NTNU
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Performance Analysis of Cloud Radio Access Network

Asrat Temare Chekol

Master of Science in Telematics - Communication Networks and Networked
Submission date: August 2017
Supervisor: Eirik Larsen Følstad, IIK
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Problem description:

Cloud Radio Access Network (C-RAN) is a novel and promising Radio Access Network (RAN) architecture that could handle the exploding mobile traffic and address the challenges mobile operators face with traditional RAN architecture. The architecture advances from the traditional RAN architecture by decoupling the Base Band Units (BBUs) from the Remote Radio Heads (RRHs) and pooled in a central place. The decoupling between BBU and RRH offers network operators an easy-to-deploy and flexible solution for increasing coverage [Rad14].

However, there are challenges in the realization of C-RAN. The two major challenges are implementation of the split between RRH and BBU, and fronthaul transport protocol that could meet strict timing requirements of the fronthaul. Both the fronthaul protocol used and type of split between BBU and RRH have influence on the performance as well as implementation complexity of C-RAN.

The split between BBU and RRH could be fully centralized or partially centralized. In the first case all higher level and BBU functionalities will be in the BBU pool while in the second case some BBU functionalities stay with the RRH. There are different options to split BBU and RRH. Each option has its own advantages and challenges. The more the functionalities of BBU are centralized the better the C-RAN performance, but the more challenging to implement the split. This implies that there is a tradeoff between performance and the requirements on the fronthaul in splitting BBU and RRH.

On the other hand, Since Common Public Radio Interface (CPRI) is used only for short distance separation and faced performance challenges for the long distance split between BBU and RRH, there is a need for new fronthaul protocol that could meet stringent performance requirements between BBU and RRH such as delay and data rate.

This thesis work focuses on performance analysis of a fully centralized (PHY-RF Split) C-RAN with Open Air Interface (OAI) open source implementations for a core network, BBU and RRH, and using Ethernet as a fronthaul protocol.

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Abstract

The mobile traffic is exploding due to an increase in number and type of devices; and complexity of services. There is also rising of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) while the Average Revenue Per User (ARPU) is falling. This is a big challenge for mobile operators and equipment vendors. Maximizing capacity, improving quality of service and reversing the falling ARPU is required and this couldn't be achieved with the traditional RAN architecture. As a result, advancements in RAN architecture, data transport solution and transport protocol for the fronthaul have been done.

In this thesis work different RAN architectures, C-RAN functional split options between BBU and RRH, data transport solutions and interface protocols for the fronthaul have been surveyed. Then, performance test has been done on a simple C-RAN implementation containing an open source core network, BBU and RRH with emulated User Equipment (UE) all from OAI. The implementation has been done with PHY-RF split between the BBU and RRH, which have been connected over Ethernet through Ethernet switch. Finally, analysis of measurement results, and comparison with theoretical results found from literature has been done.

The performance test measurement results showed that a fully centralized C-RAN implementation with Ethernet as a fronthaul protocol cloud meet strict timing requirements of the fronthaul in terms of packet delay and jitter. Packets are observed arriving successfully before the delay deadline with a tolerable loss, but further work is required to improve the throughput and increase the separation distance between BBU and RRH.

Preface

This thesis is submitted to the Department of Information Security and Communication Technology at the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the MSc. degree in Telematics - Communication Networks and Networked Services. The thesis work has been performed from January - August 2017 at the Department of Information Security and Communication Technology under the supervision of Assoc. prof. Eirik Larsen from the department as responsible professor and Kashif Mahmood, research scientist at Telenor group, Norway, as co-supervisor.

The master study, including the thesis work, was financed by the Norwegian Government under the Quota Scheme scholarship programme. The thesis topic was suggested by Kashif Mahmood and it's experiment work was initially planned to be done in Telenor lab, Oslo, with RRC-PDCP (layer 3) split between BBU and RRH. Unfortunately, the lab hasn't been ready for the experiment within the planned time. Hence, available open source implementations from OAI with PHY-RF split between BBU and RRH have been used.

Acknowledgement

I would like to thank some of the people who have directly or indirectly contributed for the accomplishment of this thesis work. First of all, I would like to thank my supervisor Eirik Larsen for his mentoring and support; thank you very much for always having an open door for my questions and help solve challenges. Special thanks to my co-supervisor Kashif Mahmood for some good discussions, and his effort to get me access to Telenor lab. I am also grateful for Lehne Per Hjalmar, Telenor, for some good discussions.

Finally, I would like to use this opportunity to thank my parents for their support throughout my life; and my wife for her support, patience and taking care of our child Nahom.

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List of Acronyms

5G Fifth Generation.

ACK Acknowledgment.

ARPU Average Revenue Per User.

ARQ Automatic Repeat Request.

BBU Base Band Unit.

C&M Control and Management.

CAPEX Capital Expenditure.

CCDF CPRI Compression-Decompression Function.

CEMF CPRI-To-Ethernet Mapping Function.

CET Carrier Ethernet Transport.

CoE CPRI Over Ethernet.

CPRI Common Public Radio Interface.

C-RAN Cloud Radio Access Network.

CWDM Course Wavelength Division Multiplexing.

DL Downlink.

D-RoF Digital Radio Over Fiber.

DSL Digital Subscriber Line.

DWDM Dense Wavelength Division Multiplexing.

eNodeB Evolved Node B.

EPC Evolved Packet Core.

EPON Ethernet Passive Optical Network.

FDD Frequency Division Duplexing.

FEC Forward Error Correction.

GE Gigabit Ethernet.

GPON Gigabit Passive Optical Network.

GPS Global Positioning System.

GTP GPRS tunneling protocol.

HARQ Hybrid Automatic Repeat Request.

HSS Home Subscriber Server.

I/Q In-Phase/Quadrature.

ID Identification.

IEEE Institute of Electrical and Electronics Engineers.

IFFT Inverse Fast Fourier Transform.

IP Internet Protocol.

ISG Industry Specification Group.

ITU-T International Telecommunication Union-Telecommunication.

KPI Key Performance Indicator.

LAN Local Area Network.

LTE Long Term Evolution.

LTE-A Long Term Evolution-Advanced.

MAC Medium Access Control.

MAN Metro Area Network.

Mbps Mega Bits Per Second.

MIMO Multiple Input Multiple Output.

MME Mobility Management Entity.

MPLS-TP Multiprotocol Label Switching Transport Profile.

NACK Non-Acknowledgment.

NAS Non-Access Stratum.

NFV Network Function Virtualization.

NGFI Next Generation Fronthaul Interface.

NTNU Norwegian University of Science and Technology.

O&M Operation and Maintenance.

OADM Optical Add and Drop Multiplexing.

OAI Open Air Interface.

OAM Operation and Maintenance.

OBSAI Open Base Station Architecture Initiative.

OPEX Operational Expenditure.

ORI Open Radio Equipment Interface.

OTN Optical Transport Network.

PBB Provider Backbone Bridges.

PBB-TE Provider Backbone Bridge - Traffic Engineering.

PDCP Packet Data Convergence Protocol.

PGW PDN Gateway, Packet Data Network Gateway.

PON Passive Optical Network.

PTP Precision Time Protocol.

QoS Quality of Service.

RAN Radio Access Network.

RAT Radio Access Technology.

RF Radio Frequency.

RFIC Radio Frequency Integrated Circuit.

RLC Radio Link Controller.

RoE Radio Over Ethernet.

ROHC Robust Header Compression.

RRC Radio Resource Controller.

RRH Remote Radio Head.

RTT Round Trip Time.

SDH Synchronous Digital Hierarchy.

SDN Software Defined Networking.

SFP Small Form Pluggables.

SGW Serving Gateway.

SONET Synchronous Optical Network.

SPGW SGW-PGW.

SyncE Synchronous Ethernet.

TCP Transmission control protocol.

TDM Time Division Multiplexing.

UDP User data protocol.

UE User Equipment.

UL Uplink.

VLAN Virtual Local Area Network.

VM Virtual Machine.

WAN Wide Area Network.

WDM Wavelength Division Multiplexing.

Chapter 1 Introduction

Due to an increase in number of users, devices and services' complexities, mobile operators are facing strong challenge of satisfying customers' needs while making revenue. To increase capacity and coverage they have to build new RANs and/or upgrade existing once. The cost to build, upgrade and operate radio access networks is becoming more and more expensive while ARPU isn't growing at the same rate [Mob11]. On the other side, the emerging technologies, like cloud computing, virtualization and Software Defined Networking (SDN) provide ample opportunity to address the exploding and dynamic mobile communication traffic.

Definition of the problem to be addressed in this thesis work is presented in Section 1.1. Section 1.2 explains the objective of the thesis work. In Section 1.3 and Section 1.4, respectively, the methods used for the thesis work and some related works in the area are covered. Finally, in Section 1.5 outline of the rest of the thesis work is indicated.

1.1 Problem statement

A RAN is part of a mobile communication system which provides connection between mobile devices and core network through a Radio Access Technology (RAT). The RAN has undergone many evolutions from generation to generation in the mobile communication system to increase capacity, resource utilization efficiency, deployment flexibility and network dynamicity. Mobile operators give high emphasis to it to provide high data rate, better quality, and ubiquitous services to mobile users.

In a traditional RAN architecture base stations connect only a fixed number of sector antennas and serve only a specific area; the system capacity, though limited by interference, can be increased by frequency reuse; and have less resource utilization with high CAPEX and OPEX. Both BBU and RRH are co-located at the same place. Mobile operators are constantly challenged to realize new RATs that can handle the exploding traffic and throughput demand, increase capacity with better Quality of Service (QoS), and manage large number of complex devices [Rad14].

To solve the limitations of traditional RAN architecture, new RAN technologies are rising. The distributed RAN architecture is one among them in which BBU and RRH are separated by a fiber. In this RAN architecture a BBU serves only one RRH.

To improve deployment flexibility and operation efficiency, a new mobile network architecture, namely C-RAN [Mob11], has been proposed to have BBUs separated from RRHs and implemented in a centralized location such as a data center [JCT+15]. In this RAN technology, also called Centralized RAN, BBUs are pooled at a central cloud, shared among many RRHs and allows long distance separation between the two RAN units.

C-RAN contains mainly three components - BBU pool, fronthaul network, and RRH. The baseband unit does baseband processing while the compact, low power RRH, located near to an antenna tower, contains Radio Frequency (RF) equipment. The RRH connects mobile devices to the C-RAN. The decoupling between BBU and RRH offers network operators an easy-to-deploy and flexible solution for increasing coverage [Rad14].

However, there are challenges in the realization of C-RAN. The two major challenges are the implementation of the split between RRH and BBU, and having a fronthaul transport protocol that could meet strict timing and capacity requirements of the fronthaul. Both the fronthaul network protocol used and split option between BBU and RRH have influence on the performance as well as implementation complexity of C-RAN.

The split between BBU and RRH could be fully centralized or partially centralized. In the first case, all higher level and BBU functionalities should be in the BBU pool while in the second case some BBU functionalities stay with the RRH. As discussed in Chapter 3 there are different options to split BBU and RRH. Each option has its own advantages and challenges. The more the functionalities of BBU are centralized, the higher the resource utilization through virtualization, the better the performance, but the more challenging to implement the split. This implies that there is a tradeoff between performance and the requirements on the fronthaul in splitting BBU and RRH.

On the other hand, fronthaul protocol that could meet stringent performance requirements of a mobile communication system such as jitter, delay and data rate is required. Since CPRI is used for short distance separation between BBU and RRH and faced performance challenges for long distance separation, studies has been done [AMG+16, JCT+15, WA15, CSN+16, AKJ16] to use Ethernet as a fronthaul protocol in C-RAN. Using Ethernet in the fronthaul between BBU pool and RRHs, could bring a number of benefits; use of existing fiber deployment, shared use of infrastructure with fixed access networks, obtaining statistical multiplexing and optimized performance through probe-based monitoring and software-defined networking [JCT+15].

1.2 Objective

This thesis work focuses on performance analysis of fully centralized C-RAN with OAI open source implementations for a core network, BBU and RRH with emulated UE, and using Ethernet as a fronthaul protocol. It covers necessary background studies, conducting an experiment to take measurements against Key Performance Indicators (KPIs), perform the analysis, and conclude whether fully centralized C-RAN with Ethernet as a fronthaul protocol cloud meet strict requirements of mobile communication in the fronthaul network in terms of packet delay, jitter, throughput and packet loss ratio.

