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Cloud Radio Access Networks (C-RAN) and Optical Mobile Fronthaul and Backhaul Networks-1

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Problem description:

Increasing demand of mobile data traffic due to the growth of Internet-connected devices and applications-based services has led to high capacity demand of mobile data network. This is fueling the necessity of deployment of next generation communication systems as pursued as Fifth Generation (5G) . 5G increases the need of optimized use of bandwidth, high requirement of latency, Packet Delay variation (PDV), Packet Loss Ratio (PLR), jitter, and time and frequency synchronization. In this context, Cloud – or centralized- Radio Access Network (C-RAN) has been introduced as a promising solution towards keeping cost at moderate level by splitting the processing unit from the radio unit. Thus, while traditional network architecture only focuses on mobile backhaul, C-RAN further dis-aggregates the network into fronthaul and backhaul.

Latency is the most important performance metrics in deploying 5G. Current C-RAN fronthaul uses Time Division Multiplexed (TDM) based protocol Common Protocol Radio Interface (CPRI) / Open Base Station Architecture Initiative (OBSAI) which is not compatible with 5G transport requirements. That is why transporting Radio over Ethernet (RoE) frame concept has developed and has caught the interest of both carriers and system suppliers as it may allow both backhaul and fronthaul traffic over the same Ethernet link, increasing the utilization of infrastructure. However, new challenges arise as Ethernet cannot meet up the demand with respect to latency and timing. These challenges and possible solutions are the focus of this thesis work. Ethernet based Integrated Hybrid Optical Network (IHON) technology called 'Fusion'; implemented by Transpacket, a start-up company, can improve the transport network architecture of C-RAN.

Thus, the goals of this master thesis are to investigate how IHON principle can be applied in a network with few wavelengths even only a single wavelength, and to examine (by simulation work) how latency can be reduced by applying IHON on 5G mobile transport network; both fronthaul and backhaul network.

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Abstract

Due to increase demand of mobile data traffic and application based services, telecom operators are thinking to improve the network architecture. Fifth Generation (5G) is the latest mobile generation that aims to support a large range of new services with high demands on bandwidth and low latency. As the requirements for bandwidth in mobile networks are growing, the need for higher cell-density is increasing correspondingly. Therefore, balancing between the cost of bandwidth and providing efficient service becomes challenging. In this context, Cloud or centralized- Radio Access Network (C-RAN) has been introduced as an architecture towards keeping cost at moderate level, by splitting the processing unit from the radio unit. However the fronthual requirements specially latency requirement of 5G fornthaul is very strict; lower than 100 µs. Current C-RAN fronthaul uses Time Divsion Multiplexed (TDM) based protocol CPRI/OBSAI which is not cost efficient solution for 5G because of their circuit switching nature. Therefore a packet based solution is needed to implement in mobile fronthaul such as Ethernet.

The challenge with Ethernet fronthaul is that Ethernet is designed for time sensitive network and the asynchronous arrival of frame creates Packet Delay Variation (PDV). Ethernet also can not aggregate fronthaul traffic on a single wavelength. Towards solving these problem Transpacket As, a Oslo based start-up company invented an Integrated Hybrid Optical Network (IHON) based node called 'Fusion' which enables statistical multiplexing of backhaul traffic without any effect on fronthaul traffic. This node also can aggregate several fronthaul streams in a single wavelength with low and fixed delay. Therefore in this thesis work the goal is to investigate how applying IHON node in transport network can improve the performance of Cloud Radio Access Network (C-RAN) and how it can assist to transport several fronthaul traffic in very few or single wavelength. Related literature gives the basic to make analytical and simulation model of IHON node. In analytical model, mathematical representation of calculating one way latency and separation distance between Radio Remote Head (RRH) and Base Band Unit (BBU) are performed for several transport option like dedicated fiber, Wavelength Division Multiplexing (WDM) , Optical Transport Network (OTN) and Ethernet.

The simulation work presents the performance of IHON node in terms of fronthaul requirements- latency, PDV and Packet Loss Ratio (PLR). Simulation result shows that Guaranteed Service Transport (GST)

(fronthaul) traffic transports through the network with absolute priority and neither PLR nor delay is affected by the Statistical Multiplexing (SM) insertion regardless of network congestion. Average latency of GST is always 1.2 µsec. For SM (backhaul) traffic with (L_{SM}^{1GE} = 0.3) it shows up to 89% utilization of wavelength.

The simulation result for GST traffic proves that using IHON node in fronthaul can increase the latency performance according to frothual requirements. Transferring SM traffic alongside of GST traffic improves resource utilization without any effect of time sensitive fronthul traffic. In addition, the proposed aggregation capability may enable IHON transporting several fronthaul streams in few wavelengths even in a single wavelength.

Preface

This thesis is submitted as the completion of MSc. degree in Information Security and Communication Technology at the Norwegian University of Science and Technology (NTNU). The thesis described herein was conducted under the supervision of Associate Professor Steinar Bjørnstad and co-supervision of Raimena Veisllari at the Department of Information Security and Communication Technology, NTNU and is the product of the master period, between October 2018 and April 2019. It has a workload of 30 European Credit Transfer System (ECTS) credits. Yours truly has a bachelor degree in Electrical, Electronics and Communication Engineering from Military Institute of Science and Technology in Bangladesh.

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My Family for giving me full support especially to my parents and my little daughter Noyli, the source of my inspiration even in very struggling period.

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List of Acronyms

1G First Generation.

2G Second Generation.

3G Third Generation.

4G Fourth Generation.

5G Fifth Generation.

ACK Acknowledgement.

ARPU Average Revenue Per User.

BB Baseband.

BBU Base Band Unit.

BER Bit Error Rate.

BS Base Station.

C&M Control & Management.

CAPEX Capital Expenditure.

CoMP Coordinated Multiple Point.

CPRI Common Public Radio Interface.

C-RAN Cloud Radio Access Network.

CU Centralized Unit.

DEMOS Discrete Event Simulation model.

DL Downlink.

DMUX Demultiplexer.

DU Distributed Unit.

EB Exabyte.

eCPRI Evolved Common Public Radio Interface.

eNodeB eNB.

eRE Evolved Radio Equipment.

eREC Evolved Radio Equipment Controller.

FDD Frequency Division Duplex.

FDL Fixed Delay Line.

FTD Frame Transfer Delay.

FTTH Fiber To The Home.

GE Gigabit Etherenet.

GPON Gigabit PON.

GST Guaranteed Service Transport.

HARQ Hybrid Automatic Re-transmit Request.

HON Hybrid Optical Network.

IETF Internet Engineering Task Force.

IHON Integrated Hybrid Optical Network.

IP Internet Protocol.

IR Infrared.

IT Information Technology.

ITU International Telecommunication Union.

ITU-T International Telecommunication Union - Telecommunication.

LAN Local Area Network.

LNA Low Noise Amplifying.

LTE Long Term Evolution.

MAC Medium Access Control.

MIMO Multiple input multiple output.

MNO Mobile Network Operator.

NACK Negative Acknowledgement.

NG-PON Next Generation-PON.

NMT Nordic Mobile Telecom.

O&M Operation and Maintenance.

OADM Optical Add drop Multiplexing.

OBS Optical Burst Switching.

OBSAI Open Base Station Architecture Initiative.

OCS Optical Circuit Switching.

OPEX Operational Expenditure.

OPS Optical Packet Switching.

ORI Open Radio Interface.

OTN Optical transport network.

PA Power Amplifying.

PDCP Packet Data Control Protocol.

PDV Packet Delay Variation.

PHY Physical.

PLR Packet Loss Ratio.

PON Passive Optical Network.

PPB Parts Per Billion.

QoS Quality of Service.

RAN Radio Access Network.

RE Radio Equipment.

REC Radio Equipment Controller.

RF radio frequency.

RLC Radio Link Controller.

RoE Radio Over Ethernet.

RRH Radio Remote Head.

RTT Round Trip Time.

RU Radio Unit.

SM Statistical Multiplexing.

TDD Time Division Duplex.

TDM Time Division Multiplexing.

TDMA-PON Time Division Multiple Access-PON.

TSN Time sensitive Network.

UE User Equipment.

UL Uplink.

Virtual Local Area Network VLAN.

WDM Wavelength Division Multiplexing.

WDM-PON Wavelength Division Multiplexing-Passive Optical Network.

ZB zettabyte.

Chapter 1
Introduction

Increasing demand of mobile data traffic due to the growth of Internet-connected devices and applications based services has lead to high capacity demand on mobile data network. 5G is the latest mobile generation that aims to support a large range of new services with high demands on bandwidth and low latency by setting some key performance indicators e.g., 10000 devices per km^2, mobility $>$ 50km/hr, Very high data rate 1 Gbps, ubiquitous 5G access in low density areas, end-to-end latency $<$ 1ms [Mic16]. Supporting high bandwidth in mobile transport network requires dense cell-structures.

Applying C-RAN in mobile fronthaul is a promising solution for delivering cost efficient networks, but requires end-to-end network latency between the RRH and the BBU lower than 100 µs. Current fronthaul transport option uses Time Division Multiplexing (TDM) based protocols CPRI/Open Base Station Architecture Initiative (OBSAI). Radio Over Ethernet (RoE) is proposed as a packet based alternative but can not meet the latency requirements; as 100 µs one-way fronthaul latency requirement is a maximum peak including PDV. Therefore equipping a fronthaul network requires the latency to be low and deterministic.

TransPacket, a start-up company, has developed and patented a technology named by "Fusion", which enables Mobile Network Operators (MNOs) to design and deploy Ethernet based fronthaul and backhaul networks. The focus of the technology is to minimize the packet delay and delay variation even in the presence of multiple traffic sources.

1.1 Problem Statement

More and more the world is becoming mobile and need for mobile data based services have been increasing. The industry have had a development of mobile networks with new generations about every ten years since analogue Nordic Mobile Telecom (NMT) (1G) came in 1981, 2G in 1992, 3G in 2001 and 4G in 2010. Around

2020 comes 5G. According to cisco global Internet Protocol (IP) traffic forecast , annual global IP traffic will reach 4.8 zettabyte (ZB) per year by 2022, or 396 Exabyte (EB) per month and mobile data traffic will increase sevenfold within 2022 [Cis19]. South Korean mobile carriers - SK Telecom, KT and LG Uplus- officially launch their 5G networks on 3rd April, 2019 [AFP19]. Telenor has demonstrated the first 5G in Norway on 20th March, 2019 with vendor Huewai [Tel19].

Coping up with the ever increasing need from subscribers' side and also towards gaining of Average Revenue Per User (ARPU) from the MNOs' side lead to the necessity of improving traditional Radio Access Network (RAN) architecture. C-RAN is considered as promising because of easing the RAN structure by pooling several BBUs from cell cite to a central office through high bandwidth transport link typically the CPRI. Where in earlier set-up each RRH was connected to each BBU; so less complex set up results less Operational Expenditure (OPEX) and Capital Expenditure (CAPEX) for MNOs.

However, because of the challenging capacity, low layer functional splitting and latency requirements, CPRI based fronthaul trasnport network is most often deployed over dark fiber or WDM solution or Optical transport network (OTN) [CCY+15]. These circuit switching solutions are too expensive for many MNOs and inefficient for 5G.

Therefore, moving towards a packet based solution for fronthaul network is considered very potential as statistical multiplexing can increase the gain, leveraging their cost efficiency of sharing bandwidth resources [VBB18]. The objective is to aggregate multiple fronthaul streams into the same channels(wavelengths) with low and fixed delay and also transport backhaul traffic alongside fronthaul traffic without creating any effect on fronthaul streams.

Considering packet based solutions in fronthaul leads the need of wide Ethernet deployment and drives new standardization work as IEEE 1914.3 radio over Ethernet (RoE)[IEE18], and Time sensitive Network (TSN) for fronthaul IEEE 802.1CM [IEE14b], Evolved Common Public Radio Interface (eCPRI) over IP/Ethernet specification [eCP18]. However through all these specifications still the one way 100 µs latency budget for high priority fronthaul traffic is challenging to achieve. The main challenge in Ethernet fronthaul is Ethernet is not designed for strict timing support and delay is dependent on traffic load, so PDV is also high [BCV18].

In addition, to ensure correct processing of the encapsulated data, a smooth PDV-free stream is required. To remove this PDV, a playout buffer can set at receiver by delaying the fastest packet to be equal to the slowest packet. For this purpose, the minimum size of the buffer has to be set for the peak PDV. Therefore, provisioning a Fronthaul network requires the delay to be deterministic and as low as possible.

In consequence of these challenges in Ethernet Fronthaul, there is need for approaching new technology to bring solution in Ethernet fronthaul. The ethernet based implementation of IHON called 'Fusion' has proved it's capability by several experiments to meet the requirement of fronthaul network in terms of deterministic delay, aggregation; those are not achieved yet by Ethernet.

1.2 Related work on IHON

There are several research works performed about IHON.

IHON enables a multi-service path supporting: (a) a GST service class with fixed delay and ultra-low PDV independent of load, and (b) high throughput efficiency through a lower-priority SM service class [VBB13].

In the very first article of IHON, R.Veisllari shows how IHON can increase the channel utilization without creating any effect on the quality or timing characteristics of the traffic (both GST and SM) passing through the wavelength for the first time by experiment with fusion network [VBB13]. In the metro network, insertion of SM in the gap of GST streams can increase the of 10 Gigabit Ethernet light path up to 97%. In another work [VBB17], it has been demonstrated a two node 100G path suitable for carrying fronthaul traffic through the GST class, while increasing the throughput through added SM traffic. In recent work of low and bounded delay [VBB18] in IHON has evaluated SM performance and has shown backahul delay is bounded within 1 ms. Thus a full converged fronthaul and backhaul network solution is proposed.

1.3 Research Question

Based on the above discussion, this study poses some relevant questions to be answered.

1. How IHON can improve the performance in terms of latency in 5G mobile transport network (i.e. the fronthaul and backhaul networks)?
2. How IHON can be applied in the mobile transport network containing only a few, or only a single wavelength channel?

