     DCCH  RRC Connection Reconfiguration
17:39:04.065    +0.039   RRC   43 (1)   1     DCCH  RRC Connection Reconfiguration Complete
17:39:04.111    +0.046   RRC  106 (1)   2     DCCH  RRC Connection Reconfiguration Complete
           -             RRC  106 (1)   2           Changing UE_ID to 0x2b
17:39:04.325    +0.214   RRC   43 (1)   2     DCCH  Measurement Report
           -             RRC   43 (1)   2     DCCH  RRC Connection Reconfiguration
           -             RRC   43 (1)   2     DCCH  Measurement Report
17:39:04.326    +0.001   RRC   43 (1)   2     DCCH  RRC Connection Reconfiguration
17:39:04.365    +0.039   RRC   43 (1)   2     DCCH  RRC Connection Reconfiguration Complete
17:39:04.431    +0.066   RRC  108 (1)   1     DCCH  RRC Connection Reconfiguration Complete
           -             RRC  108 (1)   1           Changing UE_ID to 0x2b
17:39:04.625    +0.194   RRC   43 (1)   1     DCCH  Measurement Report
           -             RRC   43 (1)   1     DCCH  RRC Connection Reconfiguration
17:39:04.649    +0.024   RRC   43 (1)   1     DCCH  RRC Connection Reconfiguration Complete
17:39:05.905    +1.256   RRC   43 (1)   1     DCCH  Measurement Report
17:39:05.906    +0.001   RRC   43 (1)   1     DCCH  RRC Connection Reconfiguration
17:39:05.981    +0.075   RRC  110 (1)   2     DCCH  RRC Connection Reconfiguration Complete
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Figure 3: Experimental setup for the inter-frequency handover.

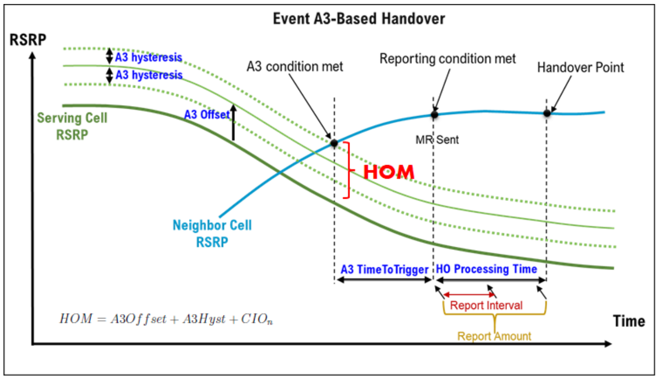

Figure 4: A3 Inter-frequency handover using Amarisoft Callbox.

networks, mobility and seamless handovers are among the essential enabling features. Therefore, in this section, we discuss briefly about handover, the associated parameters, and the experimentation involving mobility by exploiting the TurboRAN testbed. Since the TurboRAN testbed is still in its final installation phase, we conduct experiments here by using TurboRAN base stations, i.e., Amarisoft Callbox.

To maintain the Quality of Service (QoS) within the coverage range of macro base stations, it is pertinent to deploy micro base station, resulting in a heterogeneous network. However, to minimize the impact of co-tier/cross-tier interference, signaling overhead, and seamless handovers for better data rate, it is essential to optimize the handover related parameters. If the parameters are not tuned according to the defined Gold standard range, it can lead to issues such as ping-pong effect, early/late handovers, and handover failures in the worst case scenario [15]. We illustrate the devastating impact of the incorrect setting of the handover related parameters, as listed in the top right part of Figure 3, in terms of ping pong and throughput. Particularly, we focused on illustrating the impact of handovers that occur between the cells of different frequency layers known as inter-frequency handovers.

The Amarisoft Callbox experimental setup is shown in Figure 3. The SDRs are configured to act as base stations, operating in different frequencies, i.e., SDR 1 is configured to operate in Band 7 with f_c of 2655 MHz and SDR 2 to operate in Band 4 with f_c of 2130 MHz, with a maximum transmit power of 5 dBm. Both base stations are equipped with four antennas that are positioned such that the maximum possible coverage range for the mobile UEs can be achieved. The important parameters for handover (HO) are event A1, A2, and A3, we perform experiments by changing the values of these events to trigger the handover (given in the top left Table of Figure 3). Event A2 is triggered when the serving base station's Reference Signal Received Power (RSRP)/Reference Signal Received Quality (RSRQ) becomes worse than the threshold and is used to trigger the measurement gap, the UE starts measuring the signal condition of other frequency. When the offset of the neighboring base station is greater than the serving base station, then event A3 is triggered to initiate the handover process, Figure 4 shows the A3 based handover procedure in detail, involving other related parameters such as hysteresis, offset, and Cell Individual Offset (CIO) [16]. However, if there is no cell providing RSRP greater than the serving base station, during measurement gap, then the event A1 is triggered to the base station to cancel the measurement gap. All these events are triggered upon maintaining the condition until the expiration of the parameter called Time-to-Trigger (TTT).