To achieve the main objective the following specific objectives need to be achieved.

- Investigate and identify different possible methods for the thesis work
- Study different RAN architectures, possible fronthaul protocols and transport options
- Study different possible functional splits between BBU and RRH
- Study potential advantages and challenges of implementing C-RAN
- Study how Ethernet could be used for radio transportation, its advantages and challenges.
- Study Ethernet based fronthaul network performance requirements
- Study different tools, (such as Iperf [Ipe17], Wireshark [Tea17]), and OAI implementations for core network, BBU and RRH that could be used for the experiment.

1.3 Methodology

The study of performance analysis of Ethernet based fully centralized C-RAN with OAI open source implementations for core network, BBU and RRH requires deep understanding of the topic area and the requirements of current and future mobile networks. It also demands to choose the best possible way to test the performance as well as analyze measurements.

1.3.1 Research Method

Literature survey is the research method used to understand the topic area, clearly identify the problem, and see alternative ways to approach the problem. This includes reading journals, articles, conference papers, books etc. to better understand what the requirements of current and future RANs are, and what has been done so far in the area.

C-RAN performance is greatly influenced by it's architecture, the fronthaul transport solution and protocol used. The literature survey hence focuses mainly on these directions. In addition, literature survey has been done to identify performance requirements and KPIs for the experiment set up.

1.3.2 Experiment Method

The fully centralized C-RAN performance testing could be done either with simulation or experiment. For the first case, it needs simulating of a core network, BBU and RRH with PHY-RF functional split between them, a distance software that could be used to simulate the separation distance between BBU and RRH, UE, and all communication protocols to be used such as Ethernet, SCTP, Transmission control protocol (TCP).

On the other hand, the OAI software alliance [ope17], the most active group working towards developing open source implementations of C-RAN, together with Next Generation Fronthaul Interface (NGFI) has developed an open source implementation of a core network called openair-cn or Evolved Packet Core (EPC) [ope17], and a C-RAN with PHY-RF split between BBU and RRH. They are working, but not yet implemented, on other C-RAN functional split implementations. The implementations are to be used for experiment using necessary existing protocols, transport medium, and Ethernet switch.

The experiment set up used for performance testing has contained OAI RRH with emulated UE and OAI BBU both running on two different computers and have been connected over 60.6m cat5e Ethernet cable through an Ethernet switch. The OAI EPC has been running on a Virtual Machine (VM) running on the OAI BBU machine.

The set up implementation has been with PHY-RF functional split between BBU and RRH. Traffic generating and measurement tools such as Iperf [Ipe17] and Wireshark, are used during the experiment. The Iperf results and Wireshark captured data has been used for the performance analysis of the C-RAN implementation.

1.3.3 Analytical Method

Parameterized mathematical model has been used to model some performance metrics of the C-RAN implementation. After conducting an experiment and taking measurements against KPIs using available tools mentioned in Section 1.3.2, Wireshark TCP

Stream graphs and Mathematica [Wol17] has been used to produce performance graphs. The results of the analysis have been compared with values found from literature to conclude whether a fully centralized C-RAN using Ethernet in the fronthaul could meet strict delay, packet jitter, packet loss ratio and throughput requirements.

1.4 Related Works

Studies have been done to advance the architecture of RAN, realize and benefit from the potential advantages of C-RAN. Researchers have been studying different possible functional split options between BBU and RRH with their impact on the performance of the C-RAN implementation. Recently, several standardization activities are redefining the fronthaul network towards a packet-based architecture [CNS16] aiming to design a variable bit rate, multipoint-to-multipoint, packet-based fronthaul interface. C-RAN drivers under fronthaul requirements, fronthaul protocols and transport solutions are presented in [PCSD15]. In [Mob11] and [AMG+16]] problems in today's RAN architecture, potential advantages and challenges of C-RAN implementation as well as it's architectural evolution are covered. The motivation to use Ethernet in the fronthaul, it's challenges and suggested possible solutions are also discussed.

In [Rad14] four different C-RAN implementation scenarios with different splitting points between BBU and RRH are proposed. The applicability of Network Function Virtualization (NFV) concepts to RAN functions, and the challenges and tradeoffs associated with the four different C-RAN implementation scenarios with varying amounts of centralized functionality are discussed. In [CSN+16] five different functional split scenarios only in the physical layer are proposed, and their impact on the fronthaul capacity is discussed. The joint impact of different packetization methods and RRH-BBU functional splits on the fronthaul rate and latency are also presented.

In [For16] and [CT16] eight different split options between BBU and RRH are proposed, and four different fronthaul latency groups are defined as Ideal (250µs), Near-ideal (2ms), Sub-ideal (6ms) and Non-ideal (30ms). Theoretical results for fronthaul delay capabilities and bandwidth requirements of some split options are also presented.

This thesis work contributes to the discussion on the different C-RAN implementation options, possible fronthaul protocols and transport solutions. Finally, performance test on a simple fully centralized (PHY-RF split option) C-RAN implementation set up using Ethernet as a fronthaul protocol has been done and results are presented.

1.5 Thesis Outline

RAN is part of a mobile communication system which provides connection between mobile devices and the core network through a RAT. RAN architecture evolution, fronthaul transport options and protocols are discussed in Chapter 2. C-RAN is a new and promising RAN architecture that could address a number of challenges mobile operators face while trying to support the growing needs of end-users, therefore it is seen as a major technological foundation for Fifth Generation (5G) mobile networks [Mob11, AMG+16]. Chapter 3 provides an introduction to C-RAN, its potential advantages and implementation challenges. Baseband and radio units functions as well as the different protocol layers are also addressed.

Given it's ubiquitous deployment in clouds, data centers, and core networks, Ethernet could be a generic, cost-effective, off-the-shelf alternative for fronthaul transport [CSN+16]. Chapter 4 discusses requirements and the motivation towards Ethernet-based fronthaul, ways of radio data transportation over Ethernet, and challenges and technical solutions of using Ethernet as a fronthaul transport protocol.

A simple fully centralized C-RAN experiment setup has been used to carry out performance test against KPIs. Chapter 5 focuses on the experiment set up used for the performance test, and Chapter 6 provides results and discussions on the findings. Chapter 7 puts summary and final conclusions of the thesis work. Finally, in Chapter 8 future research directions are indicated.

Chapter 2

RAN Evolution

RAN provides connection between mobile devices and core network through a RAT. The RAN consists of baseband and radio units and a fronthaul network connecting the two units. The distance between baseband and radio units, the fronthaul transport option as well as the mobile data transport medium used have undergone evolution to meet current and future requirements.

Section 2.1 presents RAN architecture evolution from traditional RAN architecture to current and future candidate RAN architectures. Fronthaul In-Phase/Quadrature (I/Q) data can be transported between BBU and RRH over different transport solutions. Section 2.2 briefly discusses possible transport solutions. Finally, currently available and future candidate fronthaul protocols as well as why Ethernet is selected for the thesis work are discussed in Section 2.3.

2.1 RAN Architecture Evolution

The RAN has evolved from generation to generation in mobile communication systems to increase deployment flexibility and network dynamicity. Mobile operators are constantly challenged to realize less costly RAN technologies that can handle the exploding mobile traffic demand, increase QoS, and manage large number of complex devices [Rad14]. They give high emphasis for RAN to improve quality, and provide ubiquitous services to mobile users.

In the traditional RAN architecture, as shown in Figure 2.1, both BBU and RRH are co-located at the same place in the base station. In this RAN architecture base stations connect only a fixed number of sector antennas and serve only a specific area. To increase capacity and coverage mobile operators need to deploy an increased number of base stations. This incurs high CAPEX and OPEX due to equipments cost, high energy consumption, and lease/rental for the base stations' equipments room. On the other hand, capacity can be increased by frequency reuse by reducing cell size. But further decreasing the cell size to increase capacity is traded off by

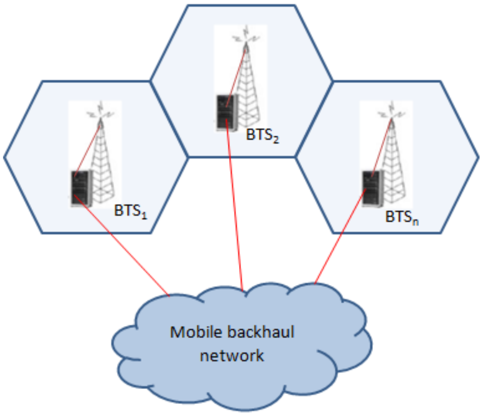

Figure 2.1: Traditional RAN architecture

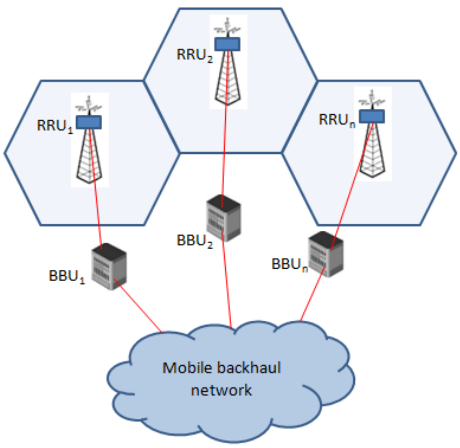

Figure 2.2: Distributed RAN architecture

interference. Besides capacity limitation and costs, traditional RANs have challenge in serving the dynamic mobile network load as they are designed to serve only users within a specific coverage area. This puts the base station utilization rate low.

To mitigate the limitations of the traditional RAN architecture, new RAN technologies have been designed. Distributed RAN architecture, shown in Figure 2.2, is one in which BBU and RRH of a base station are separated and connected by a fiber. This RAN architecture allows 20km to 40km [AMG+16] distance separation between BBU and RRH, but a BBU serves only one RRH.

To improve deployment flexibility and operation efficiency, a new mobile network

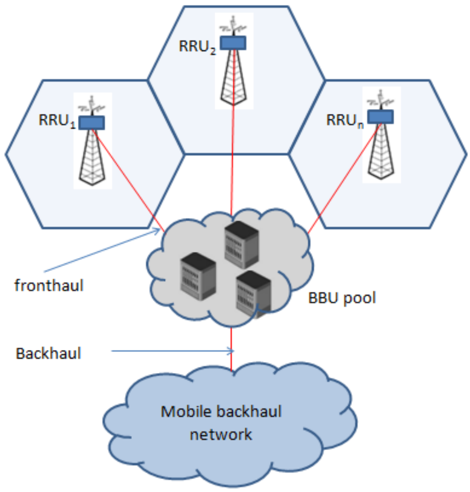

Figure 2.3: C-RAN architecture

RAN architecture, namely C-RAN [Mob11], shown in Figure 2.3, has been proposed to have BBUs separated from RRHs, and implemented in a centralized location such as a data center [JCT+15]. In this RAN architecture, also called Centralized RAN, BBUs are pooled at a central cloud, and shared among many RRHs. To further maximize resource sharing BBU functionalities are virtualized in the BBU pool and shared among all RRHs connected to the BBU pool. This RAN architecture also allows 20km to 40km [AMG+16] distance separation between BBU and RRH.

In the C-RAN architecture shown in Figure 2.3 independent fronthaul link is used to connect each RRH to the BBU pool. However, due to concerns related to scalability, cost, and multiplexing [CSN+16], it is expected that the fronthaul will evolve towards more complex shared topologies similar to the backhaul network [IJR+14]. Hence multiplexing switches will be used in the fronthaul as shown in Figure 2.4, to multiplex multiple RRHs on a shared fronthaul link. Due to this reason the C-RAN architecture in Figure 2.3 is sometimes called traditional C-RAN. The shared fronthaul link architecture can be used for both small cell and macro cell C-RAN deployments. In the later case the switch could also be used to multiplex sectors in a macro cell deployment.