1.4 Objectives of the Thesis

Towards getting the answers of above mentioned research questions following specific objectives need to be achieved:

1. Study of the optical fronthaul and backhaul architecture of C-RAN;
2. Study of the fronthaul requirements for mobile transport networks with respect to different performance metrics: latency, PDV and PLR;
3. Study of IHON principle in terms of applying this in mobile transport network;
4. Investigation and identification of the possible IHON solution for C-RAN fronthaul networks;
5. Analysis the technique by which IHON can improve the performance of mobile transport network of 5G (fronthaul and backhaul);
6. Simulation Analysis of IHON to examine the performance of node in terms of average latency, PDV and PLR

1.5 Methodology

This section specifies and justifies the process undergone to end up at suitable answers for the research questions set out at the beginning of the project. Tools that will be used, and steps to be taken are enumerated. The research design will be guided by research question, so let us revisit it-

1. How IHON can improve the performance in terms of latency of the 5G mobile transport network (i.e. the fronthaul and backhaul networks)?
2. How IHON can be applied in the mobile transport network containing only a few, or only a single wavelength channel?

To achieve the above-mentioned research questions; a list of methods is to set up including research of relevant scientific papers, white papers, standardization and specifications and conducting analytical/simulation work.

1.5.1 Background Research/ Literature review

A comprehensive study of relevant books or journals of several authors' works, white papers will be studied to obtain the details knowledge of C-RAN, IHON and also to analyse the use case of C-RAN e.g. what would outcome after applying IHON on fronthaul and backhaul. The standardization from International Telecommunication Union - Telecommunication (ITU-T), IEEE 1914.3-2018, IEEE 802.1CM-2018 (TSN), IEEE 1588, (CPRI/ eCPRI) specification and recommendation of Internet Engineering Task Force (IETF) will be studied to know about the fronthaul requirements and the overview of C-RAN.

1.5.2 Analytical and Simulation methods

To investigate the performance of IHON in the mobile transport, a simulation work will be conducted in this thesis. Besides this, an analytical model will be presented to calculate the one way end to end delay and separation distance between RRH and BBU. Analytical model would be the basis of implementing simulation model in terms of delay calculation. Object oriented Programming language 'Simula' based on Discrete Event Simulation model (DEMOS) will be used for performing simulation work.

Simula/Demos is designed and implemented as a full scale general purpose programming framework. This object object-oriented simulation language developed at the Norwegian Communication Center for designing of simulation entities. The simulation is run 10 times by varying simulation seeds and confidence interval of 95% has calculated for each performance metrics. To present the simulation result in a graphical way 'Python' programming language is used.

1.6 Thesis Outline

The remaining part of the thesis is organized as follows:

Chapter-2: Cloud Radio Access Network (C-RAN) describes the details of C-RAN; e.g. evolution from tradition RAN, architecture, components, benefits and several transport options from point to point fiber to Ethernet, frothaul requirements etc. In addition functional splitting of C-RAN towards meeting the requirements of 5G is also discussed.

Chapter-3: Integrated Hybrid Optical Network (IHON) emphasis on the principles, properties and main characteristics of IHON or fusion networking. A detailed insight on the delay and PDV of IHON and Ethernet standard switch, IHON node aggregation and an algorithm to compute the inter packet gap are also discussed

Chapter-4: Analytical & Simulation Model presents the analytical model of calculating end to end one way latency and separation distance between RRH and BBU for different transport options. This chapter also discussed simulation model of IHON in details.

Chapter-5: Results & Analysis presents the simulation result in terms of latency, PDV and PLR for GST and SM traffic. It also discusses about using fewer or only one wavelength to transport fronthaul and backhaul traffic by utilizing IHON node aggregation.

Chapter-6: Conclusion summarizes the all work to show how research questions are investigated.

Chapter-7: Future Work presents a list of task that would be taken as future work.

Chapter 2
Cloud Radio Access Network

In this chapter, brief analysis of Cloud Radio Access network (C-RAN) is presented focusing on architectural evolution, C-RAN system architecture, several transport options with challenges, Ethernet fronthaul, functional splitting and fronthaul requirements.

2.1 Why Cloud Radio Access Network

The mobile traffic is exploding due to an increase number of devices and complex services. To cope with these changed situation existing architecture of mobile transport network has to be changed. This improvement or change of network architecture impose huge pressure on CAPEX and OPEX for mobile network operators. Maximizing network capacity, improving quality of service and reversing the falling ARPU are challenging to achieve with the traditional RAN architecture.

In Long Term Evolution (LTE) there was effort for increasing capacity by adding more cells, creating heterogeneous and small cell network or by implementing Multiple input multiple output (MIMO) or massive MIMO for serving multi user. However, because of using several antennas to serve multiple users in same frequency resource lead to grow inter-cell interference and high costs. There are lot of academic and industrial research has been performed to improve the RAN architecture. C-RAN can be regarded [CCY+15] as one of the ways to evolve the mobile networks and architectures.

C-RAN is a noble mobile network architecture which has the potential of solving the above mentioned challenges by incorporating cloud computing into RANs combining wireless technology and Information Technology (IT). The concept was first proposed by China Mobile [CH11] and the idea is to pulling the BBU from multiple base station to a centralize BBU pool to acquire statistical multiplexing gain[CCY+15]. This helps network architecture adapting with non-uniform traffic and utilizing Base Station (BS) more efficiently.

2.2 Architectural Evolution of Base Station (BS)

Traditional Base Station (BS)

The architecture of BS has been evaluated time to time from First Generation (1G) to 5G. During the earlier mobile networks deployment e.g. 1G and Second Generation (2G), the radio and baseband processing functionality, power unit, battery backup is integrated inside base station. This macro BS does not consider fronthaul network. Figure 2.1 shows how antenna module is connected with radio module in few meters of distance through coaxial cables in traditional architecture.

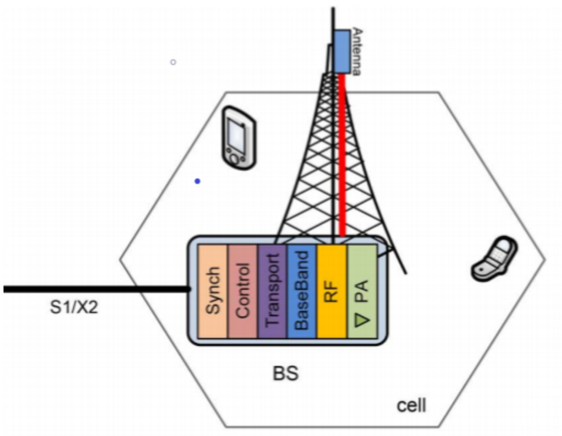


Figure 2.1: Traditional Macro BS without BBU module [CCY+15]

X2 interface creates connection among base stations, S1 interface connects a base station with mobile core network.

Base Station with RRH /Distributed RAN

During the deployment of Third Generation (3G) network, Radio module and base band signal processing unit was being separated to ease the complexity of structure. This is called base station with RRH architecture [CCY+15]. RRH contains Radio Frequency (RF) transmitting and receiving components; It along with antenna places on the top of the cell site where only few meters of coaxial cables needed to make connection between RRH and antenna.

This architecture is very common and has been used by most of the base station where 3G service exists. Infrared (IR) data transmission between RRH and BBU is implemented by CPRI protocol. Other two protocols also can be used such as OBSAI or Open Radio Interface (ORI) . Implementing optical interface in BS architecture can enhance the data rate and lessen the power consumption. There is a limitation in

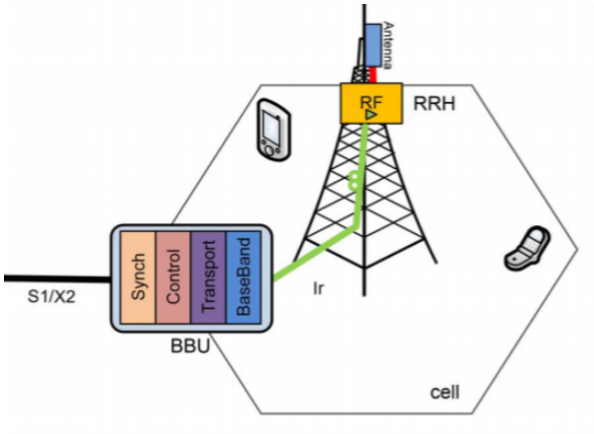


Figure 2.2: BS with Distributed RAN [CCY+15]

this set up from the processing and propagation perspective as the distance between RRH and BBU can be extended up to 40 km. Only one RRH is served by one BBU. This is shown in Figure 2.2 [CCY+15]. Therefore still the cost is high. However this architecture is the first step of BBU hosteling/pooling architecture towards implementing the concept of C-RAN.

C-RAN to Cloud RAN

To improve the implementation flexibility and operational efficiency than previous architecture, a new concept C-RAN comes into force where BBUs are being pooled from RRHs and placed into centralized cloud to share among many RRHs. Moving some radio network functionalities from cell side antenna to centralized location introduces the 'Fronthaul' concept in mobile transmission network [JCT+15]. As BBU functionalities are virtualized in the BBU pool so resource are more utilized in this architecture. One BBU is shared by many RRHs (Figure 2.3) in this step of mobile network evolution so resource could be allocated dynamically based on demand. Like Distributed RAN architecture, this also allows 20 km to 40 km[CCY+15] distance separation between BBU and RRH. CPRI based fronthaul is most often deployed over dark fiber or WDM solutions. This solutions for frontahul can meet the performance requirements of today's Fourth Generation (4G)/LTE networks. However, This solution is not so economically convenient and efficient while considering deployment of 5G for for many MNOs .

As part of upgrading mobile network from legacy to 5G, Centralized RAN architecture is yet to be improved based on functional splitting of Baseband (BB) processing, virtualization of higher layers BB function between the RRH and BBU. 5G demands efficient and flexible data transmission via packet based transport such

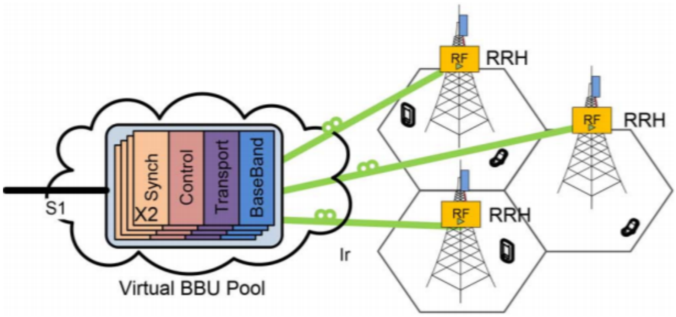


Figure 2.3: Centralized Radio Access Network Architecture [CCY+15]

as IP or Ethernet. Therefore current CPRI will be upgraded to eCPRI protocol and according to standardization Ethernet based fronthaul will connect RRH and BBU through eCPRI protocol (Figure 2.4) to acquire the strict fronthaul requirements of 5G.

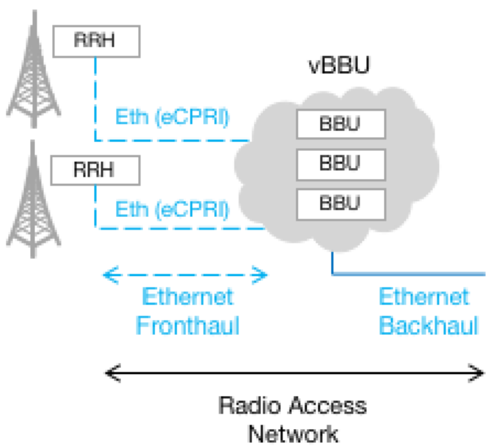


Figure 2.4: Cloud Radio Access Network Architecture with eCPRI Protocol[As18]

While the more traditional infrastructure feeding base-stations is called mobile backhaul, the cloud-based architecture is called a mobile fronthaul and puts very high demands to the underlying fibre-optical infrastructure with respect to latency and timing. The more details will be discussed in later part of this thesis.

2.3 C-RAN System Architecture

In this section, C-RAN components, backhaul network and advantage of C-RAN will be discussed.

2.3.1 C-RAN Components

C-RAN contains Radio Remote head (RRH), Baseband Unit (BBU) pool and fornthual/transport network [CCY+15]. Figure 2.5 shows a CRAN LTE network where frontahul and backhual network is illustrate briefly.

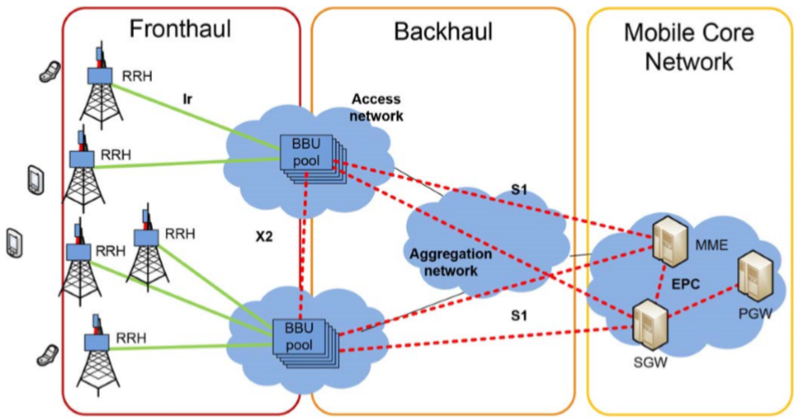


Figure 2.5: C-RAN LTE network showing Fronthaul and Banckhaul [CCY+15]

RRHs with antennas located at the remote sites

RRHs performs radio frequency (RF) amplification, up/down conversion, filtering, analog-to-digital conversion, digital-to-analog conversion, and interface adaptation [PWP15]. It provides high data rate for UEs with basic wireless signal coverage, by transmitting RF signals to UEs during downlink and by forwarding the baseband signals from UEs to the BBU pool for centralized processing during uplink. RRH conducts most signal processing functions in the BBU pool. As most of the task related to signal processing occurs in BBU, the structure of RRH module is relatively simple. Considering large scale manner the distribution of this RRH module is cost efficient.

