FlexCRAN: A Flexible Functional Split Framework over Ethernet Fronthaul in Cloud-RAN

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***Abstract*—Thorough investigation of the Cloud-RAN (C-RAN) architecture has recently shown that C-RAN can bring advanced cooperated and coordinated processing capabilities as well as the multiplexing gains toward future radio access networks. The baseband processing of each base station instance can now be flexibly split into smaller functional components, that can be placed either at remote radio units (RRUs) or baseband units (BBUs), depending on the available fronthaul (FH) performance. Additionally, with the wide adoption of Ethernet in data centers and core networks, the Radio over Ethernet (RoE) approach is now considered as an off-the-shelf candidate for the FH link. To this end, we propose a unified RRU/BBU architectural framework for C-RAN that can support both a flexible functional split and a FH transport protocol over Ethernet. Furthermore, we experimentally evaluate the main key performance indicators (KPIs) of an operational C-RAN network built based on OpenAirInterface (OAI), a software implementation of LTE/LTE-A systems, under two functional splits and different deployment scenarios.**

I. Introduction

Due to the widespread adoption of the cloud computing concept, the currently distributed radio access network (D-RAN) architecture of 3G/4G is expected to evolve toward a cloud/centralized radio access network (C-RAN) architecture that stands out as a promising solution for 5G. In C-RAN architecture, the original base station (BS) is decoupled into centralized baseband units (BBU) and the remote radio head (RRH) at the network edge. These centralized baseband processing units can be pooled and used as shared resources, offering statistical multiplexing gains and energy efficiency. Moreover, the BBU/RRH network functions can be implemented on commodity hardware and executed on a virtualized environment, further benefiting from network softwarization and network function virtualization (NFV) concepts. Finally, the C-RAN concept facilitates advanced coordinated multi-point (CoMP) processing, which is often impractical in D-RAN setups, due to its distributed manner and the stringent synchronization constraints of CoMP [1].

Despite its appeal, one key obstacle in the adoption of C-RAN is the excessive capacity requirements on the fronthaul (FH) link that provides BBU and RRH interconnections. An important example in [2] shows that shifting all baseband processing to the remote BBU pool implies that approximately 1 Gbps rate is required on the FH link, just to support a 75 Mbps user data rate. To relax the excessive FH requirement, the concept of C-RAN is being revisited, and a more flexible distribution of baseband functionalities between the RRH and BBU is considered [3]. Rather than offloading all baseband processing to the BBU, it is possible to keep a subset of these blocks in the RRH. This concept is known as *Flexible Centralization* or *Functional Split*. The simple RRH, then evolves to be the remote radio unit (RRU) that possess more baseband processing capabilities. By gradually splitting and placing increasingly more baseband processing functions at RRUs, the FH capacity requirement reduces considerably [2]. Nevertheless, flexible centralization requires more complex RRUs and reduces the opportunities to perform coordinated processing and advanced interference avoidance. Consequently, the flexible centralization is a trade-off between what is gained in terms of relaxing the FH performance requirements, and what is lost in terms of perceived user performance under few coordinated processing that was expected in original C-RAN feature.

Another key question is how the information between the RRU and BBU is transported over the FH link. A number of FH transmission protocols are under investigation and standardization, such as CPRI [4], OBSAI [5] and ORI [6]. However, these techniques mainly consider to carry raw I/Q samples in a fully centralized C-RAN architecture. In light of the flexible centralization concept, different types of information are transported over the FH link based on the split of baseband processing between RRU and BBU. Given the extensive adoption of Ethernet in remote clouds, data centers and the core network, the Radio over Ethernet (RoE) [7] approach is a generic, cost-effective, off-the-shelf alternative for FH link traffic transport. Furthermore, while a single FH link per RRU, has previously been assumed, connecting all the way directly to the BBU pool, it is expected that the FH network will evolve to a more complex multi-hop mesh network topology, requiring switching and aggregation [8]. This topology can be facilitated by applying a standard Ethernet approach together with SDN-based switching capabilities.

Nevertheless, the impact of adopting a packet-based Ethernet FH link in different C-RAN deployment scenarios are not well-studied. To better understand this impact in a more realistic setting, both the actual considered architecture for the endpoints between the FH link (i.e., RRU, BBU), as well as the specific transport scheme for the associated Ethernet-based FH link must be addressed in more detail. Moreover, there is still no clear view about which key performance indexes (KPIs) are important to evaluate future scalable software-based deployments of the various C-RAN entities involved (e.g., RRU, BBU, RRU gateway as in Fig. 1) in making up the C-RAN network. In summary, the main contributions of this work along these directions are the following:

1) We propose an architectural framework and related implementation for a flexible RRU/BBU node, together with an Ethernet-based transport protocol over the FH link, that can support different C-RAN deployment scenarios (e.g., splits and topologies);

2) We then introduce a set of KPIs to evaluate the performance of such a C-RAN network;
3) Finally, we implement the envisioned C-RAN network architecture using OpenAirInterface (OAI) [9], and evaluate a subset of C-RAN network deployment scenarios.