2.2 Fronthaul Transport Options

In the Uplink (UL), fronthaul transport options are used to transmitting baseband signals from RRH to BBU while in the DL they are used for transmitting RF signals from BBU to RRH. The type of split between BBU and RRH, as discussed in

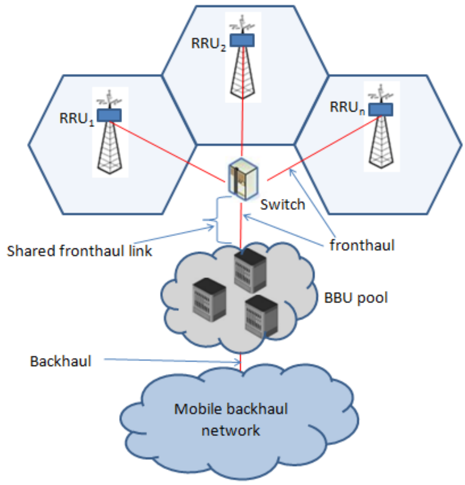

Figure 2.4: Shared fronthaul link C-RAN architecture

Section 3.3, affects the amount of bandwidth required in the fronthaul network.

In fully centralized C-RAN all BBU functionalities reside in the BBU pool while the RRH resides far in the cell site. Even though, this split has novel advantages, it puts high challenges on fiber requirement as it generates high bandwidth I/Q data transmission between BBU and RRH. On the other hand, in partially centralized C-RAN some of the BBU functionalities reside in the RRH. As a result it reduces the pressure on high bandwidth requirement between the BBU and RRH as the demodulated signal occupies 20-50 times less bandwidth [Mob11] than the modulated one. However, this solution will not allow to fully exploit the potential advantages of C-RAN such as resource utilization and NFV.

The physical medium through which fronthaul data propagates could be copper wire, microwave or fiber. The solution based on copper links is not taken into account for C-RAN, as Digital Subscriber Line (DSL) based access can offer only up to 10-100[AMG$^+$16]. Typical microwave solutions offer from 10Mbps-100Mbps up to 1Gbps range [3GP13], the latter available only for a short range (up to 1.5) [SW11]. Fiber allows huge transport capacity, supporting up to tens of per channel; and is the most prominent solution for physical medium [AMG$^+$16]. It is preferred over other solutions when high bandwidth, long distance, and immunity to electromagnetic interference are required.

Figure 2.5: Point to point fiber[PMC15]

2.2.1 Point to Point Fiber

With point to point fiber fronthaul, each RRH as shown in Figure 2.5 is connected to the BBU through a dedicated fiber. The fiber can be a bidirectional fiber or a pair of unidirectional fibers. In this solution there are separate flows for each BBU-RRH link. Point to point fiber is a preferred solution for a BBU Pool with less than 10 macro base stations [Mob11]. Dark fiber, with Small Form Pluggables (SFP), can be used with low cost [AMG+16] without additional optical transport network equipment. As there are no additional equipments in the fronthaul, the delay contribution caused by the fronthaul network over the flows is almost zero.

On the other hand, point to point fiber consumes large fiber resource. As a result expanding network coverage will be a challenge. This solution requires extra equipment for monitoring and protection mechanisms in case of failure [AMG+16], as well as additional mechanisms to implement Operation and Maintenance (O&M) needed. However, some of the challenges can be solved at the cost of fiber resource, by deploying a dedicated backup fiber. If fiber is deployed with physical ring topology it offers resiliency similar to Synchronous Digital Hierarchy (SDH) [AMG+16]; and O&M capabilities can be introduced in the fronthaul communication protocol.

2.2.2 Passive Optical Network

Optical networks are deployed in various fiber-to-the-X [GE08] applications, where X can mean home, curb, cabinet, or building. These optical networks can be active or Passive Optical Networks (PONs). Active optical networks use electrically powered switching equipment to separate data flows and route to the required destination while PONs don't include electrically powered switching equipments rather use passive optical splitters to separate and rout optical signals to the specified destination. Even though, they are better for long distance transmission, active optical networks inherently are less reliable than passive optical networks as they require power. On the other hand, PONs are more efficient (each fiber optic strand can serve up to 32

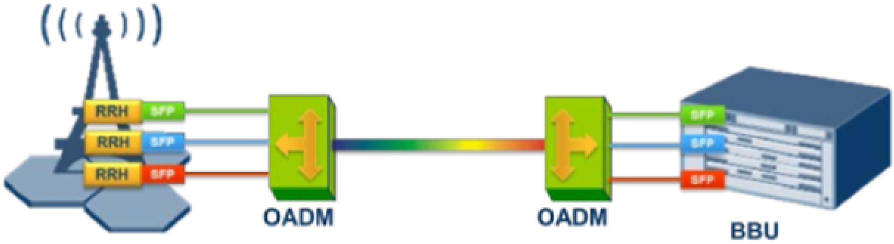

Figure 2.6: Passive optical network[PMC15]

RRHs), have lower building and maintenance costs. But, they have less geographical range (10-20km) [GE08].

PONs can be used to connect BBU and RRHs over an optical fiber with Time Division Multiplexing (TDM), or Wavelength Division Multiplexing (WDM). PON, as shown in Figure 2.6, shares fiber optic strand for portion of the network using Optical Add and Drop Multiplexing (OADM).

In order to extend the capacity of PONs into Gbit/s arena, the ITU has set standards for the Gigabit PON (Gigabit Passive Optical Network (GPON)) in the G.984.x series [Koo05]. Ethernet PON (Ethernet Passive Optical Network (EPON)) is also another TDM-PON which uses Ethernet packets instead of ATM cells. Though they are both TDM PONs, GPON offers higher aggregated bandwidth, higher bandwidth efficiency [Koo05], and supports longer distance than EPON. On the other hand, EPON, despite its lower efficiency, natively supports Ethernet as the most relevant access protocol [GE08]. However, Most agree that TDM PONs cannot cope with the requirements of future network evolution with respect to aggregated bandwidth and allowable power budget [GE08].

Using WDM PON increases bandwidth efficiency while minimizing infrastructure cost. Performance of WDM PON, i.e., bandwidth per RRH, splitting ratio and maximum reach, are the dominant criteria for commercial success [GE08]. WDM PON can be Course Wavelength Division Multiplexing (CWDM) PON or Dense Wavelength Division Multiplexing (DWDM) PON. CWDM PONs provide lower splitting ratios (1:8) than DWDM PON (1:40), and to obtain these ratios they require low-water-peak (light absorption by OH-ions) fibers [GE08]. Despite significantly higher bandwidths compared to GPON/EPON, DWDM PON architectures lead to dramatically increased cost as they use DWDM transmitters. Hence, CWDM should be considered as a low cost alternative [GE08].

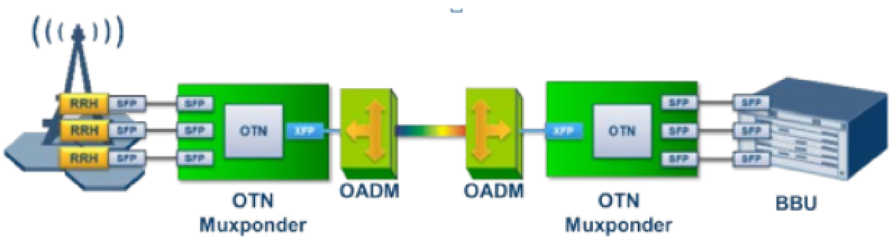

Figure 2.7: Optical transport network[PMC15]

2.2.3 Optical Transport Network

Optical Transport Network (OTN) could be used to transport fronthaul flows between BBU and RRH in TDM-over-WDM scheme. According to International Telecommunication Union-Telecommunication (ITU-T) Recommendation G.872, OTN is able to provide functionality of transport, multiplexing, routing, management, supervision and survivability of optical channels carrying client signals. In ITU-T Recommendation G.709 OTN can support an approximate data rate of 112Gbps, hence can be used to transport 100Gigabit Ethernet signal. Utilizing OTN as mobile fronthaul, as shown in Figure 2.7 brought a new standardized format for carrying different types of protocols across the optical network using a client service aggregation technology called OTN Muxponder. This standardization enables optical interconnection between equipments from different vendors and operators [Sch15]; and framing of client signal of different protocols for transport over the physical optical layer.

OTN also has standard based carrier-grade functions such as per client and per line Operation and Maintenance (OAM), and Forward Error Correction (FEC), which allows longer reach and low-cost transceivers to be utilized. It's protocol transparency [Sch15] and multiservice support property allows to combine several interfaces such as CPRI, Gigabit Ethernet (GE), Synchronous Optical Network (SONET)/SDH on the same infrastructure. It handles "any" protocol-stack and gives a physical layer to higher layer protocols [Sch15]. On the other hand, the Muxponders, OADMs and SFPs introduce delay in the fronthaul which could make OTN less reliable for C-RAN implementations.

2.2.4 Carrier Ethernet

The RRHs can also be connected to the BBU pool over Carrier Ethernet Transport (CET). The term Carrier Ethernet refers to two things [AMG+16] - set of services that enable to transport Ethernet frames over different transport technologies and a solution how to deliver these services. Carrier Ethernet has standardized services, scalability, reliability, service management and QoS attributes which are not found

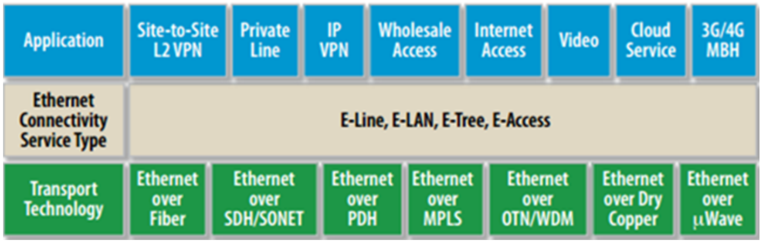

Figure 2.8: Ethernet transport technologies[Com10]

in Local Area Network (LAN) Ethernet. It is defined in Institute of Electrical and Electronics Engineers (IEEE) 802.1Qay-2009 standard. Carrier Ethernet advanced from IEEE 802.1Q Virtual Local Area Network (VLAN) standard through IEEE 802.1ad Provider Bridges (PB) and IEEE 802.1ah Provider Backbone Bridges (PBB). To achieve QoS of Ethernet transport, traffic engineering is enabled in Carrier Ethernet [AMG$^+$16]. A data packet transmitted on a Carrier Ethernet link is sent in something called Ethernet packet, which transmits an Ethernet frame as its payload. Provider Backbone Bridge - Traffic Engineering (PBB-TE) uses the set of VLAN Identifications (IDs) to identify specific paths to a given Medium Access Control (MAC) address [AMG$^+$16], which introduces connection oriented forwarding.

Once an Ethernet service is deployed, bandwidth can be added simply through remote provisioning up to the Ethernet port speed which enables service provider to sell, or enterprise to deploy, the amount of bandwidth subscribers actually need, rather than forcing them to buy a particular amount of bandwidth [Com10]. Using Carrier Ethernet as a fronthaul protocol will also allow providers, enterprises and users to use the same protocol for their LANs, Wide Area Networks (WANs), and Metro Area Networks (MANs) which will reduce the amount of cost to get connected. Hence, Carrier Ethernet provides flexible bandwidth increments and the ability to add new services using one technology [Com10]. Depending on the type of application, different transport technologies can be used as shown in Figure 2.8, for Carrier Ethernet transport.

Carrier Ethernet as transport solution requires addressing the need for its inherent delay and jitter. The maximum practical fiber length between BBU and RRH can be reduced by the inherent Carrier Ethernet delay. Moreover, fiber needs to be kept in the same track to avoid delay asymmetry for upstream and downstream [ALL15b], in order to allow calculation of Time of Day needed for synchronization. In this document the terms Ethernet and Carrier Ethernet are used interchangeably, and more about Ethernet is discussed in Chapter 4.

2.3 Fronthaul Network Protocols

Fronthaul data is transported between BBU and RRH using a fronthaul network protocol such as CPRI, Open Base Station Architecture Initiative (OBSAI) or Ethernet. CPRI is a serial line and most widely used radio interface protocol for I/Q data transmission in the fronthaul. It is a constant bit rate, bidirectional communication protocol, and requires accurate synchronization and strict latency control [AMG+16]. On the other hand, OBSAI is a packet-based interface [dlOHLA16] and aims at creating an open market for cellular base stations to substantially reducing the development effort and costs associated with creating new base station product ranges [PCSD15].