A BBU pool consisting of a large number of BBUs with centralized processors

BBU conducts BB signal processing and connects to RRH through optical fiber using Digital radio over fiber technology. It is placed in a centralized site and contains several set of time varying software defined BBUs which operate as virtual BS to perform BB signal processing from cell sites to BS and optimize the radio resource allocation. Signal processing resources are dynamically allocated in the software defined BBU. The processing capability is adaptively reconfigured based on the traffic-aware scheduling of UEs and time varying radio channels.

A fronthaul network

Fronthaul network connects RRHs to BBUs with high capacity and low time latency using protocol CPRI and OBSAI [1] in current network architecture. Fronthaul network can be established by different technologies, such as optical fiber communication, standard wireless communication, or even millimeter wave communication.

Mobile transport network has very strict requirements in fronthaul in terms of latency, Packet Delay Variation (PDV) and Packet Loss Ratio (PLR). Specially latency requirement is very high in fronthaul; a maximum of 100µs one-way delay between BBU and RRH [eCP18]. This includes both delays through the fibre or air (5 µs/km for fibre) [Net14] and any delays caused by intermediate switches. For time sensitive traffic (here it is called GST) the delay should be constant and delay variation should be very in low value as zero and packet loss ratio should be zero. Fronthaul requirements are described briefly in Section 2.9.

Current fronthaul protocol CPRI can not be compatible with requirements of the future C-RAN architecture towards deploying 5G. Thus eCPRI has been considering as this specification may support 5G and enables increase efficiency to meet the needs foreseen for 5G mobile networks. In contrast to CPRI, the eCPRI specification supports more flexibility in the positioning of the functional split inside the physical layer of the cellular BS [eCP18].

In IEEE 802.1CM-2018, Functional block of fronthaul that is mentioned RRH and BBU , can also be referred as Radio Equipment (RE)/Evolved Radio Equipment (eRE) and Radio Equipment Controller (REC)/Evolved Radio Equipment Controller (eREC). These are the two basic building blocks (Figure 2.6) into which a BS can be decomposed to provide flexible BS system architectures for mobile networks [IEE14b].

Backhaul network

The Backhaul network connects BBU pool with the mobile core network by core wired network, fiber or coaxial cable, and in some cases broadband, proprietary wireless links also. Fronthaul, backhaul, and various hybrid architectures is essential

[1]Common Public Radio Interface; http://www.cpri.info/

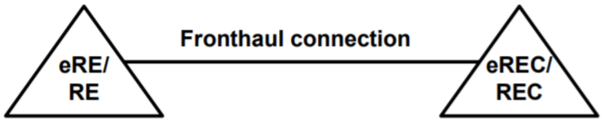


Figure 2.6: Functional Block of Fronthaul Network [IEE14b]

to accommodate cost efficient, backwards compatible, dense deployment of network infrastructure for providing broadband service and meet up the low latency demands for 5G.

Traditional architecture concerns about only backhaul where C-RAN considers both fornthaul and backhaul. In recent days there has been conducting research on one step further like integrating both fronthaul and backhaul in an unified management environment named as 'X-Ethernet' for deploying 5G [Li17]. This also called 'X-haul' and in similar way it is also called by '5G cross-haul' [XAT+17]. That will have the capability of carrying multiple traffic such as CPRI and Ethernet in same channel.

2.4 Fronthaul Architectures

According to the constraints on fronthaul and the different functional splitting between BBUs and RRHs, three types of architectures [PWP15] has been categorized which are described below-

2.4.1 Full centralization

Full centralization of fronthaul architecture denotes the responsibility of performing all the functions of baseband (e.g.,Physical layer/layer 1, Medium Access Control Layer/layer 2 and the Network Layer/Layer 3) by BBU. It is illustrated in the picture-2.5, that BBU contains all processing and managing functions of the conventional BS. On the other hand, RRH is responsible for only up/down conversion, Power Amplifying (PA) (RF signal amplification), Low Noise Amplifying (LNA), filtering and interface adaptation .

This considers as simple and principal architecture of the C-RAN configuration, however it creates huge burden on fronthaul network due to high bandwidth of BB radio signal [CSNS16] . Even though this burden on fronthaul network takes as significant benefits in terms of operation and maintenance, several ongoing researches have been conducted for developing techniques to reduce the heavy burden on fronthaul network.

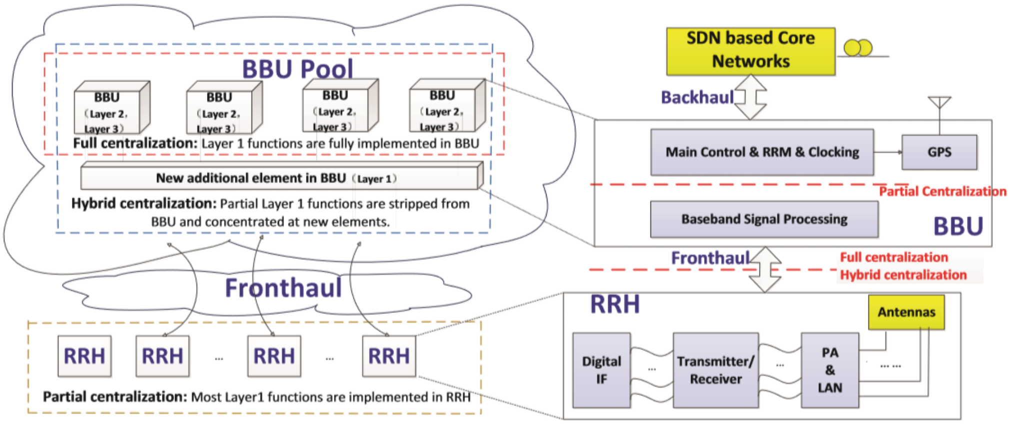


Figure 2.7: Three types of functional Splitting in C-RAN between RRH and BBU [PWP15]

2.4.2 Partial Centralization

In this type of architecture, RRH incorporates RF related BB processing functions from BBU along with its own RF function where other functions of Layer 1, 2 and 3 are still located in the BBU.

Partial Centralization reduces the functional burden of BBU because of the sharing and reduces hte RRH-BBU overhead. In contrast, some advanced features (e.g., Coordinated Multiple Point (CoMP) transmission and reception and spatial cooperative processing for distributed massive MIMO) cannot be efficiently supported [PWP15] in this architecture. Moreover, the collaboration between Layer 2 and Layer 1 makes this setup more complex.

2.4.3 Hybrid Centralization

Partial functionalities of Layer 1 such as user specific or cell specific signal processing are removed from BBUs and pooled into a new separated processing unit, which can be a part of the BBUs pool. This process often regarded as special case of full centralization and creates benefits in terms of flexible support in resource sharing and potential capability to lessen the modifications and energy consumption in BBUs [PWP15].

2.5 Benefits of CRAN

The C-RAN concept lowers operating expenses and simplifies the deployment process. By centralizing all the active electronics of multiple cell sites at one centralized location; energy, real-estate and security costs are minimized. The RRH can be mounted outdoor or indoor – on sides of buildings or any places where a power and a broadband connection exist, making installation less costly and easier [CCY+15]. The RRH is typically connected using fiber to the BBU, creating cloud-like radio access network topology. This topology saves costs both during the installation (CAPEX) and later in the on-going operation (OPEX).

2.6 Fronthaul Transport

Fronthaul network can be connected through copper wire, microwave or optical fiber. However , the solution based on copper links is not taken into account for C-RAN, as Digital Subscriber Line (DSL) based access can offer speed only up to 10-100 Megabit per Second (Mbps) [ABK+16]. The typical microwave solutions offer from 10 Mbps-100Mbps to 1 Gigabit per Second (Gbps) range, the latter available only for a short range up to 1.5Gbps [Lab13]. Fiber link allows huge transport capacity, supporting up to tens of per channel; and it is the most prominent solution for physical medium [ABK+16]. This is preferred over other solutions when high bandwidth, long distance, and immunity to electromagnetic interference are required to consider. In current technology, fronthaul network is based on optical fiber access over CPRI protocol. In the following section several transport options for fronthaul has been discussed.

2.6.1 Point to Point Fiber

In this transport option, each RRH is connected to BBU through dedicated fiber. The fiber can be bidirectional or a pair of unidirectional fibers. Each RRH-BBU has dedicated fiber link. This point to point fiber is a preferred solution for a BBU pool with less than 10 macro base stations. Dark fiber, with Small Form Pluggable (SFP), can be used with low cost without additional optical transport network equipment. Hence there are no additional equipment in the fronthaul, the delay contribution caused by the fronthaul network over the flows is almost zero.

On the other hand, this transport option consumes huge amount of fiber resources, therefore covering long distance or expanding network is a challenge. It creates burden on deploying extra equipment for monitoring and protection mechanisms in case of failure [ABK+16]. It also needs additional mechanisms to implement Operation and Maintenance (O&M) . However, these challenges can be solved by deploying a dedicated backup fiber. If fiber is deployed with physical ring topology it offers resiliency similar to Synchronous Digital Hierarchy (SDH) [ABK+16]; and O&M capabilities can be introduced in the fronthaul communication protocol.

2.6.2 Passive Optical Network

Sharing the capacity of fiber among several access point is an economic idea in mobile transport. This type of sharing is relevant when laying down fiber is a good option, economically convenient or mobile operator needs to rent physical access infrastructure (like fibres) from other entities. Optical networks is an approach for sharing capacity of fiber. Optical networks classified as active and passive are deployed in various fiber-to-the- home, cabinet, or building connection [GE08]. Active optical network is not a good choice for transporting communication despite of having better performance in long distance. Hence this optical network uses electrically powered switching equipment to separate data flows and routes to require destination.

On the other hand, Passive Optical Network (PON) does not include any electrical power switching [GE08] rather using one fiber or fiber pair to a splitting point that may be placed close to the subscriber and splitting the capacity for sharing among various access points.

PONs can be used to connect BBU and RRHs over an optical fiber with TDM (e.g., Gigabit PON (GPON)) by offering time slots to each access point, or with Wavelength Division Multiplexing-Passive Optical Network (WDM-PON) by offering wavelengths to each access point or combination of both.

WDM-PON is a good option in C-RAN fronthaul because of capability to meet the requirements of 5G; ultra low latency and 10G/s or more higher capacity.

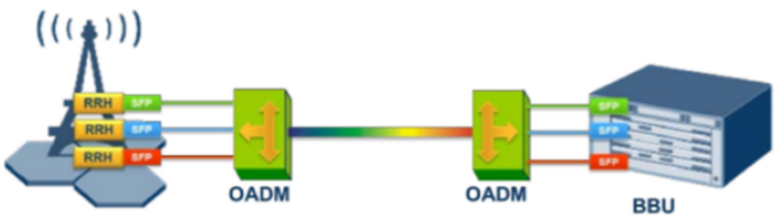


Figure 2.8: Passive WDM Network [PMC15]

Figure 2.8 presents a passive WDM fronthaul transport network where incoming wavelengths are splitted by means of passive multiplexers and are sent to separate CPRI ports of BBU. Optical Add drop Multiplexing (OADM) is used for switching. A dedicated wavelength to each access point makes comparatively less delay and can meet the capacity requirements of fronthaul network. On contrary, this dedicated wavelength occupies huge fiber bandwidth and reduces the utilization of resource. In current architecture of C-RAN, CPRI requires dedicated link for every antenna.

Therefore, CPRI does not scale the demands of 5G in terms of resource utilization and cost.

Apart from the capability of WDM-PON towards meeting fronthaul requirement, Time Division Multiple Access-PON (TDMA-PON) (e.g., GPON transport technology also shows promising capability to compatible with future forntahul network requirements [Nok17]. GPON has additional benefit in terms of saving the number of transceivers at the line side as one transceiver which is shared among different access points. Nokia bell lab has showed the possibility [Nok17] of using commercial Next Generation-PON (NG-PON) to transport ultra-low latency (achieved round trip delay was 115 microsecond and 60 microsecond delay over 6km fiber) CPRI streams via a standard single fiber running between the BBU and the RRH.

Xian Liu mentioned [LE16] how Passive optical Network can be a good choice in fronthaul transport by sharing MAC layer scheduling and the physical layer clock with RAN for achieving low-latency, synchronous forwarding of mobile signals. As consequence of this, it is obvious that PON would be a great candidate for optical frontahul network.

2.6.3 Optical Transport Network

OTN is an ITU-T G.709 standard designed for delivering Guaranteed Service Transport (GST) in the network [Sch18]. OTN is employed by TDM-over-WDM for end to end mapping traffic flows in the fronthaul network into wavelengths. According to ITU-T G.709 standard, a client service technology called OTN Muxponder (Figure 2.9) is used for carrying different types of protocol across the optical network. That's why it enables the optical communication between different vendors and framing of client signal of different protocols for transport over the physical optical layer.

Vendors have started deploying Equipment for OTN based fronthaul transport and switching equipment in the market. Huawei has recently launched an equipment [HT15] consisting of an outdoor unit OptiX OSN 810 for aggregation of CPRI/OBSAI/eCPRI client signals up to 10 Gb/s rates at the client side, into a 50 Gb/s or 100 Gb/s OTN wavelength at the line side.

TDM based technology enables OTN to provide packet transport with zero packet loss, low packet delay and delay variations. Considering latency and timing performance as important parameters in C-RAN technology specially for backhaul, OTN could give a good impression. OTN-based sub-wavelength service is accepted to support better granularity for serving high number of customers.