The rest of this paper is organized as follows. Sec. II presents some related work. In Sec. III, we introduce the considered C-RAN network topology, and possible functional splits. Sec. IV focuses on the proposed RRU framework and Ethernet-based FH transportation scheme. Sec. V proposes some important system KPIs for C-RAN deployment. Sec. VI provides the measured statistics on these KPIs from the implemented C-RAN network using the OAI platform to validate our proposed framework. Finally, Sec. VII concludes the paper.

II. Related work

In recent years, several standardization activities are redefining the FH network towards a packet-based architecture. The goal is to design a variable rate, multipoint-to-multipoint, packet-based FH interface. Ref. [10] presents the Ethernet-based Next Generation Fronthaul Interface (NGFI) network architecture, the functional split between RRU and BBU and the possible FH topology and Ethernet packet format to support NGFI. IEEE 1904.3 task force specifies the RoE encapsulations, transport protocol and the mapping from CPRI to RoE and vice-versa in [7], without considering functional splits. The Next Generation Mobile Network (NGMN) Alliance considers Ethernet as one potential technology for FH transportation [11] and the packet-form encapsulation as an efficient way to get statistical multiplexing gain, unlike the case of a constant stream (e.g., CPRI) method [12]. In [13], the authors provide the design requirements to utilize the RRU-BBU functional split and point-to-multipoint topology in packet-based FH transportation. [14] proposes to utilize Ethernet as the underlying transport layer with low-latency Ethernet switching for the RRU-BBU functional split over C-RAN. [15] analyzes factors that are challenging in synchronization of FH utilizing Ethernet network. [16] analyzes the packetization and packet scheduling impact on different functional splits considering the packet-based transportation. [17] provides a synchronization architecture for Ethernet-based FH interface. [18] measures statistical distribution for packet inter-arrival delay from a testbed transports I/Q samples and generic Ethernet traffic.

Summarizing, all these aforementioned studies are conducted assuming a packet-based Ethernet transportation for the FH. However, to the best of our knowledge, there is no related work investigating real implementation approaches for such packet-based transport, that also considers flexible functional splits under different C-RAN deployment scenarios. To this end, one main novelty of our work is to propose a flexible RRU/BBU architecture together with an Ethernet-based FH transport protocol for modern C-RANs. A further novelty is that the proposed architecture is implemented and tested using the OAI, considering a set of KPIs for different functional splits and C-RAN deployment scenarios.

III. System Model

A. Considered C-RAN Network Topology

The initial C-RAN topology only supports point-to-point FH links, with the possibility of daisy-chaining the RRUs. However, the FH network is now evolving to support a more complex topology (e.g. tree, mesh) that is expected to converge with the backhaul network [19]. In this work, we focus on a multi-segment FH network topology in Fig. 1. The considered topology can support a generic mesh deployment of the FH network, that can be shared with other (RRU) traffic flows.

First, part of the baseband processing (which depends on the chosen functional split) is performed at the respective end point (e.g., RRU for uplink, BBU for downlink). Then, samples are packetized into Ethernet frames that can be transported through the FH interface. The RRUs are aggregated and multiplexed/demultiplexed at the RRU gateways, where the packets are switched or routed between RRUs and the BBU pool. The RRU gateways can also be utilized to transport not only the C-RAN traffic, but also other traffic flows, which is inline with the concept that the C-RAN network could reuse already deployed Ethernet networks. Moreover, the BBU can be pooled and distributed centrally in the cloud, or at the network edge in some aggregated points. Finally, the remaining part of the baseband processing is performed at the respective endpoint (BBU for uplink, RRU for downlink), again depending on the functional split, after receiving all necessary packets from the RRU for each transportation time interval (TTI). Fig. 1 also shows how the considered C-RAN architecture can be mapped to the three-tier C-RAN architecture proposed by the NGFI (i.e., RRU, Radio Aggregation Unit (RAU) and Radio Cloud Center(RCC)) in [8].

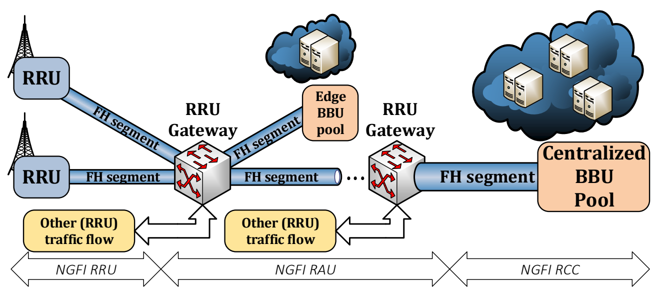


Fig. 1: Considered C-RAN network topology

B. Functional Split in C-RAN

The functional split chosen between the RRU and BBU highly affects the packet characteristics and the resulting FH data rate. In this work, we follow the split definition of [16] (split A, B, C, D, E) and extend to split H (i.e., from split A to split H) as in Fig. 2. We further consider that both downlink and uplink processing are split between the RRU and BBU. These functional splits can be mapped to the interface (IF) surveyed by different organizations, e.g., NGFI [8], small cell forum (SCF) [20], NGMN [12] and 3GPP [21] as shown in Fig. 2. The intermediate data samples, resulting from the initial baseband processing of a split, are then packetized, i.e., packed into the payload of Ethernet frames, and transported through the FH interface. In this work, we focus on I/Q data transportation over the FH links for two specific splits in cell-processing domain: split A at time-domain, and split B at frequency-domain.

