Towards Private 5G O-RAN Implementation: Performance and Business Validation

Vanlin Sathya, Lyutianyang Zhang, and Mehmet Yavuz
Celona. Inc, Cupertino, California, USA.
Email: vanlin@celona.io, lzhang@celona.io, mehmet@celona.io

***Abstract*—The requirements in terms of security, packet drop, and reliability (*i.e.,* jitter) for the applications such as Augmented Reality/Virtual Reality (AR/VR), Industrial IoT (IIoT) have become more demanding and subsequently, motivate the need for private 5G deployment. In general, 5G NR base stations (gNB) can be either deployed in integrated mode (PHY, MAC, and PDCP layers in one node) or split architecture mode, also known as O-RAN (lower PHY Radio Unit (RU), and the remaining layers from higher MAC to Packet Data Convergence Protocol (PDCP) at Base Band Unit (BBU)). This paper showcases the first private 5G NR Standalone deployment with O-RAN architecture on the shared spectrum *i.e.,* Citizens Broadband Radio Service (CBRS) frequency from 3.55 to 3.7 GHz. Since many private 5G deployments (e.g., warehouses with IoT devices such as IP cameras) are uplink heavy due to the nature of the traffic, we configure the UL-heavy 5G NR network and study the reliability of the system in the loaded and unloaded scenarios for both static and mobile environments.**

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I. Introduction

With the advent of 5G technology, various frequency bands such as FR 1 and FR 2 [1], [2][1] are utilized to support better network stability than 4G LTE. Although current 5G technology can provide stability [3], various network services have multiple requirements that often extend beyond only stability. Various communication demands have been categorized as enhanced mobile broad-band (eMBB), ultra-reliable and low-latency communication (URLLC), and massive machine type communications (mMTC). The co-existence of such a diverse variety of applications requires a versatile network that supports all features. Unfortunately, all these targets typically require an intelligent software structures that can be challenging for the traditional 5G Radio Access Network (RAN) [4], [5] to integrate these structures within a single radio unit. As a result, academia and industries are trying to make the mobile network more software-driven, virtualized, flexible, intelligent, and energy efficient. A possible and popular solution to fulfill all the given requirements is to split the RAN into various parts based on the specific functionality. Splitting can make the architecture more intelligent and versatile. This new architecture is known as Open RAN (O-RAN).

In the O-RAN model, architectural upgrades are brought to the next generation 5G networks to form a flexible and split architecture that allows multiple technologies to be highly coordinated so on-demand deployments become viable. The main ideas of O-RAN include disaggregation of different radio functions via open interfaces, open APIs, open design hardware, and Machine Learning/Deep Learning (ML/DL) [6]. An open-source platform for adaptive management and control of 5G New Radio (NR) with maximal use of generic hardware and fully standardized interfaces is proposed to add intelligent functional elements and extensions to the 3GPP NR architecture. Specifically, O-RAN has introduced the hierarchical RAN Intelligent Controller (RIC) that support programmable functions called rAPPs and xApps [6]. RICs bring forth embedded ML/DL capabilities to optimize performance while minimizing operational complexity [7], [8]. It helps the Radio Resource Management (RRM) operations (admission control, mobility management, radio link management, etc.) according to diverse applications' needs. This is particularly valuable in 5G networks when addressing various vertical industries.

The introduction of open interfaces, disaggregation, and the integration of data-driven control logic will undoubtedly make next-generation cellular networks more efficient and flexible. Nevertheless, the interoperable nature of O-RAN brings more complexity, that can present challenges for service providers. Requiring them to be more careful with RAN implementation since a poorly configured O-RAN can lead to even downtime if the O-RAN does not provide precise coordination among multiple network technology providers.

In [9], xApps on a software-defined testbed with E2 message exchange procedures in controlling O-RANs is investigated in terms of stability in a simple one based station and one UE scenario. As a more ambitious study, we fully examine O-RAN performance by presenting the integrated product-level O-RAN system. This system reflects a realistic implementation that collects corresponding data such as packet drops, network stability, handover events in various traffic scenarios such as DL/UL with static and mobility scenarios. It is noteworthy that the factory surveillance, AR/VR, and radar readings demands stability in heavy UL scenarios, so, in the implementation, we mainly focus on the performance differences of packet drop rate and the average achieved jitter in UL, DL, and UL/DL scenarios. The O-RAN system we build is for performance analysis for Celona's product [10] and can also be utilized as a business validation in important use cases.