Both CPRI and OBSAI are based on the implementation of Digital Radio Over Fiber (D-RoF) [dlOHLA16] concept; and differ in the way information is transmitted. They have mainly been considered for carrying raw I/Q samples in a distributed RAN architecture [CSN+16] in which BBU is close to RRH. They are simple protocols that serve well for short range separation between RRH and BBU, typically the distance between RRH and BBU would be from the basement to the rooftop [AMG+16]. In addition, both CPRI and OBSAI are fixed-rate fronthaul protocols based on TDM which transmits CPRI/OBSAI streams even in the absence of traffic load and therefore renders data transmission inefficiency [CPR13]. This makes them less popular in areas where tidal effect of the mobile traffic is high.

The mapping methods of CPRI are more efficient than OBSAI [NSCEB12], hence most global vendors have chosen CPRI for their products [dlOHLA16]. CPRI is usually used in fully centralized C-RAN architecture, discussed in Section 3.3, with short distance separation between BBU and RRH, and low data rate transmission. The maximum data rate CPRI can support is 12165.12Mbps (option 9) [dlOHLA16]. On the other side, in C-RAN architecture, the distance between BBU and RRH may cover several kilometers. This adds additional delay on the I/Q signal transmission between BBU and RRHs.

Currently, different groups and companies are working towards a fronthaul transport protocol that can solve the challenges of CPRI protocol. In [SW11] Alcatel-Lucent is contributing a lightRadio solution for C-RAN. This solution uses a multi-band, multi-standard active antenna array, with Multiple Input Multiple Output (MIMO) and passive antenna array support [AMG+16].

NGMN in [MOS13] predicts Open Radio Equipment Interface (ORI) as a future candidate fronthaul transport protocol. The ORI goal is to develop an interface specification envisioning interoperability between elements of base stations of cellular mobile network equipments; release four is currently close to approval [PCSD15]. Unlike CPRI and OBSAI which are developed by equipment vendors, ORI is developed by both equipment vendors as well as network operators. The interface defined by the ORI Industry Specification Group (ISG) is built on top of CPRI with the removal of some options and addition of other functions to reach full interoperability [PCSD15]. Also, as the nature of the interface between RRH and BBU is changing with an introduction of C-RAN, the existing protocols may need to be redefined [AMG+16] in order to be optimized for high volume data transport between BBU and RRH over long distances.

In [NGF15] China Mobile Research Institute, Alcatel-Lucent, Nokia Networks, ZTE Corporation, Broadcom Corporation, and Intel China Research Center are working on a new fronthaul protocol called NGFI. Their work starts from redefining the functionalities of BBU and RRH; and then changing the fronthaul point-to-point connection into many-to-many fronthaul network using a packet exchange protocol. They sate the minimum requirements that NGFI should comply with basic principles such as adaptive bandwidth changes responsive to statistical multiplexing and payload; maximum support for high-gain coordinated algorithms; interface traffic volume decoupled from the number of antennas at RRU; neutrality with respect to air interface technology.

The IEEE 1914.3 task force has been investigating ways of transferring I/Q user-plane data, vendor-specific data, and Control and Management (C&M) information channels [CPR13] over an Ethernet-based packet-switched network [CKV+17]. Given it's ubiquitous deployment in clouds, data centers, and core networks, Ethernet could be a generic, cost-effective, off-the-shelf alternative for fronthaul transport [CSN+16]. It is a variable bit rate, high capacity and extensively adopted transmission protocol for LANs. More on Ethernet as fronthaul protocol is discussed in Chapter 4.

Chapter 3
C-RAN

C-RAN is a novel RAN architecture [All15a] that could address a number of challenges mobile operators face while trying to support the growing needs of end-users. It is gaining great interest, specially, for dense urban area deployment, and some network operators have already started its deployment because of its potential advantages [PCSD15]. It is also a promising future mobile network architecture [DLG16] that will reverse the falling ARPU while delivering better quality of service. It also takes the advantages of technologies like, SDN and NFV; brings flexibility to decouple the radio unit from the BBU, allocates resources on demand from a centralized pool [Rad14], and thus maximizes the utilization of resources and improve coordination between base stations.

Generally, C-RAN architecture contains three components - BBU pool, fronthaul network, and RRH. The BBU does baseband processing while the compact, low power RRH [Rad14] contains the RF transmit and receive components and is connected to antenna to bridging mobile devices to the C-RAN. The fronthaul network connects the two units over a fronthaul transport solution. The decoupling between BBU and RRH offers network operators an easy-to-deploy, and flexible solution for increasing coverage [Rad14].

In a virtualized C-RAN, a centralized BBU pool consists of time-varying sets of software defined BBUs, called virtual base stations, used to process baseband signals and optimize radio resource allocation [PWLP14]. Centralized signal processing in C-RAN cloud greatly reduces the number of site's equipment room needed to cover the same area compare to traditional RANs; hence, reduce the cost for equipment room rent. Real-time cloud infrastructure based on open platform and base station virtualization enables processing aggregation and dynamic allocation, reducing the power consumption and increasing the infrastructure utilization rate [Mob11].

An overview of C-RAN baseband and radio units functions is presented in Section 3.1. In Section 3.2 the eNodeB protocol stack layers towards the air interface are discussed. To achieve maximum possible C-RAN performance, different C-RAN functional splitting options are under study. Section 3.3 provides some of these splitting options. At the end, the potential advantages and challenges of implementing C-RAN are covered, respectively, in Section 3.4 and Section 3.5.

3.1 Baseband and Radio Units Functions

The access network provides the ability, infrastructure, and accessibility to UE in acquiring the capabilities and services of the network. RRH contains RF equipment and stay close to the cell site antenna tower. RRHs provide UEs the interface to the fronthaul. In the DL RRHs are used to transmitting RF signals to mobile devices while in the UL they are used for forwarding baseband signals from mobile devices to the C-RAN cloud for centralized processing. RRHs also perform RF amplification, up/down conversion, filtering, analog-to-digital conversion, digital-to-analog conversion, and interface adaptation [PWLP14]. BBU performs baseband processing with it's different layers and is presented in detail in Section 3.2.

3.2 Protocol stack in LTE-A eNodeB

In Long Term Evolution (LTE) Evolved Node B (eNodeB) protocol architecture BBU has functionalities which are grouped in three main layers: Layer 1 - physical layer, layer 2 - data link layer (contain MAC, Radio Link Controller (RLC), and Packet Data Convergence Protocol (PDCP)), and layer 3 - network/control layer (contain Radio Resource Controller (RRC) and all upper layer protocols). The first two layers are the same in both the user plane and control plane of LTE eNodeB but the third is only in the control plane. The user plane protocols are used for user data processing, and tunneling this data through BBU and RRH. On the other hand, the control plane protocols are responsible for establishing connection, bearer setup, management, authentication, mobility management and security [CL13].

In the eNodeB protocol stack, as shown in Figure 3.1 and Figure 3.2, all BBU functionalities layers stay in the eNodeB. However in the C-RAN architecture, though they are baseband functionalities, depending on the type of split between BBU and RRH, some of these functionalities may stay in the RRH.

The physical layer performs functions such as coding/decoding, modulation/demodulation, multi antenna processing and mapping of signals to the appropriate physical time-frequency resources [CL13], as well as mapping of transport channels to physical channels.

The MAC layer is responsible for multiplexing/de-multiplexing of data from/to different radio bearers, error correction through Hybrid Automatic Repeat Request

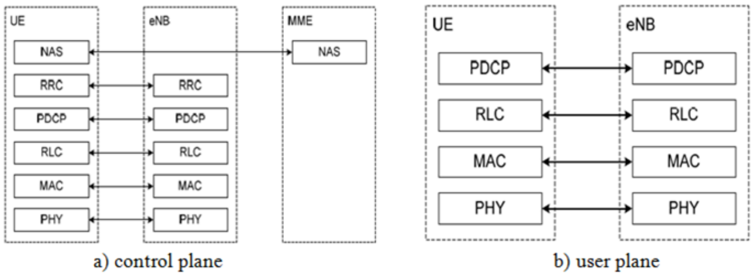

Figure 3.1: Air interface eNodeB protocol stack

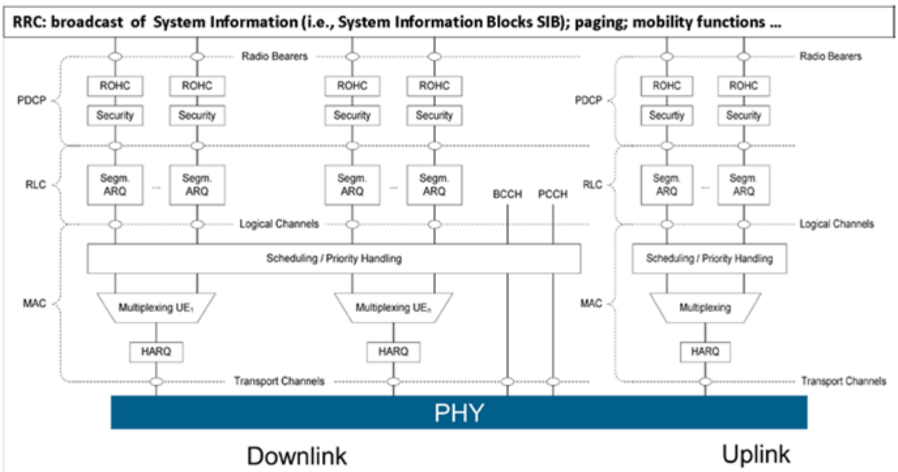

Figure 3.2: LTE-A pro eNodeB protocol stack[VKG+16]

(HARQ) and logical channel prioritization/scheduling for UL and DL.

The RLC layer is in charge of segmentation, concatenation, re-transmission and in-sequence delivery to higher layers [CL13]. It is also used for error correction through Automatic Repeat Request (ARQ).

The PDCP layer performs ciphering, integrity protection, duplicate detection, and Internet Protocol (IP) header compression using Robust Header Compression (ROHC) to reduce the number of bits to be transmitted over the radio interface. It also insures the in-sequence delivery and re-transmission of data for the different radio bearers during handover.

The RRC is a layer-3 access stratum protocol used for controlling the access stratum. It is responsible for establishing, configuration, maintenance and release of signaling of the radio bearers, broadcasting system information, transmitting paging message from Mobility Management Entity (MME), and configuring all lower layers using RRC signaling [CL13] between BBU and UE.

The Non-Access Stratum (NAS) is the highest stratum in the eNodeB control plane protocol stack between UE and MME of core network. It is used for establishment of communication sessions and maintaining continues communication as the UE moves.

3.3 C-RAN functional split

The potential advantages of C-RAN come with centralizing BBU functionalities from the cell site towards a central BBU pool. If all BBU functionalities are moved to the BBU pool, the C-RAN functional split is said to be fully centralized. On the other hand, some functionalities of BBU may still stay with the RRH near the cell site. Such functional split of C-RAN is called partially centralized C-RAN.

The fully centralized C-RAN is easy for upgrading, network capacity expansion, and maximizes resource sharing through virtualization. It is also convenient towards support of multi-cell collaborative signal processing, and has better capability to support multi standard operations. On the other hand, fully centralized C-RAN imposes big pressure on fiber resource as it requires a high bandwidth and low latency optical solution to transmit high speed baseband signal between BBU and RRH.

Partially centralized C-RAN tries to lowering the data rate and hence, reduce the high pressure on fiber resource by splitting some of the functionalities of BBU to the RRH. Even though it reduces the big bandwidth requirement, it is also less flexible in up grading, less convenient for multi-cell collaborative signal processing and reduce resource utilization as BBU functionalities near the cell site will not be virtualized.

To optimize the performance and challenges of centralizing BBU functionalities, different partially centralized C-RAN functional split options [Rad14, For16, CT16, DLG16, CSN+16, TE16, VKG+16] have been studied.