IV. RRU/BBU Flexible Architecture and Ethernet-based Fronthaul Transport

While RRUs require dedicated radio frequency (RF) front-end devices and synchronization mechanisms with the BBU,

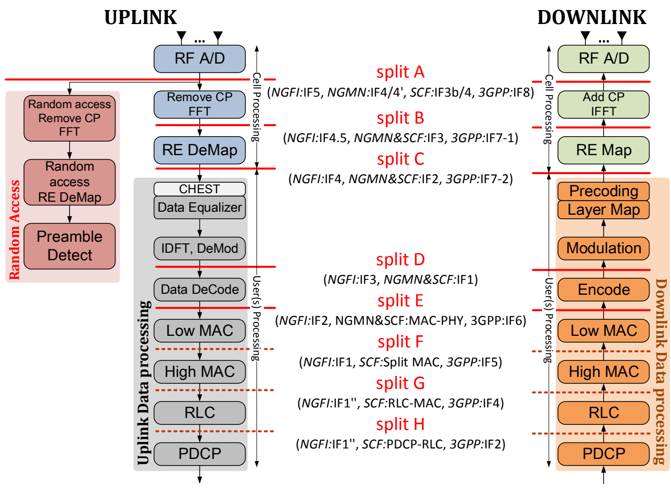


Fig. 2: Functional splits

both BBU and RRU need to share the same set of baseband functions, in order to allow for on-the-fly changes in the functional split definition per BS instance. In addition, the associated Ethernet-based FH interface needs to be designed to support the envisioned RRU-BBU dynamic relationships and associations. Towards these two directions, we provide a flexible RRU/BBU framework, as well as an Ethernet-based FH transport protocol that are implemented in OAI platform.

A. *Flexible RRU/BBU framework*

In general, the RRU is an entity that hosts multiple RF front-end devices, processes the incoming samples based on the split, and transmits/receives digitized samples through the connected FH interface. These functions are also (mostly) mirrored in the BBU as well. The flexible RRU/BBU architecture that we propose is shown in Fig. 3, and comprises the following main components:

- **RF front-end configuration and monitoring unit**: It is responsible to apply the configuration (e.g., Rx/Tx gains, Rx/Tx operating frequencies, etc.), indicated by the BBU, to the RF front-end equipment and to provide the status report to the BBU. Thus, it serves as an agent on behalf of the BBU for the (re-)configuration and monitoring of the RF front-end devices.
- **Split IF function unit**: It performs the split-specific signal processing on the incoming data samples in both uplink and downlink directions based on the different functional splits shown in Fig. 2. The underlying split is configured/reconfigured by the BBU. Moreover, there are two ways to deploy the baseband functions at RRU: (i) Split-specific deployment that only deploys the necessary functions at RRU to save the expenditures but with the loss in terms of fewer flexibility of RRU-BBU splits, or (ii) Flexible-split deployment that deploys all baseband functionalites at RRU (i.e., similar to legacy BS) to change the RRU-BBU split on-the-fly.
- **(De-)Compression unit**: It provides a (de-)compression service for the data samples, to lower the FH capacity requirements, and is configured by the BBU. Different compression approaches can be supported: (i) lossless compression that can reconstruct original data perfectly, and (ii) lossy compression that permits reconstructing an approximate version of the original data. In this paper, we use a simple lossy compression on the data samples (detailed later) to significantly decrease the FH bandwidth, at the cost of potentially higher packet loss.