II. Celona O-RAN Prototype

In this section, we focus on the Celona's O-RAN architecture, spectrum sharing mechanism, and experiment setup for

[1]FR1 consists of Sub-6 GHz frequency bands allocated to 4G or 5G. FR2 represents the millimeter wave (mmWave) region (above 24 GHz)

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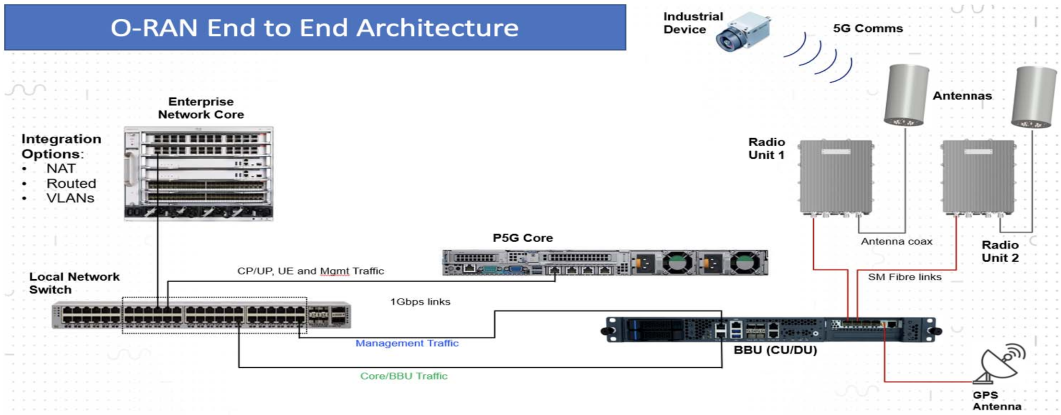


Fig. 1: 5G O-RAN 3GPP based Split Architecture.

static and mobility environments for the following business validation and performance analysis.

A. *O-RAN Architecture*

Celona's O-RAN setup is shown in Fig. 1, the UE and the Radio Unit (RU) are placed in the RF shield box[2]. The RU and BBU are connected via fiber optic cable. The GPS antenna is used for the synchronization between the RUs and BBU, i.e., 5G NR frame alignment. The Central Unit (CU) and Distributed Unit (DU) are connected to the 5GC via a local network switch. Depending on the nature of indoor or outdoor deployment, the antenna pattern can be omni- or directional sector with 33, 60, 90 or 180 degrees. The current experiment setup is based on O-RAN split 7.2, where RU has the PHY layer support, and the BBU has the higher MAC, Radio Link Control (RLC), and PDCP layer support. Typical use cases are in the warehouse, university campuses, airports, environments. The UE can run realistic traffic such as ping, iperf DL, iperf UL, and iperf DL + UL that mimics the behavior of mission-critical applications, file transfer, voice call, etc.

B. *Spectrum Sharing in O-RAN Architecture*

Most cellular operators deploy this O-RAN architecture within the licensed spectrum. In this work, we show the benefits of an O-RAN architecture using shared spectrum space *i.e.,* CBRS. In CBRS, the spectrum 3.55 to 3.7 GHz (150 MHz) with access is divided in to three tiers. The primary users are the tier 1 incumbents, and its used by government and satellite communication. The tier 2 users are the Priority Access License (PAL) users who license some portion of the spectrum *i.e,* maximum of 40 MHz per county and they can use only when there is no incumbent users near by. The third tier users are the General Authorized Access (GAA), they have rights to use all spectrum when PAL and incumbents are not on operation within the protected zone region.