3.3.1 RRC-PDCP Split

In this split option, option 1 in Figure 3.3, only the control plane is centralized to the BBU pool. RRC-PDCP split is the only split that provides a true separation between control plane and data plane [For16] allowing for the possibility that user plane IP packets may take a direct path to their destination without transiting the central virtualized platform. It is also the easiest of all split options to deploy in the near future as it eliminates the need for custom backhaul technology capable of meeting timing requirements [Rad14]. Moreover, virtualization of RRC provides important benefits in terms of providing central visibility to signal strength measurement reports and facilitates customization of mobility management algorithms to meet business requirements [For16].

The bandwidth requirements of this split could be much less than S1 (interface between eNodeB and core network) backhaul if the user plane data is immediately offloaded; otherwise, the bandwidth requirements are roughly the same as for S1 [For16]. Though layer 1 and layer 2 functionalities are not centralized, this split is considered to work with all fronthaul latencies defined in [For16], namely, ideal (250µs), near-ideal (2ms), sub-ideal (6ms) and non-ideal (30ms).

3.3.2 PDCP-RLC Split

Virtualizing PDCP and RRC layers produces added benefits of improved mobility across remote cells, where these remote small cells share the same central BBU pool for their virtualized functions, and additionally removes the need for any data forwarding [For16]. This split option, option 2 in Figure 3.3, is considered to work with all fronthaul latency groups and the fronthaul bandwidth requirements are comparable to S1 backhaul requirements [For16].

3.3.3 RLC-MAC Split

Moving the RLC layer functions to the central BBU pool increases the amount of functionality which can be scaled including load balancing, but introduces complexity as the DL RLC layer is tightly coupled to both the MAC and scheduler [For16]. RLC-MAC split, option 4 in Figure 3.3, is considered to work with ideal, near-ideal and sub-ideal fronthaul, and again requires a fronthaul bandwidth comparable to a S1 backhaul [For16].

3.3.4 Split RLC

This split option is an alternative method to decouple RLC and MAC layers. In split RLC, option 3 in Figure 3.3, the RLC will be divided as low RLC (non-real-time) and high RLC (real-time). The low RLC contains segmentation and concatenation, and high RLC contains ARQ re-transmission and packet ordering [CT16]. Split RLC is more robust under unreliable transport conditions [CT16], and will have better delay capability than RLC-MAC split.

3.3.5 Split MAC

Spliting the MAC sub layer, option 5 in Figure 3.3, is also another alternate method for decoupling the DL RLC and MAC layers. Here the majority of the MAC layer will be virtualized in the central BBU pool, but the HARQ scheduling remains on

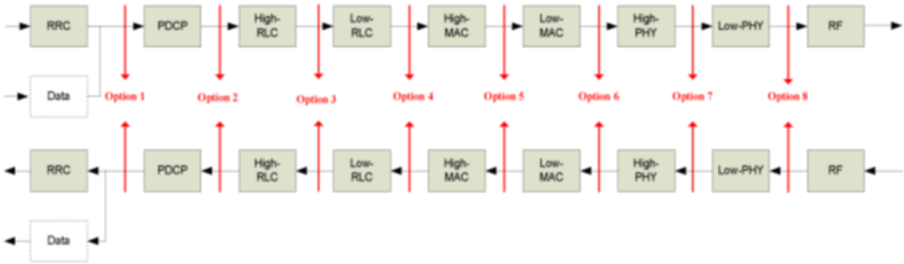

Figure 3.3: 3GPP proposed C-RAN functional split options[VKG+16]

the remote small cell [For16]. Virtualizing the scheduling function enables enhanced capability for coordinating transmissions across multiple remote small cells. This split option will result the same latency and bandwidth requirements as RLC-MAC split [For16].

3.3.6 MAC-PHY Split

In this split option, option 6 in Figure 3.3, all layer 3 and layer 2 functionalities will be centralized while only the physical layer functions reside in the remote cell. However, this split option will have tighter HARQ cycle latency constraints (4ms) [For16] on the fronthaul as a result only ideal fronthaul can be supported. The fronthaul bandwidth requirements are same as S1 backhaul.

3.3.7 PHY-RF Split

This functional split , option 8 in Figure 3.3, is what is called fully centralized C-RAN and will centralize all the three BBU layers to the central BBU pool. This option will have advantages of higher resource utilization, CAPEX/OPEX reduction, easy resource scaling, energy saving and flexibility through network function virtualization (NFVs) [Rad14]. However, there will be strict latency and throughput requirements between the physical layer and Radio Frequency Integrated Circuit (RFIC) [Rad14].

3.3.8 Split PHY

Split PHY, option 7 in Figure 3.3, is an alternative method to decouple the physical layer and the RF to relax the tight delay requirements. There are several options on how to split the physical layer and each results in different functionality located in the BBU pool, and varying fronthaul bandwidth and latency requirements [For16]. The more the physical layer is virtualized the higher fronthaul bandwidth requirements.

In summary, the more the functionalities of BBU are centralized, the higher the resource utilization by virtualization, the higher the fronthaul bandwidth requirement, and the more challenging to implement the split. This implies that there is a tradeoff between performance and complexity in implementing the BBU functional split option. Thus, for better data rate and delay capability, optimization of C-RAN functional split options and their implementation challenge is required. However, due to their complexity, deploying all the split options in the near future is less likely to happen [Rad14].

3.4 Advantages

Centralized signal processing in the C-RAN cloud greatly reduces the number of site's equipment room needed to cover the same area compare to traditional RANs; hence, reduce the cost for equipment room rent. Real-time cloud infrastructure based on open platform and base station virtualization enables processing aggregation and dynamic allocation, reducing the power consumption and increasing the infrastructure utilization rate [Mob11].

Generally, implementing C-RAN has the following advantages:

1. Efficient resources utilization: The implementation of C-RAN pools resources to a central cloud and virtualization of network functions like, base stations makes them independent of the hardware and hence can be shared among many RRHs.
2. Less energy consumption: Pooling the resources to the center, and NFV reduce hardware equipment which in turn reduces the energy consumption. Also in a C-RAN cloud idle equipments can be turned off.
3. Adaptability to dynamic network traffic: Generally, mobile traffic is dynamic in nature. During the day there is higher traffic load on RRHs around work places and shopping centers while during the night it shifts to residential places. This has been a challenge for traditional RANs but in C-RAN centralized processing could solve it.
4. Less cost to upgrade: Compare to traditional RAN, C-RAN upgrading requires less cost. It may require upgrading BBU pool processers or deploying more simple RRHs.
5. Support multiple technologies: C-RAN supports previous generations of mobile communication technologies.

3.5 Challenges

C-RAN implementation could have both macro and small cell deployments. Small cell deployment is one of the most promising technological trends to cope with the rising need for very high data rates foreseen in future mobile networks [Wan14]. But small cell deployments are more efficient in densely populated urban areas. On the other hand, indoor and RRHs surrounded by big buildings will not have line of sight to a Global Positioning System (GPS) satellite for synchronization.

In addition, performing the C-RAN functional split options that will have more benefits is challenging due to strict timing requirements. This timing requirements are again worsened by switches and other devices used in the fronthaul. Unable to split more BBU functionalities to the BBU pool will reduce the potential benefits that can be gained from the C-RAN implementation.

Moreover, a fronthaul protocol with better capacity to handle high bandwidth fronthaul I/Q data, and help achieve the timing and synchronization requirements is required. Realization of such fronthaul protocol for C-RAN implementations is another challenge.

Chapter 4

Ethernet-Based Fronthaul Networks

In traditional RAN architecture, the connection between BBU and RRH has been an interface in a device, in a distributed RAN architecture this distance spanned a few kilometers in a point-to-point connection. Whereas, in C-RAN architecture it is possible to connect many RRHs from a metropolitan area through a fronthaul to a centralized BBU pool located far from them. Data is transported between BBU and RRH through a fronthaul solution using a packet-based (e.g. Ethernet) or serial protocol such as CPRI and ORI.

Section 4.1 discuses the motivation towards using Ethernet-based fronthaul. Section 4.2 presents the requirements of fronthaul networks with respect to different performance metrics such as delay, data rate, and jitter . The way radio data is transported over the new candidate fronthaul protocol - Ethernet, is provided in Section 4.3. Finally, the challenges of using Ethernet in the fronthaul, and possible technical solutions are covered, respectively, in Section 4.4 and Section 4.5.

4.1 Motivation

As presented in Section 2.3 the legacy fronthaul protocol - CPRI has got many challenges to support current and future fronthaul requirements. It is a constant bit-rate protocol and serve a small distance (about from a basement to the rooftop of a building) separation between BBU and RRH as it requires accurate synchronization, strict latency control, and one-to-one mapping [AMG+16] between BBU and RRH. On the other hand, in C-RAN architecture the distance between BBU and RRH may cover several kilometers. CPRI is also a TDM based protocol transmitting CPRI streams independent of any user activity in the cell site which results data transmission inefficiency. Moreover, the maximum data rate, CPRI can support is 12165.12 Mega Bits Per Second (Mbps) [dlOHLA16] which is less than today's data rate requirement. Thus, using CPRI as fronthaul protocol limits the potential benefits we could have from C-RAN through resource pooling, virtualization, and dynamically sharing resources among multiple RRHs.

On the other hand, Ethernet is a packet-based variable bit-rate protocol where variable bit-rate data could be transported. It also allows longer distance separation (10 to 20km), between BBU and RRH. On top of that, using Ethernet as a fronthaul protocol will optimize the cost of the fronthaul by utilizing widely deployed existing Ethernet deployment, and enables cheaper traffic aggregation and switching [AMG+16]. Moreover, Ethernet is an off-the-shelf alternative for fronthaul transport with high capacity. Hence, Ethernet-based fronthaul architecture is of high interest for industry to meet current and future fronthaul capacity requirements.

4.2 Requirements

The requirements of Ethernet-based fronthaul networks depends for example on the type of split option between BBU and RRH, fronthaul transport solution, and MIMO implementation. On top that, while building a fronthaul transport solution, some interdependent requirements, such as technical and business aspects, regulation, and OAM constraints [PCSD15], should be considered. Depending for example on the C-RAN functional splitting option, fronthaul networks dimensioning should be carefully considered. The performance and synchronization of the fronthaul affects the interoperability of BBU and RRH. The business requirement of low cost implementation governs not only the choice of the fronthaul solution but also the cell site engineering aspects [PCSD15]. The OAM enables to monitor and detect faults on the fronthaul link, and the fronthaul solution should support the transport of alarm signals for centralized management.

Radio sites can be macro cells, which have three to six sectors with several RATs on different bands, or micro/small cells which have omnidirectional antenna with only one RRH for each RAT and frequency band. Thus, to reduce the fiber pressure in the fronthaul, multiplexing in time and wavelength is important.

In Ethernet-based C-RAN, Ethernet frames are transported from/to RRH to/from BBU through a fronthaul network. This data transmission requires strict performance, for example capacity and latency, requirements in the fronthaul. Baseband signal transmission in the fronthaul between RRH and BBU, depending on the C-RAN functional split option, requires low latency high capacity fronthaul solution. Therefore, a thorough analysis of fronthaul requirements as well as solutions to optimally transport data are of importance [AMG+16].

4.2.1 Fronthaul latency and jitter

The end-to-end delay of an Ethernet-based C-RAN is the sum of (de)packetization, queuing and processing delays at RRH and BBU, transmission and propagation delays, queuing delay at switches as well as hardware interfaces in the fronthaul link. Internal processing delays of both RRH and BBU depend on their hardware and software implementations. Increasing the distance between RRH and BBU, adding more fronthaul equipments and switches increases the fronthaul latency.

The fronthaul latency is also affected by error control and correction mechanisms such as ARQ, and HARQ processes. For example, according to the Long Term Evolution-Advanced (LTE-A) standard, for Frequency Division Duplexing (FDD) the HARQ Round Trip Time (RTT) Timer is set to 8 subframes (8ms) [3GP15], which means that the user using subframe n needs to know whether retransmission or transmission of new data should occur at subframe n + 8 [AMG$^+$16]. Data receiving BBU/RRH, depending on the type of transport protocol used, needs to prepare HARQ Acknowledgment (ACK) or Non-Acknowledgment (NACK) within a specific time bound. As in [Mob11] and [AMG$^+$16], it appears to be an industry standard that a base station needs to prepare a HARQ ACK or NACK within 3ms by decoding UL/DL data, prepare ACK/NACK and create a DL/UL frame with ACK/NACK.