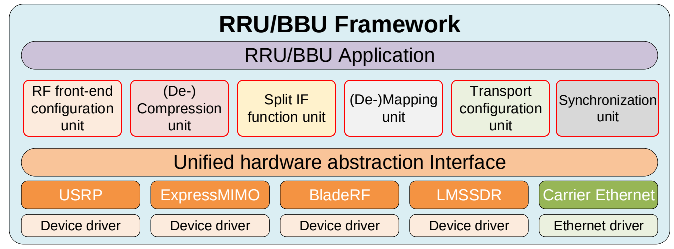


Fig. 3: Proposed RRU/BBU framework

- **(De-)Mapping unit**: It maps the corresponding BBU to each connected antenna port of the RRU and constitutes a control information transported in each packet. Via the mapping approach, the extra antenna identity is included in the header and the packet will be transported through the according interface to/from the corresponding remote BBUs. This antenna identity can be further combined with component carrier identity as the antenna-carrier (AxC) combinations per data flow.
- **Transport configuration unit**: This unit serves two purposes. First, it applies the packetization scheme, chosen by the BBU, i.e., the payload size (as a function of the radio bandwidth) and the network maximum transmission unit (MTU) for the FH link. Secondly, it adjusts the timestamp between the RRU and BBU, with respect to round trip time (RTT) statistics continuously measured between the two. The timestamp of each packet is generated to have a reference clock of the RF front-end hardware. When a packet reaches the BBU pool, it bears the time value of the RF front-end device when the payload was generated. On the other hand, when a packet reaches RRU, it is stamped with an adjusted version of this timestamp.
- **Synchronization unit**: It enables the synchronization mechanisms to provide a reliable frequency distribution from the BBU across multiple RRUs. The IEEE 1588 protocol can be used to provide a precise synchronization through a grandmaster (i.e., BBU in C-RAN) acting as a time server.

Corresponding to these six units, there are six categories of RRU parameters configured/reconfigured by the BBU: (i) RF front-end parameters, (ii) DL/UL baseband and split parameters, (iii) (De-)Compression parameters, (iv) (De-)Mapping parameters, (v) FH link transport parameters, and (vi) synchronization information. Moreover, an unified hardware abstraction interface is provided to read/write data samples from/to different types of commercial off-the-shelf (COTS) RF front-end devices as well as the Ethernet devices. This common interface enables the RRU/BBU to stream incoming/outgoing data samples through different interfaces. Further, the RRU/BBU application on top of the framework can locally configure/reconfigure the underlying framework and retrieve information for the control and management purposes.

B. *Ethernet-based FH transportation scheme*

The proposed scheme aims to provides a flexible, multipoint-to-multipoint, packet-based networking solution between RRU and BBU. Therefore, our proposed approach is aligned with the RoE standardization direction but supports functional splits. Moreover, it can be extended for more complex C-RAN topologies. A top-down description of each layer is as follows:

- **Topology Layer**: The relationship between BBU and RRU from a high-level perspective follows the *client-server model*, where a BBU acts a client and an RRU as a server. This model allows a BBU to dynamically associate itself to a set of RRUs (1:n relationship), asymmetrically in RX and TX, depending on the desired coordinated transmission and reception mode.
- **Interface Layer**: The FH interface consists of two logical streams:
  1) *Control*: It carries packets for in-band or out-of-band control used for RRU configuration and management. Out-of-band control is mainly used for parameter setup at the RRU side, during the configuration setup period.
  2) *Data*: It carries I/Q data samples that are packed in the payload of Ethernet frames. For Split B in the uplink direction, an extra flag is added in the data stream, in order to differentiate between the two types of I/Q data samples, those belonging to the random access channel and those to the non-random access channel (see Fig. 2).
- **Session Layer**: For simplicity, it is assumed that the RRU and BBU are mapped statically. It means that the association between them is pre-defined, so there is no need for network discovery and link set-up at this level. However, this pre-defined association can be extended easily with the addition of discovery and handshake messages, to be transported in the beginning. What is in place, regarding the RRU-BBU session, is the configuration of parameters on the RRU side by the BBU. In particular, the BBU sends a set of parameters to configure the RRU and, as soon as the RRU acknowledges its reception, the data samples are able to be transported between these two endpoints.
- **RoE Layer**: To utilize the off-the-shelf Ethernet approach in terms of underlying protocol and packet format, the design approach here is to make the Ethernet MAC frame to be unaware of the fact that it carries the I/Q data samples and use the pre-defined Ethernet frame structure. However, the extra sub-header is multiplexed with the I/Q data samples as the preamble for identification. The proposed encapsulation method and sub-header format are as follows:
  1) **Encapsulation method**: The packet payload is constructed using a split-aware encapsulation method, i.e., the end-point (BBU/RRU) of a FH link is aware of the data type (i.e., time-domain sample for split A and frequency-domain sample for split B) to be encapsulated. To this end, both BBU and RRU can properly initiate the sample decapsulation, based on the functional split.
  2) **Sub-Header format**: The split-dependent sub-header provides a minimum set of information, in order to decapsulate the payload. For Split A and B, the sub-header format is listed in Table I and II, respectively. The size of the payload is configured during the configuration setup stage; as a result, there is no need to include it in the sub-header. Moreover, the subtype in Table II is used to differentiate packets of different LTE physical channels in the same data stream, for example, the physical random access channel and other uplink physical channels from RRU to BBU in Split B.
- **Transport Layer**: Two approaches are considered and implemented: the UDP and RAW Ethernet transport. The RAW mode utilizes the raw Ethernet that transports packets with minimal processing delay. However, it requires a virtual LAN [1] and spanning tree to support the one-to-many relationships between RRU and BBU, as well as the multiplexing in wide area network. On the other hand, UDP-based FH transport protocol offers the ability to accommodate multiple data flows under the same Ethernet interface at the slightly higher processing cost in the protocol stack, which can be mitigated using the zero-copy methods (e.g., Intel Data Plane Development Kit (DPDK) [2] and NetMap framework [3]).