In traditional integrated 4G and 5G radio, all the layers (from PHY to Radio Resource Control (RRC)) are in unit. These radios connected to Spectrum Access System (SAS) for spectrum access. In dense deployment scenario, all the 4G/5G radios are connected to a domain proxy. In turn the domain proxy [11] requests the SAS for channel allocation. This approach is beneficial because even if one radio in the deployment goes down, the spectrum will be still available so it can be used for radio backup, otherwise the radio must repeat the SAS procedure again for channel request process. Similarly, in the O-RAN architecture, each RU is connected to the BBU system. For CBRS channel allocation procedure, the BBU will connect to the SAS for spectrum allocation. And in the dense RU deployment, all the BBUs can communicate to the doamin proxy that communicates with the SAS.

C. *RAN Intelligent Controller (RIC)*

The RIC in O-RAN split architecture enables the RU to perform more automation with respect to power control, interference management, QoS management, channel allocation, and bandwidth allocation via E2 interface as shown in Fig. 2. ML/DL applications for performance enhancement can be adopted into the RIC framework. The other essential feature of the RIC system is the intelligent or learning-based mobility management based on the use case. The traditional fixed threshold approach may not be a good approach for all scenarios, especially dynamic ones. Based on the nature of mobility, traffic flows, QoS, the dynamic threshold or additional metrics need to be considered for mobility handling. This ideally handled by the RIC platform, and the decision is sent via E2 interface. Specifically, the E2 insert procedure involves messages sent from an E2 node to an xApp to notify the xApp about a specific event in the E2 node (e.g., a UE signaling the possibility to perform a handover). It is activated upon subscription from an xApp and involves a RIC Indication message (of type insert).

D. *Static Scenario*

In the static scenario, the Customer Premise Equipment (CPE) like UE is in a good channel condition with a good Reference Signal Received Power (RSRP) value, so there is

[2]The mobility experiments are performed based on the attenuator, which triggers the threshold for handover scenarios

no fluctuation in the signal, packet drop and performance in DL and UL. Hence, the CPE will attach to the single RU. This scenario will be the base case to understand the maximum performance of the O-RAN system. In the real world, the Automated Guided Vehicles (AGVs) move at different velocities, which leads to handover (HO) within the same BBU and different BBU as discussed in detail in the next section.

E. Mobility Scenario

In a 5G split architecture, there are four types of high-level mobility possible at the real-time deployment where intra- and inter-Radio Access Technology (RAT) handover is supported [12].

- *Inter-Frequency handover:* In this scenario, where two RUs operate on two different CBRS frequency so there is no co-channel interference between the radios. Then, if the CPE moves from one RU to the other RU, when the target cell Reference Signal Received Power (RSRP) is better, we call this behavior as Inter-Frequency handover.
- *Intra-Frequency handover:* In this scenario, the two RUs operate on the same CBRS frequency leads to co-channel interference. The handover is triggered based on the RSRQ offset value.
- *Intra BBU handover:* In this scenario, the two RUs belong to the same BBU (where, CU and DU belong to the same BBU) and the handover between two RUs we call this as intra BBU handover.
- *Inter BBU handover:* In this scenario, the two RUs belong to the different BBU (where, CU and DU belong to the different BBU) and the handover between two RUs we call this as inter BBU handover.

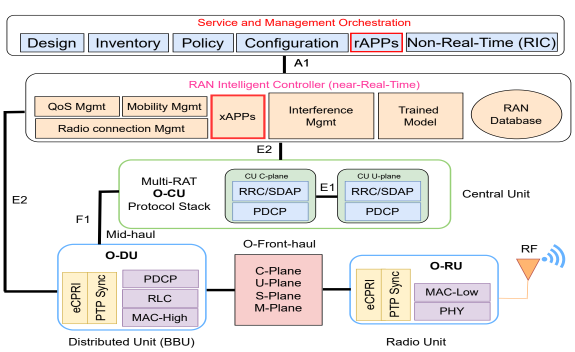


Fig. 2: O-RAN Block Architecture.

A2 entering and leaving conditions are defined as $Ms + Hys < Thresh$ and $Ms - Hys > Thresh$ respectively, where Ms, Hys, and Thresh are defined as measurement result of RSRP from the serving cell, hysteresis parameter, and Threshold parameter. Note that A2 event represents the serving cell becomes worse than threshold so that a new serving cell or operating frequency is needed.