However, OTN does not support statistical multiplexing and not enable efficient

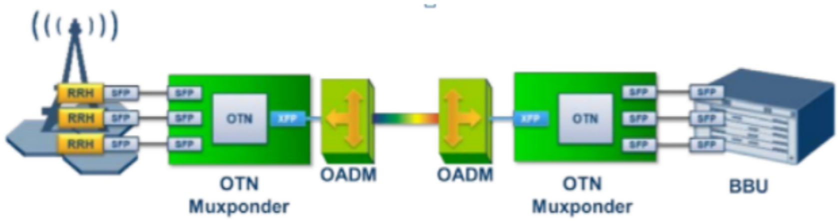


Figure 2.9: Optical Transport Network [PMC15]

capacity utilization like Ethernet. Combining fronthaul and backhaul into same wavelength channel using OTN requires fully isolated capacity to the two types of traffic [Ste18]. That's why OTN is very expensive because of the overhead, the implementation complexity and the circuit-switched mode that we cannot re-use the resources for other customers, i.e. dedicated resources as in circuit-switching.

On the other hand , Ethernet transport enables a more dynamic bandwidth allocation since statistical traffic variations in the fronthaul traffic can be utilized by the backhaul traffic. Therefore solution like Ethernet is being explored and extended to be used for the mobile transport which will be discussed in next section. However, OTNs are a promising future transport options in the long-term.

2.7 Ethernet Fronthaul

Ethernet has started out as a protocol over a shared coaxial cable medium and since then has been constantly evolved as an alternative for telecom networks, especially for metro and mobile RAN. It is the mostly deployed technology used in Local Area Network (LAN) which allows framing of data of variable bit rate into variable length frames. Thus when used in fronthaul network it can encapsulate the radio signal in an Ethernet frame. There are two competing standards for encapsulating fronthaul traffic in an Ethernet frame: a) eCPRI from the CPRI consortium [eCP18], and b) RoE from the IEEE 1914.3 Working Group [IEE18]. While the encapsulations themselves are different, the principle is similar in both cases, and they both require low delay and low PDV.

Ethernet typically applies statistical multiplexing, by allowing efficient multiplexing of variable bit rate channels with statistically distributed packet arrival patterns. As consequence, it allows for efficient multiplexing using buffers for smoothing out packet bursts [Ste18]. However buffering adds a delay depending on the traffic patterns. This occurs challenge for mobile fronthaul as it has strict requirements in packet delay and delay variation.

There are number of ways of doing multiplexing by Ethernet as no single method is explicitly defined in the IEEE 802.1Q standard [IEE14a]. As an example, one output queue may be assigned per input interface for each output interface. In this case, a multiplexing method can use Round-robin scheduling algorithm on queues, means scheduling packets from the queues one-by one to the output interface. If packets arrive simultaneously at the input interface and destined for the same output interface, one or more packets have to wait in their queues before being scheduled to the output [AAHL15]. This buffer delay depends on traffic load and it creates PDV.

In addition, if the volume of traffic being multiplexed to an output interface is larger than the bandwidth of the interface; it will experience packet loss and high delay. This principal of Ethernet may be sufficient for light bandwidth application like web browsing applying Transfer Control Protocol (TCP), but not for time and loss sensitive applications.

The Ethernet frame has asynchronous arrival pattern which means there is no deterministic approach when the next frame will arrive after service completion of current frame. Recently, a number of mechanisms have been proposed enabling zero packet loss and a low and even fixed delay in Ethernet to make it deterministic.

In the IEEE 802.1 standardization work, Time Sensitive Network (TSN) mechanisms include both mechanisms for minimizing delay and for controlling the delay variation, ensuring that all priority packets receive low and bounded delay [Ste18]. The IEEE 802.1Qbu defines a preemption mechanism enabling minimized delay on deterministic traffic when mixed with best-effort traffic within the same network [Ste18].

Preemption means high priority traffic is being served immediately after arrival; even if there is any best effort traffic is under serving will be stopped to serve those high priority packets first. However , there is no standardization of deterministic scheduling of multiple fronthaul streams (e.g., deterministic aggregation, deterministic priority) [As18].

- Deterministic aggregation: the capability to aggregate several fronthaul streams with low and fixed delay.
- Deterministic priority: the capability to statistically multiplex lower priority traffic, e.g. midhaul and backhaul traffic, with no impact on fronthaul streams

Therefore, in order to support a deterministic Ethernet-based network for fronthaul an additional scheduling mechanism is needed. Fusion Technology based on IHON can achieve the deterministic scheduling mechanism; the details of its discussed in Chapter 3.

2.8 Functional Splitting

From RRH to BBU radio signal has to go through several functional blocks. In order to ease the strict requirements in terms of bandwidth and latency on the fronthaul, a few alternative functional splits of the baseband functionalities have been proposed and discussed [ITU18]. There have been studied eight functional splitting in both 4G and 5G wireless network named by option 1 to option 8 (upper part of Figure 2.10).

In conventional LTE network most of the functionalities of layer-1, layer-2 and layer-3 are performed in BBU using CPRI that is the part of option-8 functional splitting. This functional split of tradition fronthaul (CPRI/OBSAI) requires continuous bit-rate transport whether user traffic is present or not. Though with the other split options (1-7), the amount of data to be transported scales with the user traffic.

It is important to mention that option-8 allows the centralization of all high layer processing functions, at the expense of the most stringent fronthaul latency and bandwidth requirements. However, cost is low for setting a RRH as maximum functionalities conduct in BBU.

The increased data rates in 5G makes it impractical to continue with the conventional CPRI fronthaul implementation. Latency has become a prime challenge; in order to overcome this challenge and also to overcome the functional inequalities of RRH and BBU 3GPP has proposed two types of splitting: low layer split and high layer split on April 2017.

According to 3GPP [ITU18], option 2 (Packet Data Control Protocol (PDCP)/high Radio Link Controller (RLC)) of functional splitting is taken as the high layer split point shown in Figure 2.10 as F1 Interface , while postponing the decision of the low layer split point between two contenders (Option 6 for Medium Access Control (MAC)/Physical (PHY) split and Option 7 for intra-PHY split with three different variants 7-1, 7-2, 7-3) to a later time (F_x interface in Figure 2.10).

The high-level split means that real time processing is performed by the RRH, relaxing the requirements of bandwidth and latency, but making inter RRHs coordination in connection with e.g. CoMP more challenging. The low-level split implies keeping low-complexity and low-cost RRHs and centralizing more functionality in the BBU [ITU18]. But unlike the traditional CPRI functional split, the data throughput is variable and proportional to the user data rate.

The interface for the low-level split is time sensitive, and strict latency control is required. Therefore, several standards bodies have taken initiative to identify different split points in the radio processing chain (Figure 2.10) that allow for significantly reducing the transport capacities in C-RAN architectures compared to the current approach. Nevertheless in practical, there is no any fixed functional splitting that can provide the exact solution for fronthaul.

The mapping of the functional split options introduces three logical block functions: Radio Unit (RU), DU and CU shown in Figure 2.10. Basically when existing 4G/LTE will evolve to 5G current RRH and BBU will rename as RU and CU/DU. The placement of the building block defines different networks, namely fronthaul, midhaul and backhaul, with different requirements in terms of latency, capacity, and maximum reach.

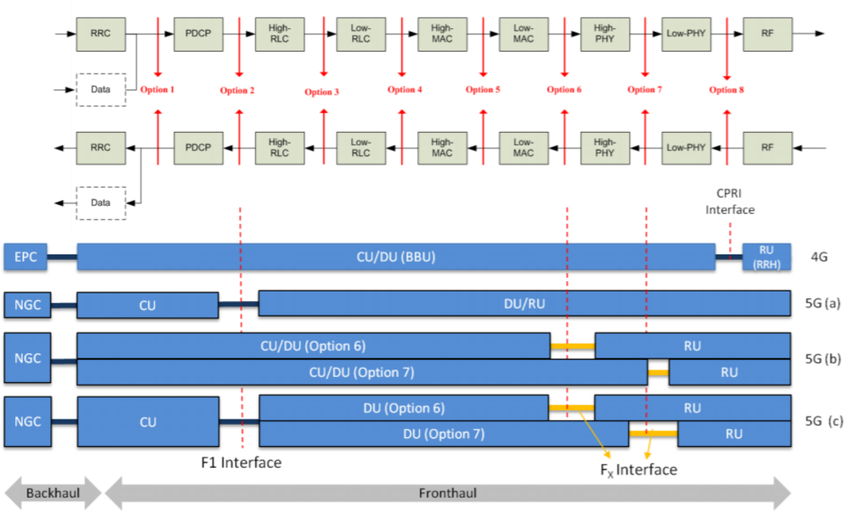


Figure 2.10: Eight Functional Splitting and Mapping of CU and DU functions according to the split points. 5G(a) defines high layer split (F1); 5G(b) defines lower layer split (FX); 5G(c) cascaded split. [ITU18]

The fronthaul network has a very strict requirement like 100 µs in 5G [IEE14b]. So, 5G would serve applications with very low latency (down to 1 ms) even if a high-level split is used where a more relaxed latency is required. As consequence these time sensitive applications, a low latency transport network is demanding. There is no exact splitting solution so the transport network will have to support a mix of splits with time-sensitive and less time-sensitive traffic [ITU18]. Therefore, this creates the need for deterministic Ethernet to support a mix of fronthaul and backhaul traffic services.

eCPRI group has focused its work on intra-PHY splits with data transport over packet networks, by creating a standard for the low layer split. They introduced two possible splits in downlink (I_D , II_D) and one in uplink (I_u) [eCP18], which allow for configurations almost corresponding to 3GPP Options 7-2 and 7-3 [ITU18].

2.9 Fronthaul Requirements

In order to meet the requirements of 5G mobile network, C-RAN architectures are considered influential to fully achieve the capabilities of 5G RANs among several propose radio access technologies like millimeter wave communication, massive MIMO. Though, RAN centralization imposes stringent requirements in terms of delay/latency, PDV, PLR, synchronization etc in mobile transport specially in fornthaul. These are important to achieving Quality of Service (QoS) benchmark for providing 5G to the end users.

The important part of C-RAN fronthaul is, its dependency on the separation distance of BBU and RRH. Delay sensitive services targeted by the 5G networks also put strict delay requirements of mobile fronthaul. Therefore, amount of latency in fronthaul network must be studied carefully.

CPRI data rate, latency/delay, PDV, PLR and synchronization are discussed based on the IEEE-802.1CM-2018 standard in following sections to understand fronthual requirements briefly.

2.9.1 Data Rate

Fronthaul traffic has very high data rate. Usually in the CPRI communications, rate can be expanded from 1.2288 Gbit/s to 24.3302 Gbit/s depending on the antenna configuration and LTE bandwidth. The CPRI data rate with corresponding application and frequency band are shown in Table 2.1. (-) means no information was able to fetch from previous literature

Table 2.1 shows that CPRI data rate is high and such high bit rate requires aggregation of flows from more than one antennas. For example, 4x2 (4x4) MIMO 5 Mega Hertz (MHz) LTE require approximately 6.144Gbit/s CPRI rate per sector. Table 2.1 also presents the transport capacity (AxC) for 20 MHz LTE. CPRI transports Inphase/Quadrature (I/Q) data of particular antenna and particular carrier. This is called AxC unit or Antenna-Carrier unit. For example, in LTE system, if I=16 bits and Q=16 bits then one AxC is of length 32 bits.

2.9.2 Latency/Delay

Latency is the measure of the time taken for traffic to arrive at the destination.

Table 2.1: CPRI Data Rate with corresponding frequency Band, Antenna-Carrier Unit and application [Ant16]

Option	CPRI Bit Rate (Gbps)	Data (IP) Rate (Mbit/s	Transport capacity(AxC) for 20 MHz LTE	Application
1	0.6144	37.5	-	2G-3G radio, 2x2 MIMO 5 MHz LTE
2	l.2288	75	1	2x2 MIMO 5 MHz LTE, 4x2(4x4) MIMO 10MHz LTE, Small Cell
3	2.4576	150	2	2x2 MIMO 20 MHz LTE, 4x2 (4x4) MIMO 10 MHz LTE, LTE Macro network
4	3.0720	-	2	-
5	4.9152	300	4	2x2 MIMO 20MHzx2(3.5G-band TD-LTE), 4x2 (4x4) MIMO 20 MHz
6	6.1440	-	5	4x2 (4x4) MIMO 5MHz LTE
7A	8.1100	150	8	4x2 (4x4) MIMO 10 MHz LTE
7	9.8304	600	8	4x2 (4x4) MIMO 20MHz LTE
8	10.1376	750	10	4x2 (4x4) MIMO 20MHz LTE
9	12.1651	-	12	-
10	24.3302	-	24	-

According to IEEE Std 802.1CM-2018 standard for time sensitive network for fronthaul [IEE14b], the end-to-end one-way latency is measured from the arrival of the last bit at the ingress edge port of the bridged network to the transmission of the last bit by the egress edge port of the bridged network. To calculate maximum end-to-end latency of fronthaul network some parameters like propagation delay of the links between the bridges, and internal delays in these bridges are needed to accumulate.

The latency requirement of CPRI protocol is very strict which creates limitation between RRH and BBU. For eCPRI the requirements are more stringent than CPRI.

Before going deep into delay requirements of fronthaul here is a short description of planes in CPRI/ eCPRI node.

A hardware or software component within an CPRI/ eCPRI node constitute three planes without which it is not possible to form a full CPRI/eCPRI node.

– Control & Management (C&M) Plane : C&M data flow is for the operation, administration and maintenance of the nodes. The C&M information flow will be considered as non-time-critical and utilize a small part of the total bandwidth between CPRI/eCPRI

– User Plane : Data flow to be transferred from the radio base station to the UE and vice versa. This is time sensitive data.

– Synchronization Plane: This plane is responsible for synchronization and timing information between nodes during data flow.

Delay Requirements in Fronthaul

1. According to IEEE-802.1CM-2018, the maximum end to end one-way latency is 100 µsec for IQ data between edge port connected to a REC (BBU) and other edge port connected to a RE (RRH) and 250 µsec for optical network. This is for high priority traffic and for low priority traffic this value is 100 ms [IEE14b].
2. According to the Requirements for the eCPRI Transport Network [eCP18], C&M information flows are not as time-critical as the User Plane data flows with 100 µsec latency budget. Therefore, the maximum end-to-end one-way latency is 100 ms for the majority of C&M Plane data between an edge port connected to an eREC and another edge port connected to an eRE.
3. The separation distance between BBU and RRH is 20 km and 25 km for optical network [Net14].