TABLE I: Sub-header format of Split A

Field	Size(bits)	Description
Timestamp	64	The time when the payload was generated by the RF front-end equipment
Antenna ID	16	Used to map a packet to the antenna of the RF front-end equipment
Sequence number	16	Specify the packet sequence number used to reception serialization

TABLE II: Sub-header format of Split B

Field	Size(bits)	Description
LTE time unit	32	Includes the indexes of frame, subframe and symbol
Antenna ID	16	Used to map a packet to the antenna of the RF front-end equipment
Subtype	16	Specify the packet type: downlink data, uplink data or random access

V. C-RAN SYSTEM KEY PERFORMANCE INDEX

In this section, we present some important KPIs for C-RAN that will be used to evaluate the C-RAN implementation using the OAI. These KPIs can be further used as the performance metrics of different deployment scenarios, e.g., RRU-BBU functional split, data sample compression, etc. Next, we elaborate these KPIs in three different categories:

A. *FH-related KPIs*

- **FH link throughput**: It measures the network throughput in terms of bits per second (bps) over the FH link between RRU and BBU. This KPI can be used for FH link capacity provisioning during C-RAN deployment. Moreover, the required capacity can be reduced under the compression scheme. In this work, we apply the *A-law* compression algorithm to compress each incoming sample with 16-bit I/Q parts into 8-bit form on both parts. That is to say, the compression ratio is 50%.
- **RTT of FH and RTT of RF front-end**: It measures the round-trip latency between the FH link and RF devices. This KPI is important to evaluate the possible RRU-BBU functional split. For example, NGMN adopt 250μs as the maximum one-way fronthaul latency [12] and SCF categorize the one-way FH latency from 250μs to the millisecond level to evaluate the applicable RRU-BBU split [20]. Our measurement on the RTT of FH is defined as the time elapsed at RRU between the start of sending the receiver data samples and the end of reading the corresponding transmitter data samples from BBU on the FH link. In detail, this RTT of FH is made up of 5 components: (i) compression time, (ii) FH link writing time, (iii) FH link RTT, (iv) FH link reading time, and (v) decompression time. Moreover, the RTT of RF front-end is defined as the time elapsed between the reading of data samples from RF devices until

[1] IEEE 802.1Q is the networking standard that supports VLANS on an Ethernet network. [2] http://dpdk.org/ [3] http://info.iet.unipi.it/~luigi/netmap/

the writing of samples to RF devices, which includes the RTT of FH. Here we use the differences of timestamps at RRU side to measure the RTT of FH and RF front-end.

B. *Endpoint-related KPIs*

- **RRU/BBU hardware load**: The hardware load at the RRU/BBU comprises the CPU utilization (the percentage of CPU processing time used by a process out of the total processing time) and memory utilization (in bytes). This KPI can be utilized for two purposes: (i) Estimate the number of RRUs that can be supported under the limited number of BBUs in the pool given fixed RRU-BBU split, and (ii) Dynamic split the Tx/Rx processing based on the hardware load to fully utilize all available resources among RRU and BBU pool.

C. *Data-plane KPIs*: Before introducing the data-plane KPIs, we first clarify the relations between data-plane and FH-related KPIs. Take the delay of FH as an example, it can be absorbed and compensated by scheduling the transmission ahead of time, which in turn reduces the total Tx/Rx processing time to provide extra time for the FH transportation. However, this shortened Tx/Rx processing might not be enough for some processing (e.g., turbo decoder) in some cases [22] and this will cause the extra data-plane delay due to re-transmission.

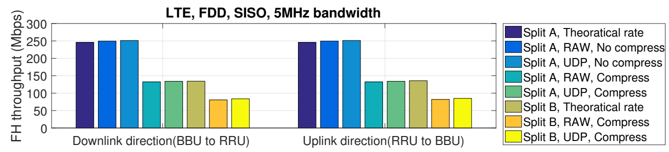
- **Data plane Quality of Service (QoS)**: To characterize the data-plane QoS in user perspective, we use the *iperf* at both user side and gateway side to measure the good-put, packet drop rate and delay jitter, both in uplink and downlink directions. Here, the good-put is the application-level successful throughput that is meaningful and significant in user perspective.
- **Data plane delay**: For this KPI, we use the application RTT over the default radio bearer utilizing the ping utility at the gateway side. This index not only considers the impact of FH link but also the Tx/Rx processing time of both RRU and BBU of both in downlink and uplink directions.