A3 event is where a neighbor becomes offset better than serving cell, whose entering and leaving conditions are $Mn + Ofn + Ocn - Hys > Ms + Ofp + Ocp + Off$, where Mn, Ofn, Ocn, Ofp, Ocp, and Off denote RSRP of neighbouing cell, the measurement object specific offset of the reference signal of the neighbor cell, the cell specific offset of the neighbor cell, the measurement object specific offset of the serving cell, the cell specific offset of the serving cell, and the offset parameter for this event, respectively. A5 entering conditions are $Ms + Hys < Thresh1$ and $Mn + Ofn + Ocn - Hys > Thresh2$. A5 leaving conditions are $Ms - Hys > Thresh1$ and $Mn + Ofn + Ocn + Hys < Thresh2$. Note that both conditions must be satisfied to trigger either A5 entering or leaving event.

TABLE I: Deployment & Configuration Parameters

Parameter	Value
Experiment Environment	Indoor
Number of RUs	2
Number of BBUs	2
Experiment Bandwidth	40 MHz
Experiment Frame Format	3U1S1D
RU Placement	RF shield box
RU MIMO Support	4×4
Mobile devices used	Industrial CPE
CBRS SAS Enabled	Yes
CPE MIMO Support	2×2

In 5G, the inter-frequency is triggered by A2 and A5 events, both of which have two different thresholds. The intra-frequency is triggered based on A3 offset value. The messages sequences of the inter-frequency or inter BBU handover is based on measurement report for A2 event, RRC reconfiguration, measurement report for A5 event, handover request, and handover successful. Similarly, for the intra-frequency or intra BBU, handover is based on measurement report for A3 offset, RRC reconfiguration, handover request, and handover successful.

III. Business Use-Case Models

In this section, we demonstrate the deployment of the private 5G system in business use case.

A. Private 5G

In the past, carrier networks, like AT&T or Verizon, were the only options available for organizations looking to leverage cellular networks in their business. These commercial networks provide little to no flexibility in terms of coverage or how bandwidth is used over your network. For example, a healthcare provider wants to guarantee the availability of their medical application. In a commercial network, there is little they can do to guarantee up-time or ensure required service levels for that application.

The main distinction between commercially available 5G and private 5G networks is that organizations own every part of their private 5G network. Similar to enterprise Wi-Fi, private 5G networks have complete control over their network resources, and how those resources are used and distributed. Private cellular networks allow operators to better control their network resources. Strict traffic handling policies can be defined, enforced and synchronized for discrete applications, groups, devices, and subnets across enterprise environments.

B. Private 5G Use-cases

Predictable performance is the most wanted feature for today's business-essential applications. For many environments, Wi-Fi is oversubscribed with unstable performance due to the random access mechanism of IEEE 802.11 DCF. With a cellular O-RAN, embracing an additional lane for wireless connectivity in the enterprise is now possible. The possible potential uses cases as listed below.

1) ***Industrial IoT (IIoT):*** Private 5G rises to industrial challenges by having the increased capacity to reliably support thousands of IIoT sensors and robotic machines in complex environments. Since factories and industrial processes cannot afford downtime, replacing machines is often costly and impractical. Instead, manufacturers leverage IoT sensors to help gain new insights on machines and send alerts to maintenance in case problems arise, where IIoT sensors require continuous and deterministic wireless access, often over an area of thousands of square feet. Consequently, private 5G networks enable factories as such to build the split O-RAN network to support IIoT sensors and other technologies. Promising 5G applications in Key Industry 4.0 are shown as follows:

- ML/DL aided robots requires high stability for large training set
- M2M communication with precise robot control
- Performance monitoring for maintenance in factories

2) ***Healthcare:*** Healthcare networks usually encompass multiple medical devices, such as patient sensors and monitoring devices. Devices must remain secure and accessible. Moreover, Patient data must remain accessible and data transmissions highly secure. Moreover, patient data must remain confidential but available to the hospital and doctors. Hospitals utilize IoT sensors to track the performance and location of vital hardware such as insulin pumps, ventilators, crash carts, and EKG machines. Since cellular devices use secure SIM authentication, cellular networks are proving to be a much more secure option than other wireless alternates, making it easier to stay compliant. Even in the busiest hours, hospital IT staff can rest easy knowing their 5G network can reliably support a growing number of patients, visitors, and device inventory. Some key healthcare 5G use cases are the following:

- Inventory management of machines, drugs, supplies, and medical waste
- Critical clinical communications between doctors and staff
- Physical location tracking of life-saving equipment
- Preventive maintenance sensors that automatically create work orders
- Secure, reliable, and fast cross-campus service for both staff and patients

3) ***Education:*** Both college campuses and K–12 schools can leverage private 5G to provide campus-wide network access. College campuses have the challenging task of providing secure network access for students and staff across the size of a small town. This can be a challenge, especially with multiple buildings and outdoor study areas that need wireless access. The higher transmit power levels that cellular networks offer to makes it easier and cost effective to provide blanket coverage over many acres of indoor and outdoor space. Through indoor and outdoor infrastructure, college campuses can ensure that lecture halls, study areas, and outdoor spaces are adequately covered.

Long-range roof-mounted antennas can extend well beyond the campus ground and allow students to access school resources from home, even without internet access. Since each device uses SIM technology, IT staff can easily manage devices and segment staff and student networks. Some key education 5G use cases are the following:

- Providing controlled internet access for students at home where commercial 5G is not well-supported
- Long range, reliable wireless backhaul for Wi-Fi
- Reliable cellular blanket coverage across campus
- Study room availability, library service, and classroom attendance tracking.
- Securely segment staff and students networks
- Fast and reliable outdoor learning

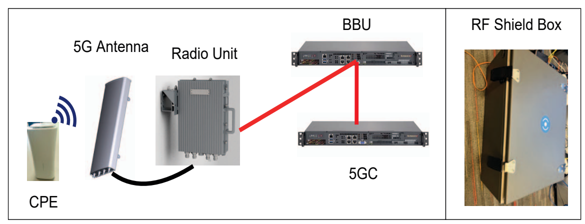
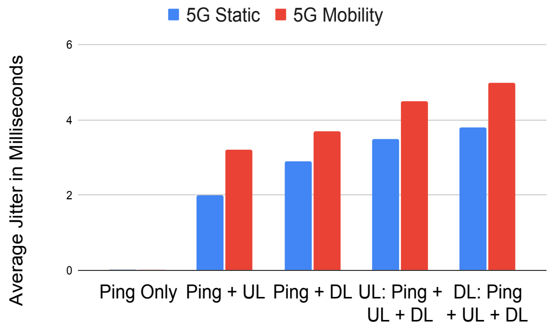


Fig. 3: O-RAN Experiment Equipment.

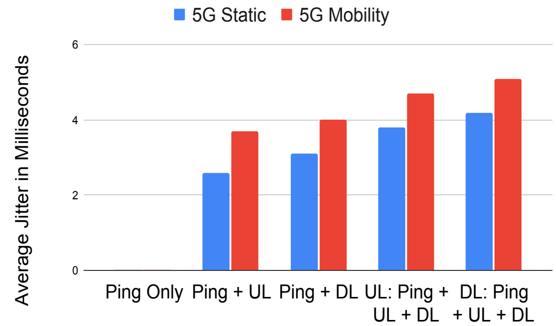
4) ***Smart Cities:*** City governments can use 5G networks to provide better services to their citizens, track public utilities, and monitor city infrastructure proactively. Services such as waste management and water treatment can use 5G networks to track their fleet and monitor critical infrastructure for issues. IoT-enabled dumpsters and trucks can monitor fleet inventory and help cities understand how much waste they produce and where that waste accumulates. Transportation departments can use 5G to monitor for highway congestion and reliably access high-definition, live video feed of traffic cameras across the city. Potential 5G use cases for smart cities include:

- Fleet tracking
- Surveillance for public safety with IoT sensors
- City-wide video surveillance and traffic cameras
- Secure and controlled internet access for residents

5) ***Military:*** In this scenario, the architecture needs to be more dynamic based on the situation, for example: *war zone*. The proposed O-RAN architecture is capable of working on any available spectrum like Department of Defense operation band (3.1 to 3.45 GHz), CBRS (3.55 to 3.7 GHz) or any special spectrum reserved for military radar operation. The proposed method even allows to move the edge cloud functions such as Access and Mobility Management Function (AMF), Session Management Function (SMF), Unified Data Management (UDM), User Plane Function (UPF), Policy Control Function (PCF), close to BBU, allowing more flexibility in the war zone area, in case of centralized node failure. In future, we plan to support 3GPP release 16 feature Integrated Access