   While mobile backhaul and fronthaul requires transport over moderate distances, typically below 100 km, the optical backbone network offers transport over several hundred or thousands of kilometers. Hence, a dominant delay-component in the backbone network is the delay in the fibre itself, given as 5 µsec/km.

2.9.3 Packet Delay Variation

PDV is the difference of end to end one-way delay between selected packets in a flow with any lost packets (components of the delay which does not vary from packet to packet) being ignored. According to International Telecommunication Union (ITU) Y.1540 "delay variation of an individual packet is naturally dened as the difference between the actual delay experienced by that packet and a nominal or reference delay. ITU Y.1540 6.4.2.1 and RFC 5481 using the minimum delay as a reference” [ITU16]. Sometimes it is referred as jitter. PDV should be lie in between 5 to 10% of end to end one way latency [IEE14b].

2.9.4 Packet Loss Ratio

PLR denotes the ratio of the number of lost packets to the total number of sent packets. Packet loss can be caused by bit errors, network congestion, failures etc. PLR is treated separately from service availability ITU-T Y.1563. Since, PLR is not meaningful for characterizing the quality of the service when the service is not available. The maximum tolerable PLR between edge ports of a fronthaul bridged network for a User Plane data flow is 10^-7 and for Control and Management data is 10^-6 [IEE14b].

2.9.5 Jitter and synchronization

Usually Proper synchronization is essential requirements for mobile fronthaul operation. In order to sending data from RRH on specific frequency it needs to know the maximum tolerable Bit Error Rate (BER), frequency error contribution and phase synchronization. It is important to keep the carrier frequency sharp for signal coming from base stations operating in different frequency band not to overlap. For successful Time Division Duplex (TDD) network operation RRH needs to follow time frames precisely to avoid the overlap of Uplink (UL) and Downlink (DL) frame.

There are 2 types of synchronization:

- Frequency Synchronization, where clocks are synchronized in frequency if the time between two rising edges of the clock match
- Phase/time synchronization, where rising edges must happen in the same time.

According to CPRI specification, BER must be at most 10^-12 and the jitter introduced by the CPRI link should not exceed the value of 2 Parts Per Billion (PPB) [AAHL15]

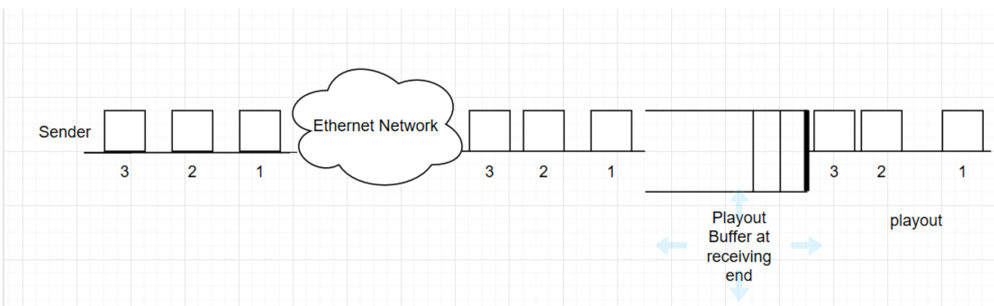


Figure 2.11: Playout Buffer at the receiving end for packet synchronization

Packet synchronization is important requirement in fronthaul to avoid PDV at the output. There is a way of solving PDV/jitter by using playout buffer at the receiving end shown in Figure 2.11 . Playout buffer add additional delay in order to replay packets according to the frequencies of packet streams. Therefore, using this approach PDV can be removed.

1

Chapter 3
Integrated Hybrid Optical Network (IHON)

In this Chapter, an Ethernet-based implementation of Integrated Hybrid Optical Network (IHON) known as 'Fusion' which merge the circuit and packet switching into a single architecture without using time slot will be discussed briefly. The main focus is to describe the design and operation of IHON (also called 'Fusion' in this thesis) node followed by delay and inter packet gap calculation and aggregation process of fronthaul traffic by using IHON Node.

3.1 Why Hybrid Optical Network?

The capacity utilization by legacy circuit switching system has limitation in terms of bandwidth despite of offering low latency, guaranteed QoS, low latency variation and synchronization. Specially when serving an Internet Protocol (IP) layer with highly dynamic and bursty traffic pattern [Bay01].

Packet Networks, on the other hand offer a higher throughput and efficiently utilize resources by employing Static Multiplexing. In this context, Optical Circuit Switching (OCS) networks needs migrated to Optical Packet Switching (OPS) network; specially low latency packet based technologies are expanding toward the core network to meet the higher throughput needs [Bay01].

However, Optical Packet Switching (OPS) can not meet up the essential requirements for modern application based services when requires support from underlying transport layer [Mah01]. Therefore, providing support to various service requirements and efficient use of the bulk capacity of optical networks, a new concept of combining both technology in same architecture called Hybrid Optical Network (HON) comes into force.

3.2 Classification of Hybrid Optical Network Architectures

HON architecture combines two or more basic technologies (packet and burst switching as well as wavelength, waveband and fiber switching) to improve the overall network performance [CPE+06]. Based on the degree of interaction and integration of the network technologies HONs are classified in 3 types which are described in next subsections.

3.2.1 Client-Server Hybrid Optical Network

This class employs a hierarchy of optical layer networks with different network technologies adopted by ITU-T. It is shown in the Figure 3.1 that the lower layer acts as wavelength switched server layer which set up a virtual topology for upper client layer. Since the client layer is an Optical Burst Switching (OBS) or OPS network, it consists of several OBS or OPS nodes. These nodes mostly aggregate traffic at the edge of the core network and connected to server layer by light path. Resources for transmission and switching can be either dedicated or shared with the different network technologies.

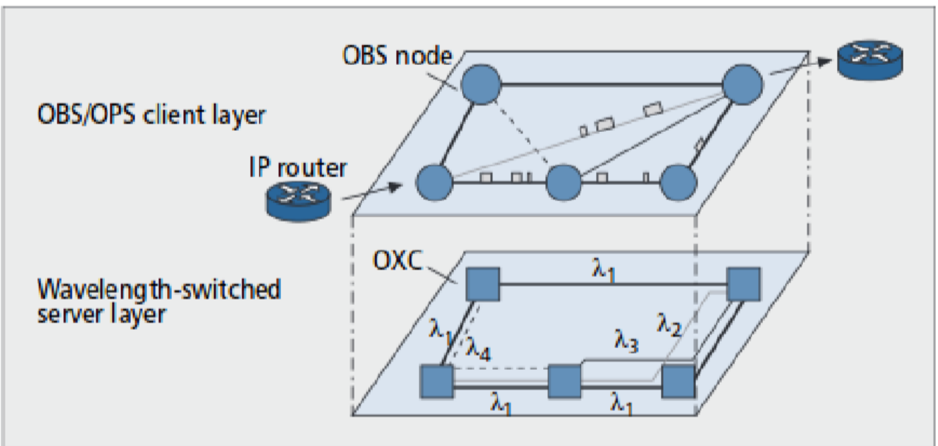


Figure 3.1: Client Server Optical Network [CPE+06]

Hence optical layer has less memory so this type of optical network architecture depends on high SM gain to utilize wavelength for ensuring QoS. However, It is not possible to utilize wavelength at good extent by deploying Client-Server Hybrid Optical Network. As increasing the connectivity of a network by virtual topology links produces less traffic per link and thus reduced multiplexing gain [CPE+06].

3.2.2 Parallel Hybrid Optical Network (PHON)

Two or more optical layer network is parallelly installed to offer different services in Parallel Hybrid Optical Network (PHON) [CPE+06]. Figure 3.2 shows that OBS and Optical Circuit Switching (OCS) netwokr is parallelly placed and connected through IP router.

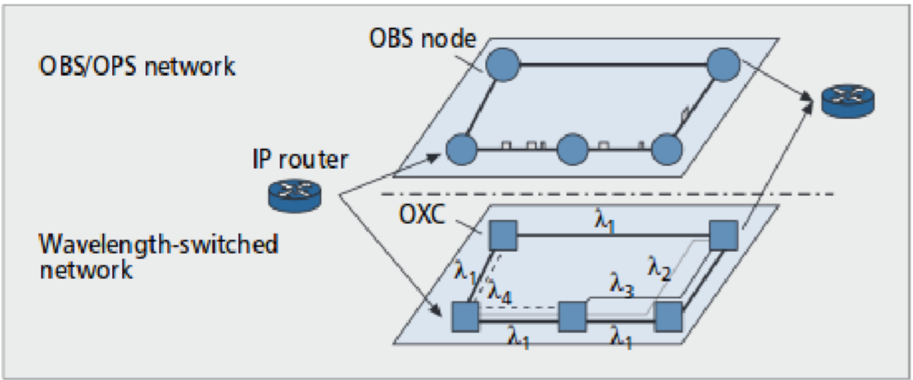


Figure 3.2: Parallel Hybrid Optical Network [CPE+06]

The wavelengths in node use one technology at once either circuit or packet. Therefore, the circuit wavelength might still be underutilized.

3.2.3 Integrated Hybrid Optical Network (IHON)

Integrated Hybrid Optical Network (IHON) is a parallel hybrid optical network where the service edge node selects for arriving traffic to be transmitted either as bursts or continuous byte stream. This edge node selects the arriving traffic transport nature either as optical burst or byte stream based on the traffic nature such as QoS requirement, bandwidth, and user request [BHS06].

IHON integrates both wavelength-switching and packet/burst switching completely [CPE+06] (Figure 3.3). This means all network technologies share the same bandwidth resources in the same network simultaneously .

In IHON, each node comprises a wavelength-switched and a packet-switched device. Usually, a node transmits packets over the end-to-end lightpath, since it removes the need for intermediate processing by subsequent nodes. However, the mode can be changed to packet switch in case of congestion.

In addition, the selection between the two modes can also be motivated by QoS differentiation such as wavelength-switched for high-priority traffic and packet

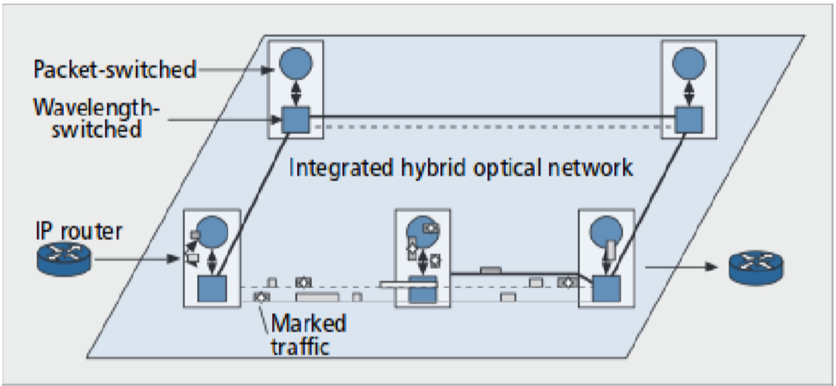


Figure 3.3: Integrated Hybrid Optical Network [CPE+06]

switch for low priority traffic. For well behaved smooth traffic, wavelength paths can be used, while dynamic traffic can be handled by employing the packet-switched mode.This technology is very optimal from resource point of view. However, it is also the most complex than the other two hybrid optical networks from technology and control points of view. As each node sees the entire network in two ways, a full integration of the wavelength-switched and the packet switched data and control plane is needed.

There are two technologies based on IHON such as Optical Packet Switched Migration Capable Network with Service Guarantee (OpmiGua) [BHS06] and Fusion [VBB13]. For both case, the capacity of the same wavelength is shared between the high priority and the best effort traffic flows. In addition, the node is fully integrated for wavelength and packet switched devices. In Section 3.2.4 invented 'Fusion' node based on IHON technology will be discussed.

3.2.4 Fusion Node/ IHON Node

An Ethernet-based implementation of IHON called 'Fusion' that uses packet switched nodes to transport both Guaranteed Service Transport (GST) and Statistical Multiplexing (SM) traffic classes. It combines the best properties of circuit and packet switching for utilizing the wavelength as well as resource utilization [VBB13].

Traffic is divided into two service classes in IHON while using the capacity of the same wavelength-

1. GST service class which satisfies QoS demands such as fixed low delay and no packet loss for the circuit switched traffic.

2. SM service class which provides high bandwidth efficiency for the Best Effort packet switched traffic.

3.3 Design of IHON Node

The main principal of IHON is that the GST packets follow preassigned wavelengths from the sender to receiver and SM packets are inserted in between the gaps of GST packets.

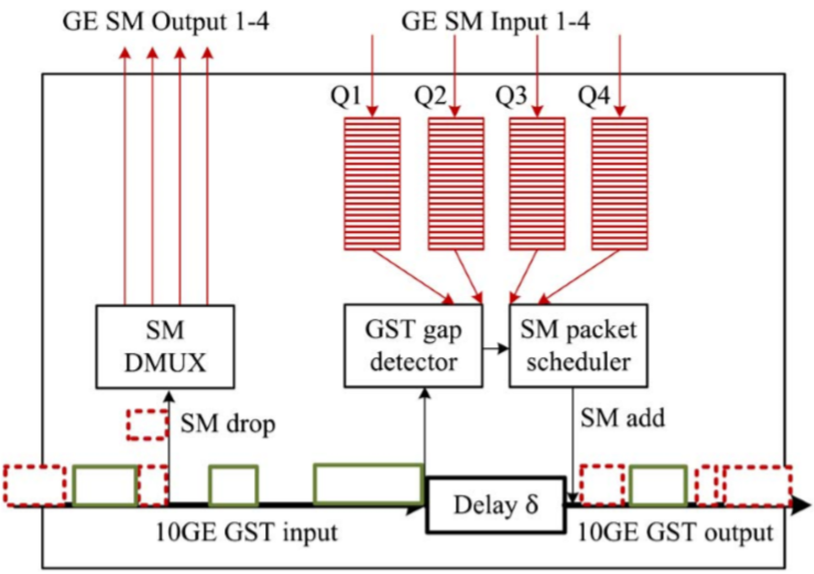


Figure 3.4: Block Diagram of Integrated Hybrid Optical Network (IHON) node [VBB13]

Figure 3.4 illustrates a simple block diagram of an IHON node. Each node consists of SM, Demultiplexer (DMUX), GST gap detector, SM Packet scheduler, two 10 Gigabit Etherenet (GE) line interfaces (Xe0 and Xe1), and ten 1GE client interfaces (ge0-ge1). The line interfaces can give 1+1 or 1:1 protection and enable add/drop functionality of transparent Ethernet lines.