Timing requirements in the fronthaul, depending on the C-RAN functional split implementation, has to be fulfilled in such a way that the actual fronthaul latency should be less than the maximum possible latency the implantation can handle. Regardless of different possibilities in C-RAN functional split, the fronthaul should still maintain the latency requirement to meet the HARQ deadlines [N.15]. To meet these timing requirements fronthaul needs to have an upper bound for the maximum one-way latency. In [For16] four fronthaul latency capability groups are defined as Ideal, Near Ideal, Sub Ideal and Non Ideal with fronthaul latency capabilities of 250µs, 2ms, 6ms and 30ms respectively. Table 4.1 shows one-way delay capability of different C-RAN split implementations.

Queues and processing delays in the fronthaul also causes delay variation between arriving packets. Nowadays, BBUs and RRHs read the delay at the boot up time, therefore the delay needs to be constant [AMG$^+$16]. This requirement can be relaxed by using buffering devices which however will add higher delay in the fronthaul. Furthermore, clock synchronization across BBUs and RRH over the fronthaul also imposes a very low jitter [N.15].

4.2.2 Data rate

A fronthaul design for current and future mobile networks should maximize the successful transportation of packets from/to RRH to/from BBU. The fronthaul

Table 4.1: Delay and bandwidth throughputs for each split option [For16]

Split Option	One-way delay	DL bandwidth	UL bandwidth
RRC-PDCP	Non Ideal - 30ms	151Mbps	48Mbps
PDCP-RLC	Non Ideal - 30ms	151Mbps	48Mbps
RLC-MAC	Sub Ideal - 6ms	151Mbps	48Mbps
Split MAC	Sub Ideal - 6ms	151Mbps	49Mbps
MAC-PHY	Ideal - 250µs, Near Ideal - 2ms	152Mbps	49Mbps
PHY-RF	Ideal-250µs	2457.6Mbps	2457.6Mbps

requires a high data rate, low latency fronthaul solution that can handle the aggregate radio data from one or more antennas. Because a typical BBU pool should support 10 - 1000 base stations, transport of the I/Q samples from BBU to RRH requires a high fronthaul capacity [N.15]. Besides the carrier bandwidth, the data rate also depends on the type of RAT, C-RAN split implementation and MIMO implementation. Even though reduces the potential benefits of C-RAN, offloading BBU functionalities to RRH reduces the fronthaul data rate requirement as more baseband processing is done at the RRH. Table 4.1 shows UL and DL data rate requirements of different C-RAN split implementations.

The fronthaul data rate (C) as in [N.15] depends on the number of transmitting/receiving antenna ports (N), maximum antenna sectors (M), sampling rate (F), bit width of an I/Q symbol (W), number of carrier components (C), ratio of transport protocol and coding overheads (O), and compression factor (k). The factor 2 is for the in-phase and quadrature components.

$$C_{fronthaul} = 2 \cdot N \cdot M \cdot F \cdot W \cdot C \cdot O \cdot K$$

In addition to I/Q data there is also C&M as well as synchronization data transport in the fronthaul. Thus, the total fronthaul data rate is the sum of I/Q, C&M and synchronization data rates.

4.2.3 Synchronization

In the traditional C-RAN architecture synchronization and timely delivery of traffic are ensured by using a synchronous protocol - CPRI, or the less popular OBSAI [AMG+16]. The frequency and phase synchronization requirements of current and future mobile networks is high. In C-RAN implementation synchronization is also required between BBU pool and RRHs through a communication protocol in the fronthaul. More on synchronization is presented in Section 4.5.

4.3 Radio over Ethernet

Ethernet is an asynchronous, nearly ubiquitous, and widely deployed technology for LANs. As discussed in Section 2.3 Ethernet is a variable bit rate, packet-based off-the-shelf communication protocol. Additionally, (Carrier) Ethernet offers fully standardized OAM for telecommunications [AKJ16].

Data packet is transmitted over an Ethernet link as an Ethernet frame in an Ethernet packet payload. Unlike CPRI, data transmission in an Ethernet link is done only when there is data to send. When a packet is completely processed the time when the next packet will arrive is uncertain. This synchronization challenge of Ethernet could be solved using any of the techniques mentioned in Section 4.5. PBB-TE uses the set of VLAN IDs to identify specific paths to a given MAC address [AMG+16]. This introduces connection oriented forwarding. Ethernet's grade of service can also be assured by using Multiprotocol Label Switching Transport Profile (MPLS-TP) [AMG+16].

In Ethernet-based C-RAN, the payload to be transported between RRH and BBU could be digitized radio payload, vendor specific flow or C&M flow with some additional overhead. During the Radio Over Ethernet (RoE) encapsulation the digitized radio payload could be samples of CPRI flows (also known as CPRI Over Ethernet (CoE)), or native sampled radio signals (also called native RoE).

According to IEEE 1904.3 Task force, there are two types of RoE encapsulation alternatives for transporting radio signals over Ethernet between RRH and BBU: structure-aware and structure-agnostic. Structure-aware encapsulation uses knowledge of the encapsulated and digitized radio transport format content, whereas structure-agnostic encapsulation is a container that encapsulates bits into Ethernet frames irrespective of the encapsulated protocol [CKV+17]. In the encapsulation of radio data over Ethernet, there are no changes to the Ethernet packet format, MAC or narrative queuing, timing, and synchronization definitions. The encapsulation requires to ensure that the desired RoE traffic, with the encapsulation overhead, fits to the available fronthaul link capacity, and have a realistic chance to meet its respective timing requirements.

4.3.1 CPRI over Ethernet

To reduce the limitations of CPRI, and to use the potential advantages of Ethernet in the fronthaul, encapsulating CPRI data over Ethernet is suggested [WA15, All15a, CKV+17] as one solution. However, whether Ethernet can support stringent CPRI requirements in terms of delay and jitter is under scrutiny [CKV+17]. Encapsulating CoE is a cost-efficient solution that can leverage existing Ethernet interfaces and switching equipment for mobile fronthaul [CKV+17].

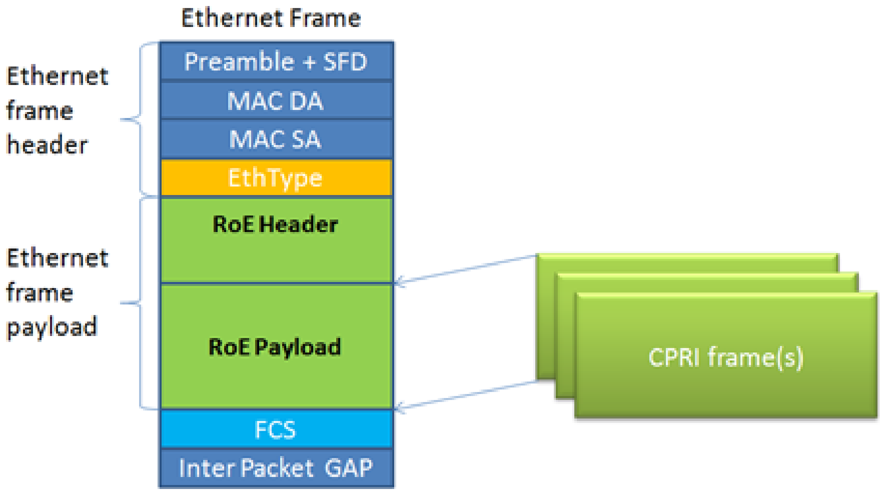

Figure 4.1: CoE encapsulation

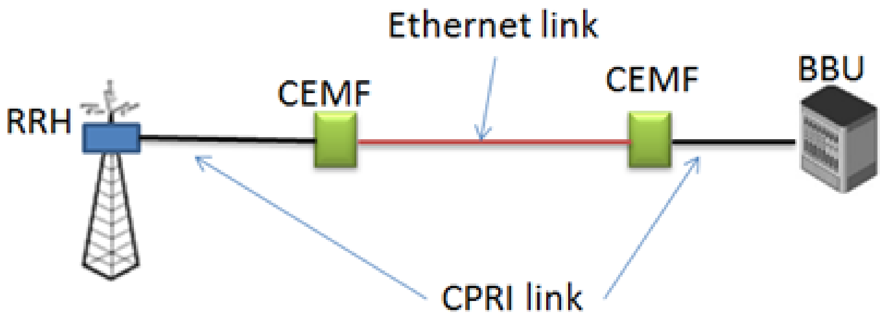

Figure 4.2: CPRI to Ethernet mapping in CoE transport

In CoE encapsulation, the sampled I/Q data is put into a CPRI frame and this CPRI frame, with RoE header as shown in Figure 4.1, is transported between RRH and BBU as a payload in an Ethernet frame. The total encapsulation header is the Ethernet header plus the RoE header and the CPRI header.

This encapsulation also requires mapping of CPRI and Ethernet frames using CPRI-To-Ethernet Mapping Function (CEMF) [ALL15b]. The CEMF could be placed in the fronthaul link, as shown in Figure 4.2, or as part of RRH and BBU.

Moreover, CoE encapsulation, due to the stringent timing requirements of CPRI, is challenged by an end-to-end delay caused by the transport solution as well as the inherent store-and-forward delay based on capacity [ALL15b]. It is also challenged

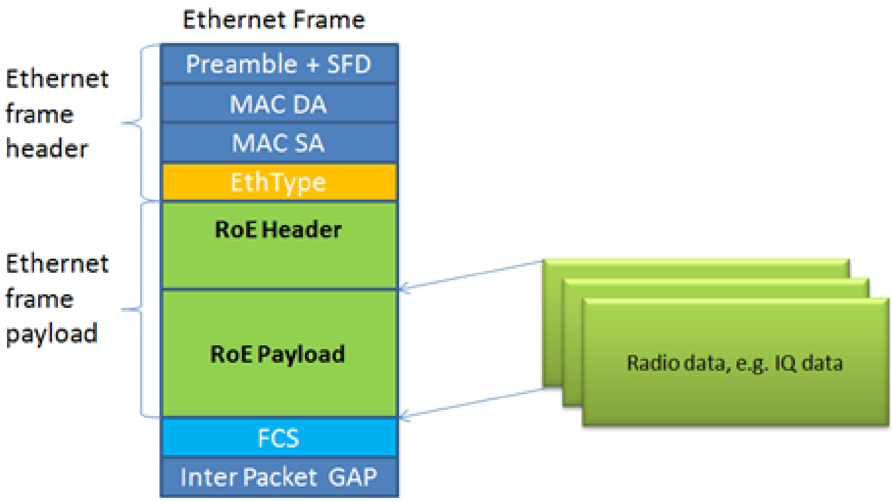

Figure 4.3: Native RoE encapsulation

by the capacity requirement of 2.5Gbps [ALL15b] which raises the need for data compression using CPRI Compression-Decompression Function (CCDF).

4.3.2 Native Radio over Ethernet

In LTE RoE transport, the sampled radio is quantized, framed into radio frames [AKJ16], and then inserted into an Ethernet frame as a payload, as shown in Figure 4.3, for transport. The RoE header contains different sub-fields such as version, flow type, flow identification, sample size, frame length and sequence. In a synchronized Ethernet-based fronthaul the radio frame could be I/Q data, C&M or synchronization data. Inserting the sampled signals into an Ethernet frame involves a mapping of the quantized outputs of the Inverse Fast Fourier Transform (IFFT) [AKJ16] , together with a RoE header, into the payload portion of an Ethernet frame. Thus, the overhead of the encapsulated frame is the overhead of the Ethernet frame plus the overhead of the RoE frame.

In the UL, the encapsulation and decapsulation of radio frames is done, respectively, at the RRH and BBU, whereas in the DL the encapsulation and decapsulation of the radio frames is done, respectively, at BBU and RRH. The different RRHs and/or sectors within RRHs are addressed through VLAN IDs, with the use of dedicated VLANs, while individual antennas are addressed through flow IDs [AKJ16].

The encapsulation overhead will vary depending on the size of the Ethernet frame used and whether jumbo frames are supported over the network [AKJ16]. Most networking device vendors support jumbo frame sizes in excess of 9000 octets [AKJ16], and according to the IEEE P1914.3 Standard for Radio Over Ethernet Encapsulations and Mappings for the latest packet formats, the RoE header is assumed to be a size of 8 octets [AKJ16]. As discussed in Section 4.2.2 the sampling rate and size, provided it is within the Nyquist limit, determines the data rate in a transmission channel.