VI. Implementation Results

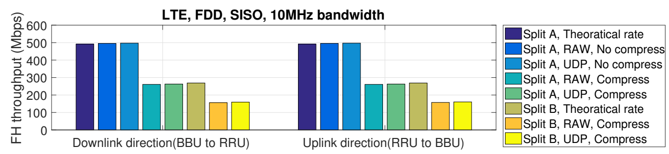
In this section, we evaluate the C-RAN implementation using the OAI [9], a software-based LTE/LTE-A system implementation spanning the full 3GPP protocol stack. Since our focus is on the evaluation of the RAN part, a third party EPC, COTS UE (e.g., Samsung Galaxy S6) and USRP B210 software defined radio are used. In following evaluations, we consider two C-RAN network deployments: (i) 0 RRU gateway (i.e., direct connection with 1 Hop between RRU/BBU) and (ii) 1 RRU gateway (i.e., 2 Hops between RRU/BBU), with each FH link segment to be made up to a 3-meter cable. For simplicity, we consider the case that the C-RAN network is composed of 1 RRU and 1 BBU. In addition, we use the LTE FDD SISO mode with 5MHz/10MHz bandwidth. As stated in Sec. III-B, only Split A and Split B that transport I/Q data samples in cell-processing domain are focused in this work.

A. FH-related KPIs

The FH link throughput as well as the theoretical rate of both 5MHz and 10MHz cases are in Fig. 4(a) and 4(b) respectively. Firstly, the RAW transmission throughput only has little overhead (between 3 to 4Mbps) compared with the theoretical rates. The UDP transportation shows little further overhead (up to 3Mbps) compared with RAW mode. Moreover, the applied *A-law* compression scheme reaches almost 50% reduction in the FH link throughput as expected. Further, using Split B shows the gain of 43.8% in terms of FH link throughput reduction compared with Split A via moving FFT/IFFT operation to RRU. This reduction ratio is close to the analysis result [2] that shows 45.3% of throughput reduction.



(a) FH throughput of 5MHz bandwidth



(b) FH throughput of 10MHz bandwidth

Fig. 4: FH throughput of 5MHz and 10MHz bandwidth

Based on the definition of the RTT of FH and RF front-end, the results are shown in Fig. 5(a) and 5(b), respectively in boxplot, and each component of the FH RTT described in Sec. V are in TABLE III and IV except for the FH link RTT. The reduction of the RTT in FH is proportional to the reduction of throughput (by a factor of 2) when applying the compression which comes at the cost of an extra processing time to perform the compression and decompression (see TABLE III) but with few FH link reading/writing time (see TABLE IV), which confirms the benefit of the compression in FH network.

In addition, it can be seen from Fig. 5(b) that the average RTT of RF front-end remains comparable for 5MHz case except when the reception over FH link in the current TTI is finished before the end of RF reading for the next TTI. However, in case of 10MHz, the RTT of FH without compression, as in Fig. 5(a), is significantly larger than the duration of 1 TTI (1ms), which in turn greatly increases the RTT of RF front-end. Finally, the results also reveal that all considered deployment scenarios can fulfill the recommended one-way delay of 250μs made by NGMN [12].[4]

TABLE III: Average time for compression/decompression

Bandwidth	Compress Time (μs)	Decompress Time (μs)
5MHz	16.53	23.43
10MHz	31.79	35.93

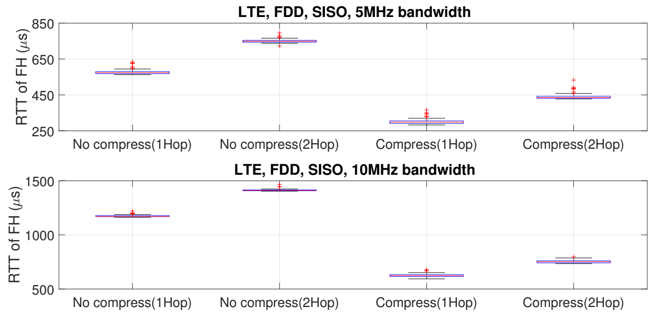
TABLE IV: Average time for FH link reading/writing

Bandwidth	Compression	Read Time (μs)	Write Time (μs)
5MHz	No	224.37	69.19
	Yes	53.13	68.80
10MHz	No	469.53	72.35
	Yes	170.13	71.95

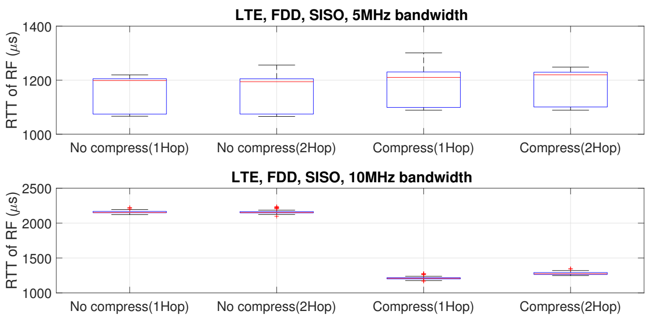
B. Endpoint-related KPIs

As for the endpoint-related KPI, we investigate the two different deployments based on the OAI platform: (i)RRU/BBU in C-RAN, and (ii) eNB in legacy D-RAN. The results are listed in TABLE V where the CPU utilization ratio is the percentage of CPU processing time of the process and the

[4] The one-way delay is computed by subtracting the FH link reading and writing time (TABLE IV), compression and decompression time (TABLE III) from one-half of the RTT of FH (Fig. 5(a)).