3.3.1 Operation of IHON/Fusion Node

At the input port of Fusion node, each traffic class (GST or SM) is identified by VLAN (Virtual Local Area Network) and perform switching of traffics. A fixed delay δ is applied electronically to the GST stream of packets and it corresponds to the service time of a maximum length SM packet. Fronthaul traffics treat as GST;

midhaul and backhaul traffics treat as SM. The GST traffic stream bypasses the packet switch and continues toward the output link, while SM packets are extracted from the channel through a SM demultiplexer (DMUX) (Figure 3.4) and processed based on their header.

A GST gap detector senses the arrivals and exits of GST packets at the input and updates the information on the vacant gaps. The dropped SM packets are placed inside a queue and is processed according to their header information [VBB13]. This information is given to the SM packet scheduler; scheduler chooses appropriate size of packet from the SM class to fill the gaps between GST packet with best effort packer SM, thus increases the light-path utilization.

Significance of Fixed Delay in IHON

A fixed delay applied in between the GST packets in IHON Figure 3.4. This fixed delay δ corresponds to the transmission time in the channel of capacity C of a maximum length SM packet L_{max}. Now this delay can be expressed as, $\delta = L_{max}/C$. It prevents SM preemption by GST packet [VBB+15]. Preventing preemption means if the channel is free and no GST is detected in the delay line at time t_0, then the SM scheduler will start the transmission of an SM packet of size less than maximum length ($L<L_{max}$) and service time continuation until complete even though a GST packet arrives before this.

In the meantime, if a GST packet is detected immediately at the input of the delay line at time $t_1 > t_0$, the delay ensures that the GST arrival at the output channel does not preempt the SM packet until SM finishes the service first ($t_1 + L_{max}/C > t_0 + L/C$) [VBB+15].

The effect of δ on the end to end GST delay is deterministic. This enables the look head for identifying gaps within fronthaul streams and filling less delay sensitive backhaul/midhaul packets only in fitting gaps. The advantage of deterministic scheduling is that fronthaul traffic can remain unaltered with gap and loss of backhaul traffic can be prevented. Therefore, fixed delay is significant in IHON based 'Fusion' node which is not present in current Ethernet Fronthaul.

3.3.2 Packet Delay and Delay Variation in IHON

Packet Delay and Packet Delay variation (PDV) mechanism in IHON is very significant towards implementing this in fronthaul transport. As it is described in Section 3.3.1, after detection of a gap, SM packet scheduler put a suitable size of SM packet from the input queues of the SM interfaces without affecting the timing of the packets in the GST stream Figure 3.4.

The inter packet time gap Δ_i between GST packet is sensed by the gap detector when packets enter the delay line, shown in Figure 3.4. At output channel on time t+δ all the gaps (Δ_i) between packet are remain unchanged as all packets undergo the same fixed delay δ Figure 3.5.

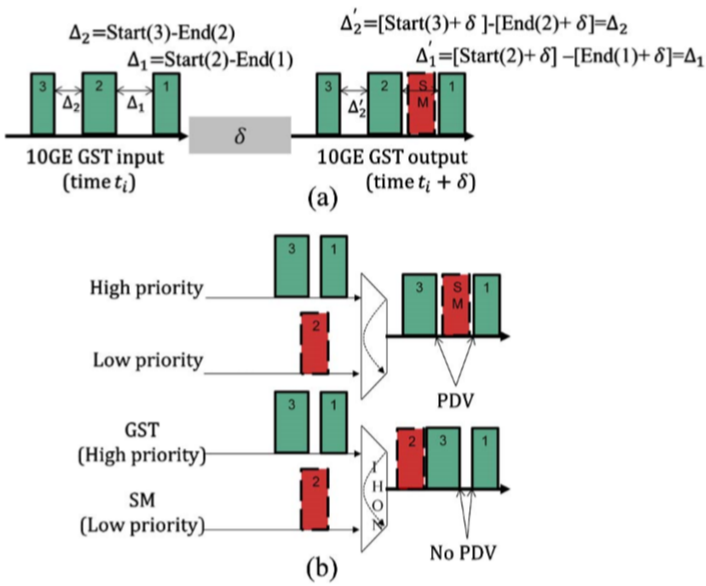


Figure 3.5: (a) Same Fixed delay between Inter GST packets, therefore there is no changing in GST output and no PDV is present. (b)the difference between GST scheduling in an IHON (lower part) and a high priority stream in an electronic packet switch (upper part) with non-preemptive scheduling [VBB13]

It can be expressed as following equations in accordance with the figure

$\Delta_1 = Start(2) - End(1)$........................(3.1)

$\Delta_2 = Start(3) - End(2)$.............................(3.2)

At the output channel,

$\Delta_1' = [Start(2) + \delta] - [End(1) + \delta] = \Delta_1$............................(3.3)

$\Delta_2' = [Start(3) + \delta] - [End(2) + \delta] = \Delta_2$ ....(3.4)

Therefore, theoretically IHON does not add PDV to the circuit traffic.

The difference between IHON scheme and a packet switch scheduler with non-preemptive priority streams lies on the PDV. The priority scheduler always schedule

Table 3.1: Definition of symbols used in gap calculation

$T^{w}_{a,i}$	The arrival time of GST packet i to the delay line of output channel λ_w
$T^{w}_{e,i}$	The exit time of GST packet i from the delay line of output channel
g^{w}_{i}	The current gap on channel w for packet i
δ	fixed delay
S_i	Service Time

the high priority packets first. If there is no packet from high class then the scheduler checks for lower priority class queue and transmit the first packet from there. If a high priority packet arrives (For example, Packet-3 in Figure 3.5) during the transmission of low priority packet (Packet-2 from Figure 3.5), the high priority packet will be delayed until the low priority packet is being done with transmission. PDV is introduced in between high priority packets.

Unlike general preemptive priority scheduler that does not introduce PDV but preempts low traffic; it is important to mention that IHON does not preempt any on-going scheduling of best effort GST packets with zero PDV while minimizes the processing and energy usage [VBB13]. This principal makes IHON energy efficient as it only transmits SM packet when it will be successful.

3.3.3 Calculation of Inter Packet Time Gap

Inter packet time gap calculation is important to fix the SM (backhaul) packets in between the GST (fronthaul) packets for the utilization of wavelength. The arrival and exit times of GST packets to the output channel is used to compute the inter packet gap. Fixed Delay Line (FDL) monitoring module senses these arrival and exit times. Round Robin gap scheduling algorithm is used to to select the appropriate size packet from the head of the SM queues.

The time values and corresponding gaps are saved in a time-ordered list and the first gap on each channel is made available to the SM scheduler. Afterwards, the scheduler which knows the sensed gaps tries to find the appropriate size packet by round robin manner [1] from the head of SM queues to fit in the gap. The technique of gap computation according to round-robin gap filling scheduling algorithm for one channel is described below. The notations are used in the description are presented in the Table 3.1.

1) When GST packet i enters the delay line at time t_i, it updates the arrival time to the output channel λ_w Figure 3.6, from then busy time is started to count: $T^{w}_{a,i} = t_i$

[1]Round Robin is a scheduling algorithm where each process is assigned a fixed time slot in a cyclic way

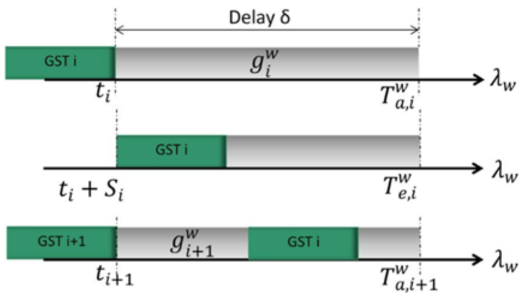


Figure 3.6: Detection of free time gaps within the time window created by the fixed delay δ. Arrival and exit times are updated each time during start and end of a GST packet at the beginning of the delay line [VBB13]

+ δ. It is recommended to check that if it is the only GST packet in the delay line and the previous GST packet (i-1) has already excited the delay: if $T_{a,i}^w \geq T_{e,i-1}^w + \delta$ then the current gap on channel λ_w is $g_i^w = \delta$, equal to the maximum packet length;

Otherwise $g_i^w = T_{a,i}^w - T_{e,i-1}^w$.

2) At time $t_i + S_i$, when GST packet i with service time S_i enters completely to the delay line (the last bit of the packet), the exit time of packet i from the delay line been updated and output channel w been released. The end of busy time $T_{e,i}^w = (t_i + S_i) + \delta$.

3) The curren gap value that is sent to scheduler is updated at time $T_{a,i}^w$. If there is a packet i+1 in the delay line, then the current gap is equal to g_{i+1}^w; otherwise it is δ.

3.4 IHON Node Aggregation

5G needs for more capacity and use of high frequency bands will drive densification [Mic16]; these are mentioned several times in earlier sections of this thesis. It is projected that there will be small cells at every block in busy areas to support 5G services [Mic16]. This clearly leads a need for aggregation.

IHON defines a deterministic scheduling by aggregation mechanism of preserving the packet gaps between the packets of individual GST packet streams being aggregated on a single wave length during the transmission across a network and de-aggregation at output channel.

This concept is opposite to OCS where traffic between ingress and egress nodes may have one or more paths. Each path contains separate wavelength. In IHON based fusion node, one or more GST streams can be aggregated on a single wavelength by scheduling each GST stream on different time-slots.

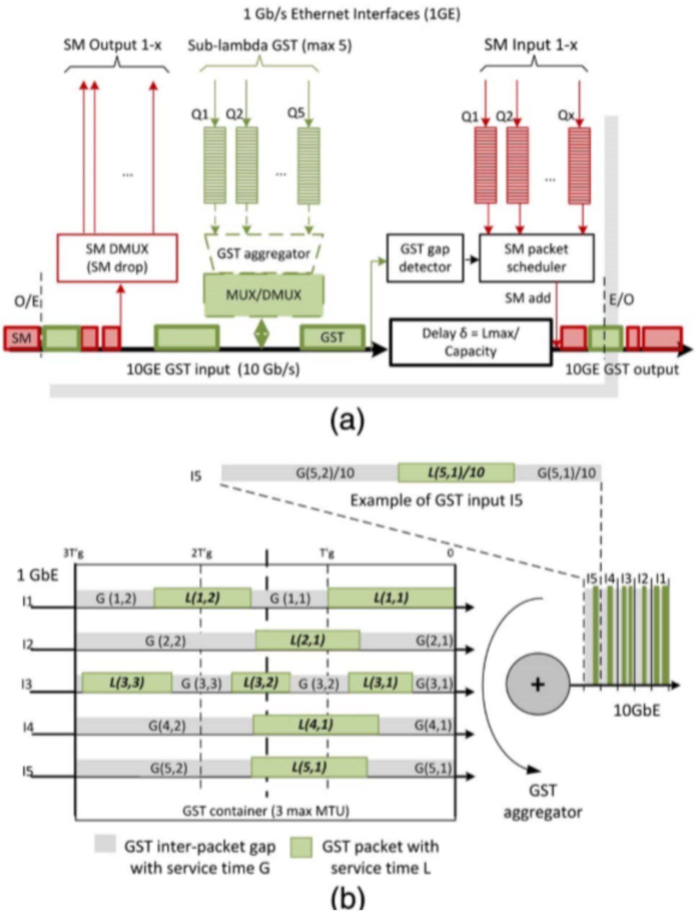


Figure 3.7: a) Illustrates the block diagram of aggregation of five GST streams and SM packets insertion. b) Illustrates how aggregation scheme of five GE GST input streams to one 10GE GST output channel with preserving packet gap inside GST container [VBB+15]

Figure 3.7a illustrates the aggregation of five 1 Gb/s input streams called GST into the 10Gb/s output link. GST streams are tagged with corresponding Virtual Local Area Network tags when entering the GE ports. The output link is called trunk port as it transports all Virtual Local Area Networks. Each of the input is logically divided into corresponding data containers called Virtual Container which begin with a synchronization packet. In the aggregation time of the virtual container both packets and gaps between packets are framed. Figure 3.7b shows how GST inter-packet gap with service time G and GST packet with service time L are presented at the output of GST aggregator [VBB+15].

In the meantime, SM traffic is dropped at the SM DMUX for processing. The time period reserved for each port varies depending on the maximum expected GST packet size and the number of ports being aggregated. SM packet is queued and processed according to their header information when GST packet bypasses the packet switch. GST packets are compressed in time with compression factor of 1Gb/s to 10Gb/s in order to sent out via trunk port 10Gb/s. Aggregation containers are being identified by synchronization packets. The fusion node is capable of aggregating maximum nine 1 GE ports as the rest 1 GE port is used for overheads. The GST gap detector computes the gap between GST packets and containers to pass the gap information to the SM packet scheduler when GST packet arrives at the delay line. Afterwards SM packet scheduler can insert the packets in the suitable gap from the SM queues.

At the output node, inverse time compression factor is used to deaggregate the aggregated GST packets to reconstruct the streams as exact as before using the inter-packet gaps.

How Virtual Container contributes in node aggregation

Virtual containers are data containers used for framing packets. Let's assume two Packet Streams (PS) (Figure 3.8) PS1 and PS2 on client side being aggregated are divided into virtual containers on the line side before being aggregated to the output. The bit rate of the output is larger than the sum of the bit rate of the inputs being aggregated.