For the execution of handover experiments in this study, a mobile UE covers a certain distance within the range of two base stations, i.e., moving away from the range of one base station towards the range of the other one. Figure 5 shows the number of handovers and average cell utilization time for three different experimental settings. For the experiment 1, the parameters are optimized in the Amarisoft software terminal, to easily perform the handover between the two base stations. A3 offset, A2, and A3 TTT parameters are set to a low value (as shown in the top left Table of Figure 3) such that the handovers are triggered even if the RSRP of the target base station is lower than the serving base station. In case of experiment 2 and experiment 3, the parameter settings are configured moderately stringent and stringent, respectively, to avoid the handover procedure. To observe the impact of mobility on handover, the UE moves for different time duration (180, 360, and 540 seconds) as shown in Figure 5. The number of handovers and the serving time are captured by using a mobile application (G-NetTrack Pro). Another insightful observation is that the increasing number of handovers cause the performance degradation and ping-pong effect.

To study the impact of handover and average RSRP while the UE is not moving, we perform another experiment by placing the smartphone at three different locations within the coverage range of the two callboxes of different frequency band, referred to as position 0, 1, and 2 in the Figure 3. Position 0 is when the smartphone is placed in the center

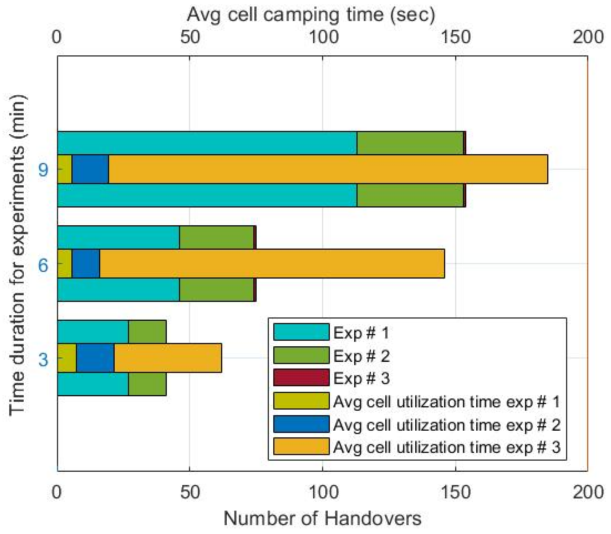

Figure 5: Impact of user mobility on handover.

TABLE III: RSRP values for different HO parameter settings for a static user.

Simulations	Position 0	Position 1	Position 2
RSRP values for exp Setting 1 (dBm) & no. of HO	-83.62 & 22	-87.08 & 13	-91.50 & 4
RSRP values for exp Setting 2 (dBm) & no. of HO	-85.80 & 5	-90.71 & 4	-93.04 & 2
RSRP values for exp Setting 3 (dBm) & no. of HO	-86.79 & 0	-95.35 & 0	-96.76 & 0

of the two base stations, whereas at position 1 and 2, the smartphone is placed near the base station 1 and base station 2, respectively. Also, we tune the parameter configurations, which further discourage the handover to occur causing low RSRP values. It can be observed in Table III that even when a user is not moving, the settings for experiment setting 1 (default settings recommended for events) cause ping-pong effect with highest number of handovers. For experiment setting 2, the configurations are optimized within the given ranges, therefore, the number of handovers occur when required for achieving consistent data rates. Finally, for experiment 3, handover does not happen at all. These experiments demonstrate the working functionality of the AMARISOFT Callbox. From these experiments, it is clear that the optimization of the handover configuration parameters should be performed with precaution, as it can impact the overall user QoS.

V. CONCLUSION AND FUTURE WORK

In this work, we have presented the TurboRAN testbed that is deployed to investigate performance of 5G&B cellular networks. Based on our hands-on experience, we highlighted and discussed the deployment challenges and approach we took to address these challenges. We also provided details of all the hardware components selected for the testbed and provided reasons behind our choices. Finally, we showcased the working of TurboRAN via a case study related to the detrimental impact of mobility parameters to user experience. It is also important to highlight that the TurboRAN testbed currently targets sub-6 GHz and features MIMO capabilities, however, the aim is to extend it by incorporating Massive MIMO, mmWave, and even TeraHertz band to enable 6G communications in the future.