(a) RTT of FH of 5MHz/10MHz bandwidth



(b) RTT of RF of 5MHz/10MHz bandwidth

Fig. 5: RTT of FH and RF of 5MHz/10MHz bandwidth

memory usage is measured based on the proportional set size (PSS) in KByte. Since this index depends on the air-traffic throughput, we use the following traffic generated by iperf to measure the hardware load: 15Mbps/30Mbps in Downlink and 5Mbps/10Mbps in Uplink for 5MHz/10MHz bandwidth.

The RRU, BBU and eNB are deployed in a 6-core machine each with Intel i7 Sandy Bridge architecture in 3.2GHz; as a result, 2 CPU cores are required to deploy the proposed RRU for 10MHz Bandwidth in Split A and 3 cores for Split B[5]. Moreover, we can observe that the sum of CPU resource required by RRU and BBU is slightly higher than the one required by the eNB deployment. In addition, the memory usage at RRU and BBU does not have large differences since our C-RAN deployment is considered to support the full flexible function split, i.e., the baseband processing can be dynamically allocated between RRU and BBU. Hence, all baseband functionalities are still required at both RRU and BBU. We also observe that if we only have necessary functionalities based on the split, i.e. split-specific deployment, the required memory can be largely reduced, for instance, to 16 KBytes for RRU in Split A.

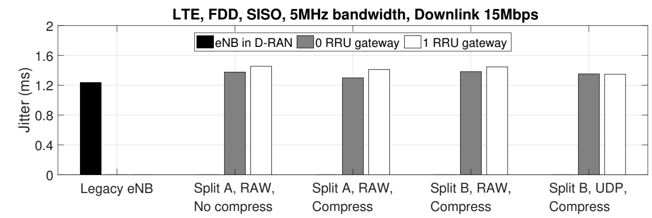
TABLE V: Hardware load of RRU/BBU

Bandwidth	Split	Endpoint	CPU Ratio (%)	Memory usage (KByte)
5MHz	eNB		40.15%	1002019
	A	RRU	16.76%	917486
		BBU	26.57%	918794
	B	RRU	24.19%	917478
		BBU	22.71%	917174
10MHz	eNB		65.02%	1195059
	A	RRU	29.23%	1107382
		BBU	45.70%	1180126
	B	RRU	41.12%	1107374
		BBU	32.40%	1124989

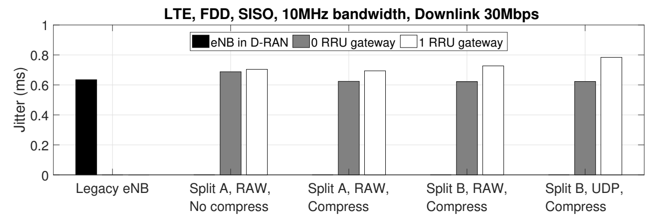
[5] The required number of cores can be reduced when using new series of Intel processor, e.g., Haswell, Skylake, etc.

C. Data-plane KPIs

To evaluate the data-plane impact, we compare the results with legacy D-RAN using 15 Mbps and 30 Mbps user throughput for 5MHz and 10MHz in downlink direction separately. First, we compare the packet jitter in Fig. 6(a) and 6(b). Due to the extra route from the user to the gateway that leads to less available Tx/Rx processing time as explained in Sec. V, the jitter of C-RAN deployment is larger than the one in legacy D-RAN and the jitter of the case with 2 Hops is larger than the one in 1 Hop case.



(a) Packet jitter of 5MHz bandwidth



(b) Packet jitter of 10MHz bandwidth

Fig. 6: Packet jitter for 5MHz/10MHz bandwidth

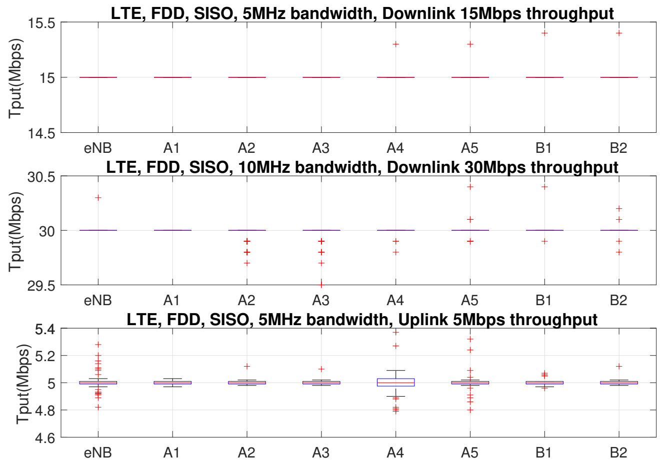
Then, we present the packet drop rate in TABLE VI. The drop rate of the C-RAN deployment is close to the D-RAN case except in the case when applying compression scheme of split A. This degradation is due to the time-domain samples of split A have large dynamic range but the applied compression scheme can only use less bits to represent each sample. In the sense, some extra packet are dropped in the protocol stack (e.g., hybrid automated repeat request of LTE medium access control layer, acknowledgment of LTE radio link control layer, application layer) and incur the re-transmission.