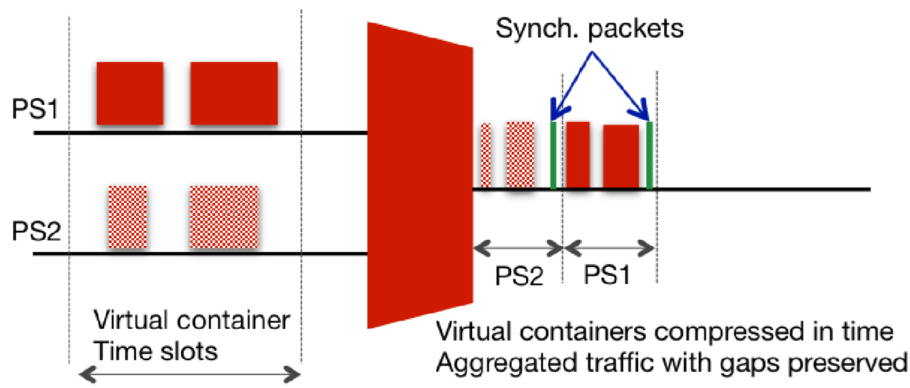


Figure 3.8: Aggregation process in Virtual Container [BCV18]

Virtual containers are compressed in time while the number of bytes and gaps are preserved. Generally each virtual container is formed from each packet stream within defined cycle. Therefore, each of the ports is served one time during a cycle period. As consequence of this, a fixed delay corresponding to one cycle time is added to each of the packet streams. At the output side, each of the containers is deaggregated by forwarding its packets to an interface dedicated to each stream [BCV18]. Inter-packet gaps in the streams are also preserved at the deaggregation process, enabling re-assembling the packet stream without adding PDV.

Chapter 4
Analytical and Simulation Model

Analytical model focusing on calculating end to end latency, Packet Delay Variation (PDV) for different transport media and simulation model of IHON switch is presented in this chapter. The analytical model provides sufficient logic for calculation in simulation model of IHON.

4.1 Analytical Model

Maximum end to end latency & Distance between Radio Remote Head (RRH) & Base Band Unit (BBU)

In analytical model, mathematical functions are used to compute the minimum distance between RRH and BBU and to compute maximum end to end latency in terms of different fornthaul medium like WDM, OTN, dedicated fiber and Ethernet.

Maximum end to end latency refers to time taken for a signal or packet to be transported across a network from source to destination. To explain how this latency is calculated in a network let us consider a LTE Frequency Division Duplex (FDD) radio interface with C-RAN infrastructure, where Hybrid Automatic Re-transmit Request (HARQ) is processed between RRH and BBU from central office Figure 4.1.

The maximum distance between RRH and BBU should be secured in C-RAN to achieve the most efficient utilization of BBU resources [Net14]. That is why, synchronous HARQ protocol is used as re-transmission mechanism as it can limit the distance between UE and eNodeB in an LTE network. As seen in Figure 4.1, according to the synchronous HARQ requirements, UE should receive Acknowledgement (ACK)/Negative Acknowledgement (NACK) from BBU or eNodeB in LTE network in three subframes after sending UL data. For example, when UL data packet is received at the frame number i, it must be sent back at the frame number (i+3) in DL (Figure 4.1). Because UL and DL subframes are time-aligned. This time alignment implies that latency budget for Round Trip Time (RTT) of BBU-RRH is exactly 3ms [Net14]. However, in practice, it is obvious to deviate the value of RTT from 3 ms.

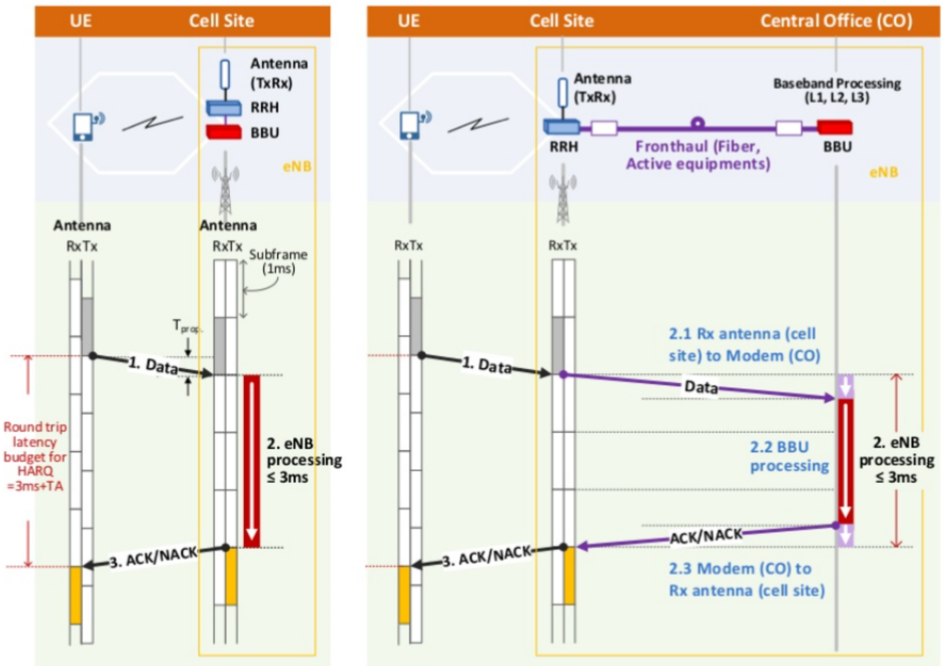


Figure 4.1: Illustration of Latency Components of C-RAN and Round Trip Latency (RTT) budget from UE to BBU/eNodeB is less than 3 ms; means acknowledgement receives at the frame number i returns from BBU to UE within frame number (i+3) frame [Net14].

Generally in C-RAN, BBU and RRH are located several kilometer away from each other. Therefore, additional delays like transmission delay (for example delay in optical fiber medium), processing delay (time in transmission network caused by active equipment in fronthaul network) are considered to calculate RTT. RTT can be expressed as-

RTT = 2* Additional delay + Delay in RRH uplink (RRH processing) + Delay in RRH downlink + Delay in BBU uplink + Delay in BBU downlink .... (4.1)

Here in equation 4.1, 'additional delay' may refer any other delay in fronthaul nodes or in any components. '2' is for both UL and DL.

In order to maintain the timing (3ms), the additional delay caused in fronthaul network is compensated in some point to expedite the BBU processing. As part

Table 4.1: Delay components of fronthaul network, extracted from [Net14]

RRH to BBU	BBU Processing	BBU to RRH
a. RRH/RF Processing (UL)	e. BBU/CPRI Processing	j. Fiber Latency (BBU to RRH)
b. RRH/CPRI Processing	f. PHY: UL Frame Decoding	k. Active Equipment Processing
c. Fiber latency (RRH to BBU)	g. MAC: ACK/NACK Creation	l. RRH/CPRI Processing(DL)
d. Equipment Processing	h. PHY:DL frame Creation	m. RRH/RF Processing
	i. BBU/CPRI Processing	

of this compensation, telecom vendors design Base Station (BS) in such a way as if it completes the BB processing and sends ACK/NACK within 2.75 ms, instead of 3 msc [Net14]. Therefore after considering addition delay it would possible to keep the delay value within 3ms. The fronthaul delay components of each parts of Figure 4.1 are presented in Table 4.1.

The typical value of the delay components of Table 4.1 are presented in Table 4.2. Delay components (No1-No3) caused at RRH and BBU must be minimized by base station vendors while delay components No-4 must be kept minimum by fronthaul vendors [Net14].

Maximum fiber distance between cell cite (RRH) and Central office (BBU) can be calculated by using the delay values presented in Table 4.2. The calculation of maximum end to end latency and maximum fibre distance for different transport technologies will be presented in next section.

4.1.1 Calculation of Maximum End to End latency and fiber distance for active WDM

Fronthaul network with active WDM contains the delay components which are involved in the data transmission after RRH receives data from UE and before it sends ACK/NACK to the UE.

First minimum RTT is be calculated using the value from Table 4.2, the minimum RTT for OTN encapsulation can be computed as :

Minimum Fibre RTT= 3 msec - (40 μsec + 10 μsec + 2700 μsec + 45 μsec) = 205 μsec........ (4.2)

Table 4.2: Typical delay values for the delay components of Table 4.1

Delay components	Related network Equipment	Description	Typical values
1. RF processing time for round trip	RRh	a+m	25-40 µsec
2. CPRI processing time for round trip	RRH,BBU	b+e+i+l	10 µsec
3. Round trip baseband processing time for BBU	BBU	f+g+h	2700 µsec
4. Round trip processing delay for Fronthaul	Fronthaul Equipments	d+k	40 µsec (OTN encapsulation), few µsec non-otn encapsulation

The value from equation-4.2 is two way latency; for one way it will be 205/2 = 102.5 µsec. The classical value of one way latency per link is 5 µsec/km [Net14]. Therefore,

Minimum Fiber distance = 102.5 µsec/ 5 µsec/ Km = 20.5 Km

In Similar way, maximum one way End to end latency can be found for active WDM when OTN encapsulation is considered.

Maximum RTT= 3msc - (25 µsec + 10 µsec + 2700 µsec + 45 µsec) = 248 µsec......(4.3)

Therefore, using the value of equation-4.3, the maximum one way End to end latency is 124 µsec and the maximum fiber separation distance is calculated as-

Maximum Fiber distance = 124 µsec/ 5 µsec/ Km = 24.8 Km

According to above analysis and calculation, it is shown that the value of one way latency in OTN transport varies in the range of 102.5 to 124 µsec, while fronthaul separation distance varies in the range of 20.5 to 24.8 KM (considering one way fiber propagation delay 5 µsec/km).

4.1.2 Calculation of Maximum End to End latency and fiber distance for Dedicated Fiber

Processing time for fronthaul transport depends on the nature of transmission medium. However, there is no processing time delay for dedicated fiber. Therefore the the calculation of RTT by using the data of Table 4.2 can be done as-

Maximum RTT = 3 msec (40 µsec + 10 µsec + 2700 µsec + 0µsec) = 250 µsec..................(4.4)

Taking the symmetrical assumption in fronthaul standard specification into account, using equation-4.4 the maximum one way end to end latency is 250/2 = 125 µsec, hence the maximum fibre distance can be calculated as - Maximum Fiber Distance= 125 µsec/ 5 µsec/ Km = 25K

The maximum RTT is in accordance with the fronthaul requirements described in IEEE-802.1CM-2018 [IEE14b] for dedicated (optical) fiber.

The values calculated in Section 4.1.1 and 4.1.2 are in accord with the typical range of separation distance 20 to 25 km between RRH and BBU presented in the fronthaul requirements in Section 2.9 .

4.1.3 Calculation of Maximum End to End latency and Packet delay for Ethernet

When an Radio over Ethernet (RoE) sender calculates the presentation time at the RoE receiver, it must take into account the entire end-to-end delay between the sender and receiver reference planes.

The end-to-end Frame Transfer Delay (FTD) consists of the networking delay (transit delay or propagation delay), processing delay, and enough buffering time to compensate for Frame Delay Variation (FDV) introduced by the network and by both endpoints [IEE18].

The method for measuring the end-to-end delay is implementation and deployment specific. The presentation time can be expressed as-

Presentation time = Networking / Propagation delay(Transit Time)+ Ingress time(Packet Processing Delay) + Buffer delay

The above describes parameters related to calculate end to end delay for Ethernet network is described briefly below [IEE18]:

– **Propagation Delay** Definite amount of time taken by packet to propagate over a link and is constant for a given link length; depends on link length (5 µsec/

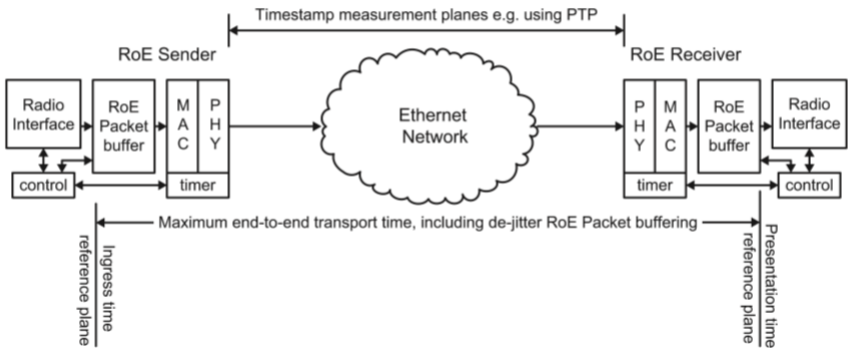


Figure 4.2: Components involved in calculating end to end delay for Ethernet [IEE18]

Km).

– **Packet Processing delay**: This delay involves in processing the packet at ingress and egress bridge to arrange those in accordance to their order, to select their route as part of route look-up process, packet differentiation etc. This delay value is constant for switches and routers.

– **Buffering Delay**: The buffering or queuing delay is the total amount of waiting time of the timing packet within different buffers or queues in a given Network Environment before being processed and finally transmitted to the next network environment on the communication path. Buffering delay variation is partially due to the competition between timing packet flows and other packet flows, and competition between different timing packet flows themselves according to their relative arrival time at different waiting queues and the priority policies implemented. Buffer delay creates Packet Delay Variation (PDV).

According to ITU-T Recommendation Y.1540 [ITU16], PDV is the difference in end-to-end one-way delay between selected packets in a flow (minimum delay) with any lost packets being ignored. Hence it is significant to compute the minimum and maximum delay to find PDV .

Minimum and Maximum Delay

Play out Buffer delay has main responsibility to occur maximum and minimum delay in Ethernet network. When a packet never encounters any queue front of it on egress link,network gets minimum delay. Therefore, minimum delay is just the summation of packet processing and link propagation delay [IEE18].