ACKNOWLEDGMENT

This work is supported by the National Science Foundation under Grant No. 1730650 and Qatar National Research Fund (QNRF) under Grant No. NPRP12-S 0311-190302. The statements made herein are solely the responsibility of the authors. For more details about these projects please visit: http://www.ai4networks.com.

REFERENCES

[1] ITU-R, “Minimum Requirements related to Technical Performance for IMT-2020 Radio Interface(s),” International Telecommunication Union, Report ITU-R M.2410-0, November 2017.

[2] M. Nabeel, U. Hashmi, S. Ekin, H. Refai, A. Abu-Dayya, and A. Imran, “SpiderNet: Spectrally Efficient and Energy Efficient Data Aided Demand Driven Elastic Architecture for 6G,” *IEEE Network*, 2021.

[3] S. Pratschner, B. Tahir, L. Marijanovic, M. Mussbah, K. Kirev, R. Nissel, S. Schwarz, and M. Rupp, “Versatile mobile communications simulation: The Vienna 5G link level simulator,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2018, no. 1, p. 226, 2018.

[4] F. Gringoli, P. Patras, C. Donato, P. Serrano, and Y. Grunenberger, “Performance assessment of open software platforms for 5G prototyping,” *IEEE Wireless Communications*, vol. 25, no. 5, pp. 10–15, 2018.

[5] K. Kondepu, F. Giannone, S. Vural, B. Riemer, P. Castoldi, and L. Valcarenghi, “Experimental demonstration of 5G virtual EPC recovery in federated testbeds,” in *2019 IFIP/IEEE Symposium on Integrated Network and Service Management (IM)*, 2019, pp. 712–713.

[6] A. Banerjee, J. Cho, E. Eide, J. Duerig, B. Nguyen, R. Ricci, J. Van der Merwe, K. Webb, and G. Wong, “Phantomnet: Research infrastructure for mobile networking, cloud computing and software-defined networking,” *GetMobile: Mobile Computing and Communications*, vol. 19, no. 2, pp. 28–33, 2015.

[7] J. Breen, A. Buffmire, J. Duerig, K. Dutt, E. Eide, A. Ghosh, M. Hibler, D. Johnson, S. K. Kasera, E. Lewis *et al.*, “POWDER: Platform for open wireless data-driven experimental research,” *Computer Networks*, vol. 197, p. 108281, 2021.

[8] V. Marojevic, I. Guvenc, R. Dutta, M. L. Sichitiu, and B. A. Floyd, “Advanced wireless for unmanned aerial systems: 5g standardization, research challenges, and aerpaw architecture,” *IEEE Vehicular Technology Magazine*, vol. 15, no. 2, pp. 22–30, 2020.

[9] *UNIVERSITY OF BRISTOL 5G TESTBED*. [Online]. Available: https://5ginfire.eu/university-of-bristol-5g-testbed/

[10] *ESPOO Aalto 5G research infrastructure*. [Online]. Available: http://5gtnf.fi/sites/espoo/

[11] *Ericsson 5G radio test bed biggest contribution to 5G development in Asia*. [Online]. Available: https://www.ericsson.com/en/news/2015/10/ericsson-5g-radio-test-bed-biggest-contribution-to-5g-development-in-asia

[12] *5G Playground*. [Online]. Available: ”https://www.fokus.fraunhofer.de/go/en/fokustestbeds/5g playground”

[13] S. Malkowsky, J. Vieira, L. Liu, P. Harris, K. Nieman, N. Kundargi, I. C. Wong, F. Tufvesson, V. Öwall, and O. Edfors, “The world?s first real-time testbed for massive MIMO: Design, implementation, and validation,” *IEEE Access*, vol. 5, pp. 9073–9088, 2017.

[14] “Nitos - network implementation testbed using open source platforms, [online] available: http://nitlab.inf.uth.gr.”

[15] S.-J. Yoo, D. Cypher, and N. Golmie, “Timely effective handover mechanism in heterogeneous wireless networks,” *Wireless Personal Communications*, vol. 52, no. 3, pp. 449–475, 2010.

[16] Y. Li, Q. Li, Z. Zhang, G. Baig, L. Qiu, and S. Lu, “Beyond 5g: Reliable extreme mobility management,” in *Proceedings of the Annual conference of the ACM Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication*, 2020, pp. 344–358.