(a) Average Jitter in Intra BBU



(b) Average Jitter in Inter BBU

Fig. 4: *Network Reliability: Loaded and Unloaded Scenario for Static and Mobility Environment*

and Backhaul (IAB) as a wireless solution, which enable more robust communication. The potential use cases are as follows:

- Provides coverage in all types of terrains
- Broad wireless coverage across all types of terrains
- Enabling IAB support reduces the need of cabling in the O-RAN setup, which allows to have the node anywhere in war zone for example: Helicopter

*6) **Entertainment**:* Indoor Gaming, AR/VR, stadiums, and theme parks all face challenges regarding reliability. Increased transmit power levels for 5G allows organizations to cover large areas with significantly less hardware than other wireless technology. Using multiple frequency bands and various hardware, entertainment companies can ensure reliability and stability either indoor or outdoor. Small and medium cell towers throughout the park can provide blanket coverage for guests and staff members. Since 5G has such a large device capacity, the network will not grind to a halt when the park is full, or the stadium is packed. A few key entertainment 5G use cases are the following:

- Secure and reliable guest access through neutral host services
- High-speed indoor and outdoor network access
- Reliable wireless service to a large unpredictable number of devices

In this section, we fully describe the potential business use case for 5G O-RAN. To be more realistic with the industry 4.0 environment, performance of 5G O-RAN such as packet drop rate and jitter will be concentrated on the UL since the network that is mostly loaded with UL data resulted from IoT in industry such as factory surveillance, radar readings, etc. We implement real setup of Celona 5G O-RAN, collect corresponding data and fully explain the performance superiority in the following section.

IV. Experiment Results and Discussion

In this section, we analyze the performance of ping with Transmission Control Protocol/User Datagram Protocol (TCP/UDP) loaded and unloaded scenario for static and mobility environment. Please note that in this section we refer 5G O-RAN as 5G for simplicity in this section.

A. Experiment and Traffic Scenarios

In our 5G O-RAN system, the DL and UL iperf traffic go through our own deployed server (in the 5GC edge). Both the DL and UL traffic is TCP. We loaded the network by enabling multiple TCP connections (*i.e.,* 60 parallel streams) over the iperf. This emulates the scenarios with 25 to 30 UE and 1 DL 1 UL or 2 DL 2 UL devices. We also run the experiment on UDP with the different packet size. The ping packets are transmitted at the interval of 10 ms, and the time to live is 64 hops with the ICMP packet mode. The timeout duration of the ping packet in the experiment is 1000 ms. In the experiment, the RSRP is in the range of -66 to -94 dBm, SINR is in the range of 18 to 33 dB and the MCS is in the range of 16 to 27. The total number of packets sent in this experiment is 2000. The experiment procedures are as follows.

- Ping-only experiment with the packet interval of 10 ms
- Ping experiment with iperf TCP UL experiment
- Ping experiment with iperf TCP DL experiment
- Ping experiment with iperf TCP UL and DL experiment
- Ping experiment with iperf UDP UL and DL experiment

TABLE II: Average 5G Ping Packet Drop in %

Different Types of Traffic	Intra BBU Static	Intra BBU Mobile	Inter BBU Static	Inter BBU Mobile
Ping Only	0	0	0	0
Ping + UL	0.001	0.01	0.002	0.05
Ping + DL	0.001	0.03	0.002	0.1
Ping + UL + DL	0.006	0.05	0.005	0.15

B. TCP Static: Intra and Inter BBU Analysis

In this experiment, we configure each RU to the UL heavy frame format *i.e.,* 3 uplink and 1 downlink (3U1D) slot to meet the warehouse requirements. The 40 MHz bandwidth is configured to each RU in the system with the maximum indoor transmission power to 30 dBm (as specified by OnGo alliance for CAT A in CBRS spectrum). Fig. 3 shows the hardware experiment setup. For 2 RUs, we configure both intra and inter BBU scenarios. We use the NR subcarrier spacing (SCS) as 30 KHz to support CBRS specification. In both static and mobility scenarios, we guarantee the QoS for different types of traffic on the system by enabling different QoS Class Identifiers (QCIs). The MAC scheduling algorithm allocates the radio resources effectively based on the QCI marking (for example, QCI 1, Guaranteed Bit Rate (GBR) for traffic 1 and QCI 9 for traffic 2). In both intra and inter BBU scenarios, the UE/CPE is static, and RSRP fluctuation is low.