TABLE VI: Packet drop rate for 5MHz/10MHz bandwidth

Deployment	Split	Protocol	Compression	Drop rate (5MHz)	Drop rate (10MHz)
D-RAN				0.002%	0.013%
C-RAN	A	RAW	No	0.001%	0.008%
	A	RAW	Yes	0.009%	0.040%
	A	UDP	No	0.001%	0.018%
	A	UDP	Yes	0.010%	0.023%
	B	RAW	Yes	0.001%	0.017%
	B	UDP	Yes	0.003%	0.014%

Further, the measured good-put at application level is in Fig. 7, and seven different C-RAN deployments (A1 to A5, B1, B2 in the table below Fig. 7) are considered to be compared with eNB in D-RAN. In the uplink direction, we take 5MHz bandwidth with 5 Mbps user throughput. We observe that these deployment scenarios show almost the same good-put variation as the D-RAN one; that is to say, there is no observable difference in the experienced good-put among C-RAN or D-RAN deployments.

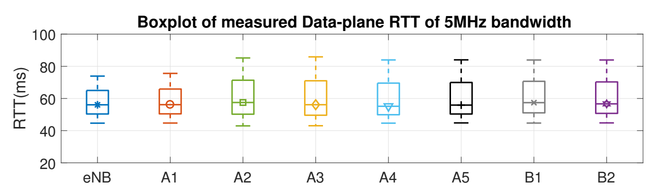
Finally, we also measure the RTT between user and the gateway in Fig. 8 using the *ping* utility with the packet size set to 8192 bytes and inter-departure time set to 0.2s. We observe that the average RTT in C-RAN deployment is only a little more than the one in legacy eNB deployment. However, in the



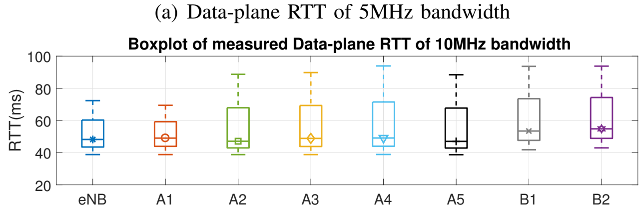
Mode	Split	Protocol	Compression	Hop count
A1	A	RAW	No	1
A2	A	RAW	No	2
A3	A	UDP	No	2
A4	A	RAW	Yes	2
A5	A	UDP	Yes	2
B1	B	RAW	Yes	2
B2	B	UDP	Yes	2

Fig. 7: Downlink/Uplink good-put of deployment scenarios

2 Hop cases (i.e., A2 to A5, B1, B2), the long tail distribution is exhibited. This phenomenon is due to the extra route from the user to the gateway that reduces the time of Tx/Rx processing as explained in Sec. V. In the sense, the Tx/Rx processing can not be finished within the available time and the negative acknowledgment (NACK) will be transmitted to notify the re-transmission scheme.



(a) Data-plane RTT of 5MHz bandwidth



(b) Data-plane RTT of 10MHz bandwidth

Fig. 8: Downlink packet RTT for 5MHz and 10MHz BW

To sum up, the packet-based C-RAN architecture can be realized through OAI platform and several different deployment scenarios are supported. As we can observe, several advantages are observed via using the compression scheme, i.e., less FH throughput, shorter RTT of FH and RF front-end; however, it potentially increase the packet drop rate. Moreover, the data-plane KPIs reveal two main performance degradation cause: (i) Reduced Tx/Rx processing time due to FH transportation can trigger the NACK and re-transmission scheme and (ii) Packet loss in the FH and packet drop due to de-compression lead to re-transmission at the receiver side over the protocol stack. Thus, utilizing these deployment scenarios, the C-RAN network can reuse several existing Ethernet network for its own deployment.

VII. Conclusions and Future Work

To conclude, in this work we propose a unified RRU/BBU framework that supports flexible functional split and Ethernet-based FH transportation approach in the C-RAN network. Moreover, three categories of KPI are used to evaluate different C-RAN deployment scenarios. Based on the implementation over the OAI platform and the KPI measurements, the C-RAN concept is proved to be applicable and it shows the compatible user experience can be provided with D-RAN.

In future, we will further extend our work to more functional splits (e.g., Functional Split C, D, E and Protocol splits) to investigate their characteristics over the Ethernet-based FH link as well as more complex deployment scenarios.

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