4.4 Challenges

In C-RAN implementation synchronization is required between the BBU pool and RRHs through a communication protocol in the fronthaul. But Ethernet isn't synchronous in its nature. Thus, supporting synchronization through Ethernet is a challenge for current and future fronthaul networks.

In addition, Ethernet-based networks, depending on the network traffic, may have queues in the hardware devices such as switches used in the fronthaul which cause packet delay, delay variation, and packet loss due to network congestion. The packetization process itself needs extra time to get enough samples and build a packet [CSN+16]. Hence, assuring strict packet delay, and packet delay variation requirements of current and future Ethernet-based fronthaul networks is another challenge.

Moreover, in Ethernet-based fronthaul, packetization introduces additional overhead traffic due to the Ethernet header and application specific control information such as BBU-RRH port mappings and time stamps [CSN+16]. This puts pressure on the fronthaul fiber capacity requirement.

4.5 Technical Solutions

The delay in Ethernet-based fronthaul can be minimized by considering the trade offs, for example, between packetization delay and packet overhead. As in [CSN+16], ideally, the packetization method should minimize both the latency and overhead simultaneously. However, reducing the Ethernet header overhead per frame requires waiting to fill up every frame with data, which in turn introduces additional latency that might lead to violating the one way delay deadline [CSN+16]. Using a smaller payload size can replace a large packet with few small packets [CNS16], so the RRU and BBU queuing delays are decreased, as packets get full soon, but with extra overhead. The optimal payload size that minimizes the fronthaul delay for a given split can be known after exhaustive simulations [CNS16] or experiment trials. Hence, for a given split between BBU and RRH, an optimum payload size has to be used to minimize both packetization delay and overhead.

As in [CNS16] the delay also can be optimized by using a scheduling algorithm; and classifying the samples of symbols as time-critical and non-time-critical. Samples of time-critical symbols are packetized immediately and doesn't need to wait until payload is full whereas samples of non-time-critical symbols do not need to be packetized immediately as there is no delay constraint on them. Non-time-critical packets are formed until payload is full. On the other hand, reducing the sampling rate, given it is above the Nyquist rate, compresses the amount of data to be transmitted by 66.7% [Mob11] hence reduce network congestion and delay.

In current networks BBU is typically equipped with a high precision clock having the time source in the form of GPS or IEEE 1588 Precision Time Protocol (PTP) [Sta08] possibly supported by Synchronous Ethernet (SyncE). SyncE is often used as a complementary solution to GPS or IEEE 1588 to enhance frequency accuracy [AMG+16]. These synchronization solutions could be adapted to future Ethernet-based networks as well. One possible solution for delivering synchronization for Ethernet-based networks is by equipping RRHs with GPS. Though, assure both frequency and phase synchronization, it increases cost and has problems for small indoor and lamped RRHs in a high building as they will not have line of sight communication with GPS satellites. The second possible solution is to implement an IEEE 1588 PTP slave in the RRH. This solution assures lower equipment cost, however, it will be affected by variable network delay present in Ethernet networks [AMG+16] which could be in the order of µs per Ethernet switch [Smi14].

Chapter 5
Experiment work

In Chapter 2 shared fronthaul link C-RAN architecture, and Carrier Ethernet as a future candidate fronthaul transport protocol are discussed. Also in Chapter 3 different C-RAN functional split options between BBU and RRH; and in Chapter 4 the motivation and performance requirements of Ethernet based fronthaul are presented. In this chapter the experiment work for performance test on a simple C-RAN implementation is discussed.

The set up had open source implementations from OAI for a core network (called openair-cn or EPC), BBU, and RRH with emulated UE; and has been done with PHY-RF functional split between BBU and RRH, which were 60.6m apart and connected over Ethernet through Ethernet switch. Copper, Cat5e Ethernet cable, was used as a transport medium. The OAI BBU and OAI RRH with emulated UE were implemented in two different computers and the OAI EPC together with Home Subscriber Server (HSS) was implemented on a VM running over the OAI BBU machine. The two computers used for the BBU and RRH were HP compaq 8200 Elite with 64bit Ubuntu16.04 and low latency kernel. They have Intel core i7 cpu860@2.80Ghz with 8 cores processor, 12GB RAM and 500GB hard disk. Similarly, the EPC was running on the VM with 64bit Ubuntu16.04 but generic kernel from OAI. The Ethernet switch used was HP Procurve gig-t Z1 module J9307A and the ports were configured for 100Mbps.

There are two deployment scenarios for the OAI EPC- Separate EPC Platform and All in one platform [Eur15]. For the first case, the MME is implemented separately from Serving Gateway (SGW) and PDN Gateway, Packet Data Network Gateway (PGW) while in All in One Platform OAI EPC platform all the three components (MME, SGW, and PGW) are implemented together as one; and interact with OAI HSS. The HSS isn't part of the EPC but has been implemented with the EPC. Currently, only the All in One EPC Platform is released and hence used for the experiment. In this EPC deployment the MME interacts with SGW through a virtual S11 interface, HSS through S6a interface, and with BBU through a control plane

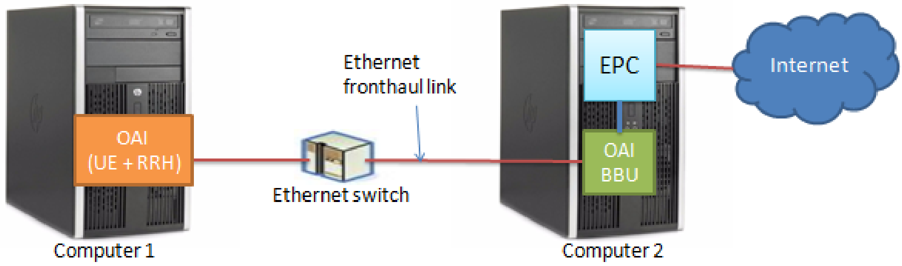

Figure 5.1: Experiment set up

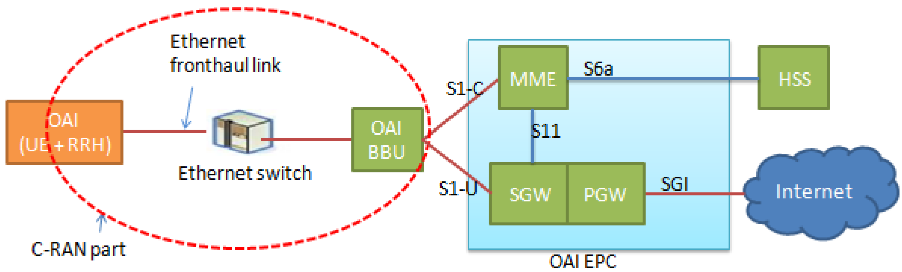

Figure 5.2: Experiment set up with EPC internal components connections

interface (S1-C or S1-MME) interface. The SGW and PGW are merged together, and sometimes called as SGW-PGW (SPGW), hence,there is no S5 or S8 interface between the two functional entities [Eur15]. The SGW communicate with the UE via BBU through the user plane interface (S1-U) and connects UE to the Internet via PGW through SGI interface.

There are two implementations for the BBU and RRH-IF5 (partially centralized physical layer) and IF4P5 (fully centralized physical layer). Since the experiment was to be done on the fully centralized C-RAN IF4P5 was used with frequency band 7. Other configuration details are listed in Table 5.1.

The total C-RAN UL fronthaul delay is the sum of the packetization and processing delay in the RRH, propagation delay over the fronthaul link, queuing and switching delay at the Ethernet switch, and depacketization and processing delay at the BBU. As the same path is used for both UL and DL communication, UL and DL delays are assumed symmetrical and equal. The propagation delay is very small (ns) hence its effect on the fronthaul delay is very small.

C-RAN delay = RRH delay + Switch delay + propagation delay + BBU delay

Table 5.1: Set up configuration details

Parameter	Configuration
Node function	NGFI IF4p5
Antenna technology	SISO
Frame type	FDD
TDD configuration	3
Number of antenna ports	1
Frequency band	band 7
DL frequency	2660MHz
UL frequency offset	-12000000
Number of resource blocks	50
Tx-gain	90
Rx-gain	120
Bandwidth	20MHz
MTU	1500byte

The flow on the fronthaul link is the sum of the actual IP packets to be transmitted and headers added on each packet by the PDCP, RLC, MAC and PHY layers. The UL and DL flow of the C-RAN for PHY-RF Split may also include C&M and synchronization data.

Thus, for both UL and DL the total fronthaul throughput for PHY-RF Split option is the number of IP packets per transport block (IP_{DL}^{TB}) times the number of transport blocks (N_{DL}^{TB}) times the sum of IP packet and headers (Hdr) data in the fronthaul.

$$Throughput_{DL}(Mbps) = \frac{IP_{DL}^{TB} * (IP_{pkt} + Hdr_{(PDCP+RLC+MAC+PHY)}) * N_{DL}^{TB} * 8}{1000000}$$

$$Throughput_{UL}(Mbps) = \frac{IP_{UDL}^{TB} * (IP_{pkt} + Hdr_{(PDCP+RLC+MAC+PHY)}) * N_{UL}^{TB} * 8}{1000000}$$

As discussed in Chapter 4, the C-RAN fronthaul performance could be affected, for example, by the arrival rate of packets, fronthaul bandwidth, sampling rate at the RRH, transport block length, modulation technique used, distance between BBU and RRH, MIMO implementation, number of Ethernet switches, scheduling and data buffering algorithms used, and so on so forth. These parameters could be used to vary the fronthaul traffic load (congestion level), delay of packets, packet jitter, compression of data for transport, received data quality etc., and observe the performance of the C-RAN. With the set up in Figure 5.1 and available tools for traffic generation and measurement, some of these parameters are not easily controllable and not used as a parameter during the performance test.

Iperf [Ipe17] has been used as a traffic generator and measurement tool. It generates a constant bit rate traffic of chosen bandwidth and other parameters such as segment length, transport block length, type of packets (TCP or User data protocol (UDP)). It has been used as a client and echo server on the two machines on which the RRH and EPC are running. It produces average packet jitter and packet loss ratio as a summary. Wireshark [Tea17] has been also used to capturing packets exchanged between EPC and RRH, via BBU, for later analysis.

The effect of varying transport block length on the C-RAN performance has been examined. Performance test measurements have been done by injecting a fronthaul traffic through a tunnel created by GPRS tunneling protocol (GTP) after RRH with emulated UE and BBU are all connected to the EPC. The UE must also be attached to the EPC; and assigned a bearer. The tunnel had two interfaces called gtp0 from EPC side and oip1 from RRH with UE side. Both interfaces got IP address from an IP address pool advertised by PGW.

Chapter 6 Results and Discussion

Measurements have been done using Iperf and Wireshark by injecting TCP or UDP packets between UE and EPC using Iperf. The round trip time and throughput measurements in Figure 6.1 and Figure 6.2 are plotted using Wireshark TCP Stream graphs of captured TCP packets between UE and EPC. Packet jitter and packet loss ratio measurements are done with UDP packets and results are produced by Iperf as a summary. By varying the transport block length measurements were taken and results are plotted using Mathematica in Figure 6.3 to Figure 6.6.

The measured average round trip time, shown in Figure 6.1, of TCP packets between the UE and EPC for a transport block length of 9kB wass less than 2ms, and hence the one-way delay, assuming delay symmetry, wass less than 1ms. The delay in Figure 6.1 wasn't only the sum of the delays in the RRH, fronthaul with Ethernet switch, and BBU, but also included processing delays in the emulated UE and EPC.

The DL throughput, Figure 6.2, for the same transport block length of 9KB was 56.2Mbps and segment length of the transport block, in general, varies about 1500 byte (one packet), 3000 byte (two packets) and 4500 byte (three packets). The same measurement for the UL showed a throughput of 21.7Mbps. As iperf generates a constant bit rate traffic the throughput seems flat over time.