Table II and Fig 4 (a) show that the average packet drop rate and jitter between the intra BBU scenario with different realistic traffics such as ping only, ping + UL, ping + DL, ping + UL + DL. We observe that, as the load of the network increases, packet drop rate is higher and the average jitter decreases slightly. However, the jitters of the DL and UL system are maintained stable in 3U1D frame slot configuration. This is because, though there is only one DL slot NR frame pattern compared to three UL slot, the RU is capable of four parallel stream transmission and UE is capable of two parallel transmission, which leads to balanced DL and UL in 40 MHz bandwidth. Table II and Fig 4 (b) show the average packet drop and jitter between 5G inter BBU static scenario. The average packet drop rates for the intra and inter BBU are less than 0.15%.

C. TCP Mobility: Intra and Inter BBU Analysis

In this section, we discuss the mobility scenario between the intra and inter BBU in 5G. In intra BBU, the RU 1 and RU 2 are connected to the same BBU where CU and DU are connected. As for the inter BBU handover, the RU 1 and RU 2 are connected to two different BBUs, so when the CPE moves from one BBU to another BBU in the contention-free preamble, the 5G control signal and PDU session need to be routed from one BBU to another BBU, which are in turn routed to the corresponding RU. Mobility testing with two enabled different QCIs shows good result in Fig. 4 (a), (b) and Table II. Compared to the static scenario, we see slight fluctuation on the packet drop and jitter performance for intra BBU 5G system. This is because the attentuator at the RF shield box triggers a handover by decreasing the threshold serving RU which in turn leads to low MCS and better stability compared to the static scenario. The mobility average performance is measured over 100 handovers from RU1 to RU2 and vice versa.

D. UDP Static and Mobility: Intra and Inter BBU Analysis

To mimic the realistic nature of UDP, we transmit the low demand data in DL. The ping packets are transmitted in the interval of 10 ms. The average SINR is in the range for static and mobility experiment is 28 to 32 dB on 5G system.

As the focus of the deployment is warehouse with UL heavy traffic, we slightly decrease the DL traffic *i.e.,* 50 Mbps and maintain the full UL traffic with the existing ping, then for the intra BBU static scenario, we observe that the 5G system can achieve the packet drop of 0.01% in ping + UL + DL. In ping + DL, ping + UL, and ping only, there is no packet drop. For intra BBU mobility scenario, we observe that the 5G system can achieve with the packet drop of 0.05% in ping + UL + DL. In ping + DL and ping + UL, the packet drops are less then 0.04% and there is no packet drop in ping only traffic. Similarly, for the inter BBU static and mobility scenario in 5G, we observe the packet drop of 0.03% in ping + UL + DL. In ping + DL, ping + UL, and ping only there is no packet drop. And on inter-BBU mobillity scenario, we observe the packet drop of 0.08% in Ping + UL + DL. In ping + DL and ping + UL, the packet drops are less then 0.01% and there is no packet drop in ping only traffic.

V. Conclusion and Future Work

In this paper, we extensively describe the deployment of the first private 5G with split O-RAN architecture aided by the CBRS shared spectrum model. We test the setup with realistic ping traffic, which mimics the behavior of mission-critical applications. The O-RAN architecture yields a great benefit in reliability for both static and mobility with loaded and unloaded (ping only) scenarios since it shows robust performance in terms of packet drop and jitter, *i.e.,* stability. Future work involves investigations of the dense deployment with more RUs and more BBUs in terms of performance. Also, optimize the handover thresholds for inter and intra BBU based on ML/DL at RIC and visualize the performance benefits in the dense mobility scenario.

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