The one-way packet delay, Figure 6.3, increases as the transport block length increases. This increase in delay is mainly due to the packetization delay in the RRH. All packets to be included in a transport block or the buffer of a transport block should get full before transmission, and this require some time and hence the packets delayed. Further increase in the transport block length increases the delay, and eventually the packets arrive after the delay deadline the PHY-RF split can tolerate.

The time required to fill all the packets of a transport block also affects the

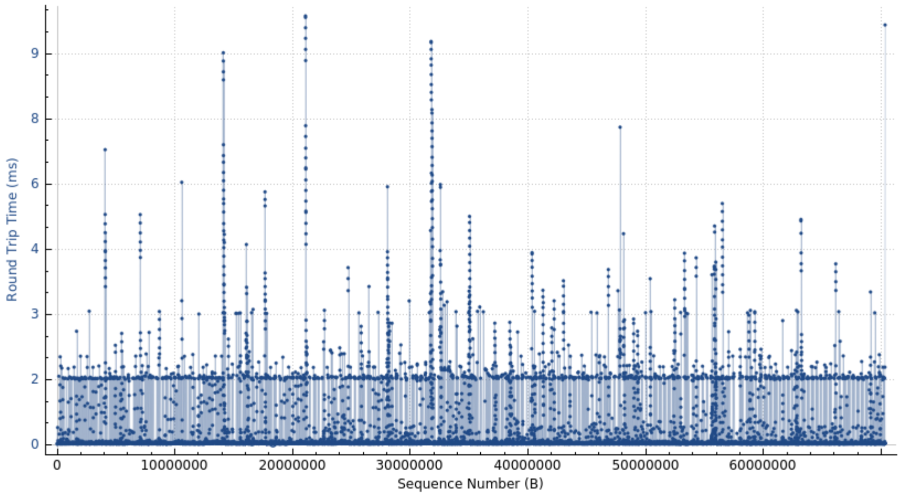

Figure 6.1: Round trip time for transport block size of 9KB

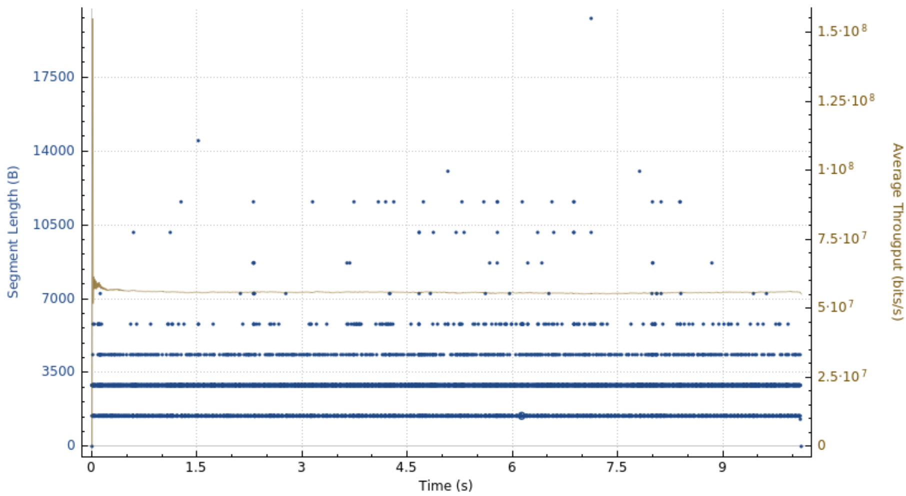

Figure 6.2: DL throughput for transport block length of 9KB

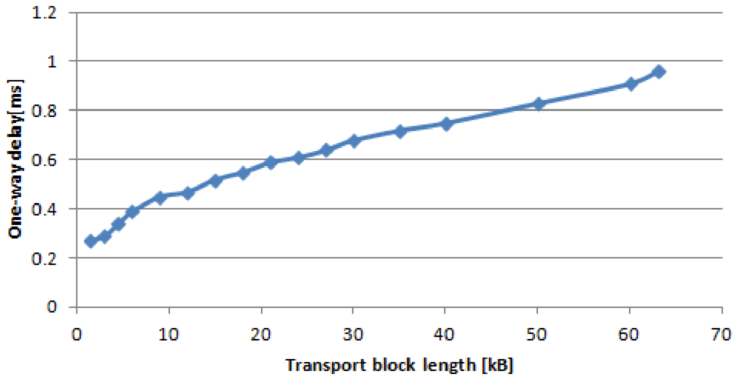

Figure 6.3: One-way delay as a function of transport block length

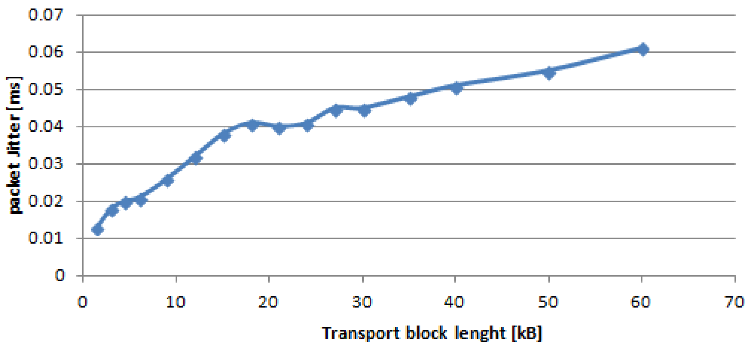

Figure 6.4: Packet delay variation as a function of transport block length

packets' delay variation (packet jitter). The delay variation between packets within a transport block may not be significantly high, but the delay variation between packets of different transport blocks is significantly higher. As the packetization takes more time, the delay variation increases, and hence the delay variation increased with an increase in the transport block length in Figure 6.4.

The DL throughput graph in Figure 6.5, on the other hand, deceases but very slowly at the beginning and faster after 21kB. The decrease in the throughput at the beginning is small as, though delayed, most of the packets have arrived at the RRH before the delay deadline. But further increasing of the transport block length has resulted transport blocks' packets arrival after the tolerable delay deadline for the functional split, as a result further increasing of the transport block length decreased the throughput faster.

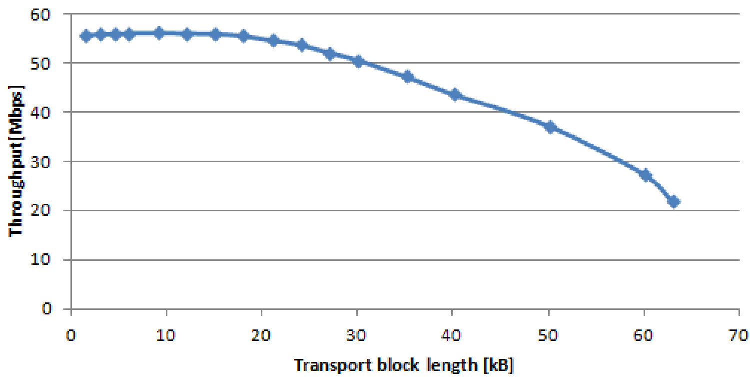

Figure 6.5: Throughput as a function of transport block length

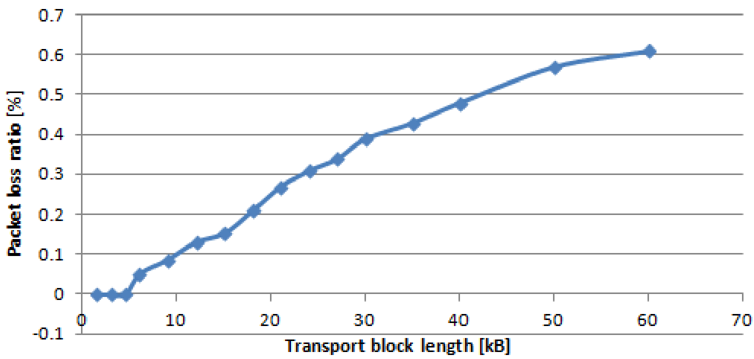

Figure 6.6: Packet loss as a function of transport block length

An increase in the packets delay resulted packet loss. As the transport block length is increased, the packets get delayed and arrive after the delay deadline. This contributed to a packet loss. At the beginning, even though, the average delay was within the delay deadline, some packets have delayed beyond. The packet loss ratio graph in Figure 6.6 also shows that the packet loss ratio increases with an increase in the transport block length.

In summary, the C-RAN implementation with PHY-RF functional split had better performance with respect to delay, delay variation, throughput, and packet loss ratio for lower transport block length. Specifically, the throughput performance of the split has been better for transport block length between 1.5KB and 9KB.

Chapter 7
Conclusion

According to [For16], the PHY-RF split was expected to work only in Ideal fronthaul (250us), but the performance measurements in Chapter 6 using copper fronthaul medium, though for a short distance separation between BBU and RRH, showed that using Ethernet as fronthaul protocol the PHY-RF C-RAN functional split has one-way delay capability up to 1ms. This also agrees with [Mob11] that the one-way delay requirement for the PHY-RF (layer 1) split is 1ms. The performance test done by varying the transport block length also showed that the PHY-RF split can tolerate packet delay up to 1ms.

Unless more Ethernet switches are used, increasing the fronthaul link length, depending on the medium type used, contributes a small fraction of microseconds to the fronthaul delay. Fore example, Cat5e Ethernet cable has delay skew of 45ns per 100m. Hence, for a given transport block length, the fronthaul separation distance could be increased as long as the total delay is less than the one-way delay deadline (1ms).

on the other hand, in [For16] the packet delay variation is defined to be less than 2ms for a Sub-ideal fronthaul, and a minimal for the PHY-RF split. Performance test measurements in Figure 6.4 showed that a fully centralized C-RAN could have a packet delay variation from 10us to 60us depending on the transport block length. Also in [RV15] the user plane tolerable packet loss ratio is indicated to be less than 0.1%. Performance measurement results in Figure 6.6 also showed that the packet loss ratio for a fully centralized C-RAN could vary from 0.013% to 0.6% for different transport block length. Packet loss ratio less than 0.1% was measured for transport block length less than 10kB.

From current OAI community discussions [ope17], the OAI LTE implementation maximum achieved throughput over s1 link between UE and EPC (without any C-RAN functional split) is 60Mbps for DL and 23Mbps for UL. With the PHY-RF split C-RAN set up in Chapter 5 a maximum throughput of 56.2Mbps was achieved with a transport block length of 9KB. Though close to the s1 link throughput, the achieved throughput is less than what is expected for real implementation of C-RAN with PHY-RF split as in Table 4.1. But the throughput could be improved through further work on the OAI implementations and using better transport medium, like Ethernet over fiber instead of copper.

In conclusion, the performance test measurements showed that a fully centralized C-RAN implementation with Ethernet as a fronthaul protocol cloud meet strict timing requirements of the fronthaul. Packets arrived from/to UE to/from EPC within the delay deadline with tolerable packet loss ratio and jitter; and the performance was better for lower transport block length. But the throughput needs further improvement of the set up in Chapter 5, specifically, the transport medium used.

Chapter 8
Future work

The different C-RAN functional split options discussed in Chapter 3 have different timing requirements for the UL and DL. For example in the DL RRC-PDCP split option has better delay capability than split RLC, but in the UL both have relaxed timing requirements. Thus, using different split option for the UL and DL might have better performance.

On the other hand, in the experiment set up used in Chapter 5 only one RRH is considered. The fronthaul link performance and the delay at the Ethernet switch could also be tested with many RRHs connected to a BBU pool through an Ethernet switch. In this case the shared fronthaul link performance and delay at the Ethernet switch will be affected. In addition Scheduling and data compression algorithms could also be used to reduce the fronthaul delay and data rate requirements respectively. Reducing the sampling rate, provided it is above the Nyquist rate, at the RRH is one mechanism to compress I/Q data.

In addition, in the performance test set up only a constant bit rate traffic generator (Iperf) wass used. But using different traffic profile or using commercial UE devices with an RF device could better approximate the real mobile traffic. Also the transport medium used for the performance test set up was copper Ethernet cable (Cat5e). The copper wire has limited bandwidth, higher loss and delay, hence, using Ethernet over high bandwidth low latency fiber could have better performance.

Finally, to choose the optimum C-RAN functional split option performance test on the other C-RAN functional split options discussed in Chapter 3 could be carried out and compared with the PHY-RF split measurement results obtained.

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