Minimum delay = Sum of Propagation Delay + Sum of Packet Processing delay

Maximum delay in a network is occurs when the packet faces one or more packets in front of it at egress link of each and every node. In this case,

Maximum Delay = Sum of Propagation Delay + Sum of Packet Processing delay + Sum of playout buffer delay

Packet delay varies between lowest and highest end to one way delay. So, PDV is calculated as PDV = Maximum Delay- Minimum Delay

4.2 Simulation model of IHON

In simulation model, the quality of IHON node is measured based on latency, PLR and PDV to investigate its compatibility with 5G fronthaul requirements. To simulate IHON node, programming language Simula is used here based on non-preemptive scheduling. Simula/DEMOS is an object-oriented simulation language developed in Norwegian Computing training Center in Norway for designing of simulation entities. It is a technique for representing a dynamic system by model in order to gain information about the underline system. If the behavior of the model correctly matched the relevant behaviour characteristics of underlying system, it is possible to draw interference about the system.

Before going deep into demos programming, a model was formed defining entity and showing relationship between entities. The designing of IHON Node implementation is described below.

IHON Node Implementation

The simulation model of IHON node contains several entities , resource and queues. To generate GST and SM packet and simulate their arrival process generator entities are created. These are :- GST_generator, GeneratorSM. The packets created from these generators are also entities: GSTpacket, SMPacket. A packet scheduler is significant in IHON node (described in Section 3.3) so SM_Packet_Scheduler entity is created to select appropriate size SM to insert in between the gap of GST packets. In addition to these, three queues like SM_waiting, SM_pkt_line, GST_pkt_line are formed to manage the SM and GST packets. These entities are modeled based on entity-entity synchronization.

– **GST_generator**: The ’GST_generator’ entity generates ’GSTpacket’ entities in a loop where inter arrival time of GST packet is defined by negative exponential distribution. Since GST packets get the absolute priority according to their principal, they are not interrupted by SM packets. Therefore, GST packets are scheduled immediately right after generation and the output wavelength is acquired until the packet is completely transmitted. Packet generated continuously from this GST_generator by using **FOR** loop.

– **GeneratorSM**: The 'GeneratorSM' entity generates 'SMPacket' entities in a loop with mean arrivals per second defined by the poisson 'SMpkt_'. Before scheduling a new SM packet this entity checks a queue called 'SM_pkt_line' for the number of SM objects. If the number of SM packet object is more than zero, the SM packets from SM_pkt_line queues are co-opted and scheduled before scheduling a new SM packet.

  The number of SM packet generated by 'FOR' loop from this entity and it is fixed in every simulation time.

– **GSTpacket**: This entity is the output of 'Gst_Generator'. When every time first bit of a GST packet is arrived at the delay line if delay line is free then this free line is given to arrival bit to be served. 'Fixed_delay_line" is a bin which is used to check if there is already a GST packet in line to find out when to change the pointer of the current GST packet to next GST packet. GST packet is directly linked to output wavelength. For each scheduled packet, the corresponding output wavelength is marked as busy (acquired). When the last bit of the GST packet arrives at FDL, it is delayed for an FDL time. Delay line is busy until the last bit of packet being served and this time is hold. After holding the FDL time, GST packet take the resource and hold it up to service time of GST. After service completion of GST packet, both FDL and output wavelength is released.

  In this process, when GST packets arrives at the output link, the arrival, service and exit time of this packet is registered and these parameters are renewed for new packet for every time. The statistics of end to end delay of GST packet is the base of calculating average latency and finding maximum and minimum delay is the base of computing PDV inside this entity.

– **SMPacket**: 'SMPacket' entity is the output of 'GeneratorSM' entity. In order to define the number of SM input streams to the IHON node a parameter called 'input' is used inside this entity. Each input channel has a dedicated line/queue to the output wavelength. When a SM packet is generated, the queue associated to this respective source is checked whether it exceeded the maximum buffer size or not. After checking, SM packets are stored in their buffer index if the buffer size is less than the maximum buffer size. Packets those come after filling the buffer marked as dropped or lost packet. The statistics of end to end delay of SM packet is the base of calculating average latency and finding maximum and minimum delay is the base of computing PDV inside this entity.

– **Sm_Packet_Scheduler**: This entity takes appropriate size SM packets from the 'SM_Waiting' queues. The buffer length of each SM packet is checked at the beginning. When a buffer with exact size SM packets are found, the packets are taken with service time equivalent to service time of their length. Inside this entity, the status of output wavelength and FDL is checked. If both the output wavelength and FDL are free, the SM packet taken from any of the buffer is served freely. If the delay line is occupied and there is an available gap, the length of the gap is calculated based on the round robin algorithm. If the gap is less than the minimum length of SM packet then this SM packet has to be waited for finding an appropriate gap after scheduling GST.

– **SM_waiting**: This is bin in the simulation model which is used to inform 'Sm_Packet_Scheduler' entity about appropriate size SM packet to be served right after their (SM packets) arrival.

– **SM_pkt_line and GST_pkt_line** These two are used as queues in the simulator to hold the SM and GST packet in queue. In this way huge number of unprocessed packets can be avoided thus increase the simulation capacity.

How output results of the simulation is presented in the simulator described in A.2.

Chapter 5
Results and Analysis

The results obtained from simulation such as latency, PDV and PLR are discussed in this chapter. How the obtained results from IHON simulation is in accordance with the C-RAN fronthaul requirements presented in Section 2.9.2 is analysed here. All the necessary results have been presented with 95% confidence interval. Calculation of confidence interval shown in Appendix A.4 . In addition, the knowledge achieved from literature review regarding transport systems of C-RAN, fronthaul requirements, design and operation of IHON are used in term of addressing the research questions of this thesis.

5.1 Parameters of Simulation

To simulate IHON node, few parameters related to traffic length, traffic load, capacity, number of buffer, buffer size, number of packets for different interfaces are set as input of simulation. Table 5.1 shows the list of parameters and Table 5.2 shows the notation (used for different traffic load for GST and SM traffic respectively).

Logic behind setting Parameters

In demos, ten different values are set as Seeds in order to make simulation non-repeatable. The minimum and maximum length of SM packet are defined according to the standardization of IEEE-802.3. This packet length follows an uniform distribution between 40 Mb to 1500 Mb. GST length is follows a constant distribution with fixed length 1500 Mb. GST and SM load varies from the input between 0.1 to 0.9 load. The buffer size is selected as 19 MB; usually there is not any optimal buffer size. It depends on the load and delay we want to tolerate. Larger the buffer size smaller the chance is to have packet loss.

Table 5.1: Simulation parameters

Parameters	value
Seeds	4943 4988 3798 7480 5837 4372 8702 4964 4865 7635
Capacity	10 Gb/s
Length of GST Packet	1500 Mb
Minimum Length of SM Packet	40 Mb
Maximum Length of SM Packet	1500 Mb
GST load	varies
SM Load	varies
Number of SM buffer in a node	4
Maximum Number of buffer	4
Size of Buffer	19 Mb
Number of Packets	40000

Table 5.2: Symbols of Parameters used for analysing simulation result

Description of used symbols	Symbols
SM traffic load on 1 Gb/s interface	L_{1GE}^{SM}
GST traffic Load on 10 Gb/s interface	L_{10GE}^{GST}
Total Load of SM and GST Traffic on 10 Gb/s interface	L_{10GE}^{T}

5.2 Performance of IHON

For studying the behaviour and performance of complex systems of IHON node during SM and GST traffic transmission, the traffic has been transported to 10 GE output wavelength. A network model showing how different entities are connected in IHON node are shown in Figure 5.1 for this simulation.

At first, GST and SM traffic are generated from the respective traffic generators. GST traffics are sent to 10 GE output link directly and SM traffics are kept in queue in a buffer until a suitable gap is detected. Packet scheduler selects the appropriate size SM packets from queue. In the end both GST and SM traffics are processed and sent to same 10GE output port.

The simulation results reflect the performance in the area of average latency, PDV and PLR of SM and GST traffic. Fixing the SM load at 0.3 and varying the GST loads a set of result from simulation is shown in figure below Figure 5.2. The Average latency of SM is presented with 95% confidence interval.

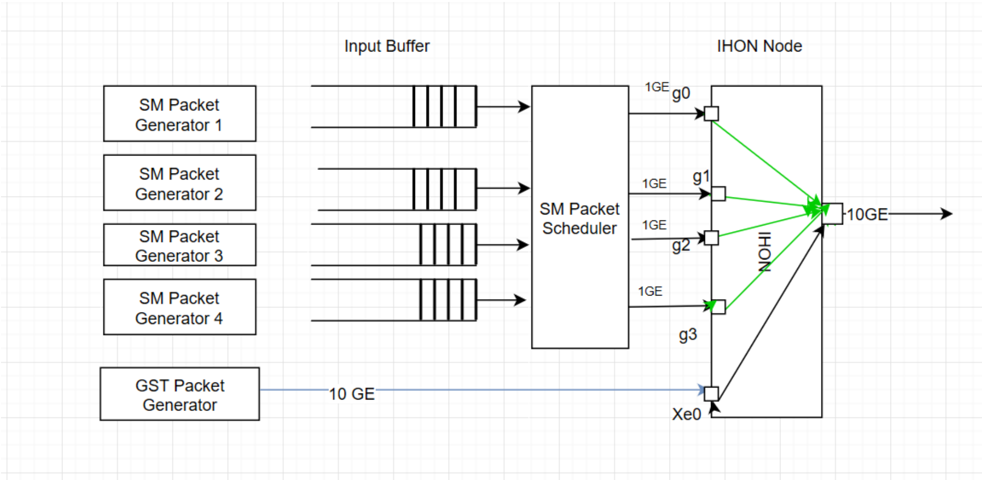


Figure 5.1: IHON Network model of showing the connection of IHON node with packet generators

No	SM Load	GST Load	Average Latency (SM) (second)	PDV of SM (second)	PLR of SM	Average Latency of GST (second)	PDV of GST
1	0.3	0.1	1.45933E-06 ± 6.415E-06	2.98766E-05	0	0.0000012	0
2	0.3	0.2	0.005698888 ± 0.00013435	0.000954936	0	0.0000012	0
3	0.3	0.3	0.026208934 ± 0.00015546	0.000569717	0	0.0000012	0
4	0.3	0.4	0.036456806 ± 0.00015452	0.000418683	0	0.0000012	0
5	0.3	0.5	0.042602677 ± 0.00016220	0.000316773	0	0.0000012	0
6	0.3	0.6	0.044442076 ± 0.00009477	0.000376465	0.0479368	0.0000012	0
7	0.3	0.63	0.044665684 ± 0.00009983	0.000377995	0.0625075	0.0000012	0
8	0.3	0.65	0.044795619 ± 0.00009395	0.000360969	0.0714112	0.0000012	0
9	0.3	0.67	0.044891095 ± 0.00009530	0.000405449	0.0800712	0.0000012	0

Figure 5.2: Results from IHON simulation as Average Latency, PDV, PLR of GST and SM traffic as function of GST load with fixed SM load 0.3

5.2.1 GST Traffic Performance

In order to measure the GST traffic performance, GST traffic load L_{10GE}^{GST} is varied with fixed SM load L_{1GE}^{SM} , upto total load L_{10GE}^{T} 0.97. The goal is to observe the results; how much these in accordance with fronthaul requirements of C-RAN described in Section 2.9.2. The average latency, PLR and PDV of GST traffic is discussed below.

Average Latency

The end-to-end one-way latency is measured from the arrival of the last bit at the ingress edge port of IHON node to the transmission of the last bit by the egress edge port (at the end of Fixed Delay Line) [VBB13]. This value has significance in network as it defines the usability of the nodes.

Every sub-simulation provides an average latency value of GST packet by averaging all the delays experienced by every single packet. The average latency of is observed by varying total system load and every time constant delay 1.2 µsec (Table in Figure 5.2) is obtained. This value is equal to FDL time (1.2 µsec) which is calculated by dividing Maximum length of SM packet to capacity of node. As GST traffic is transmitted with absolute priority, therefore a constant delay is obtained regardless of the change of system loads and node congestion.

Packet Delay variation

Packet Delay Variation (PDV) is the difference of end to end one-way delay between selected packets in a flow with any lost packets (components of the delay which does not vary from packet to packet) being ignored. According to ITU Y.1540 "delay variation of an individual packet is naturally defined as the difference between the actual delay experienced by that packet and a nominal or reference delay [ITU16]. ITU Y.1540 and RFC 5481 recommends to use minimum delay as a reference [Int09] [1].

From the definition, it is clear that computing maximum and minimum delay of packet is significant to find PDV. Time has to be recorded when the first bit of the packer arrives at the delay line and when the last bit of the packet leaves the FDL to compute maximum and minimum delay. Applying this concept the result of the simulator shows PDV of GST traffic is zero.

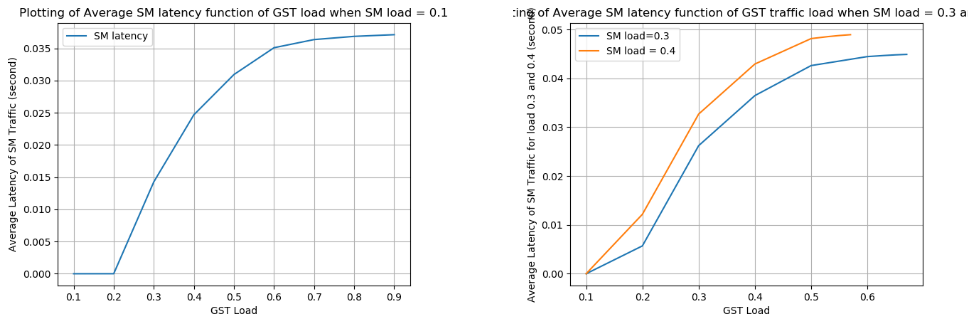
The reason for getting the zero PDV for GST traffic is that no PDV is introducing during insertion of SM traffic [VBB13]. The inter arrival or packet gap of GST traffic is fixed and all packets undergoes the same delay 1.2 µsec corresponding to the service time of a maximum length SM packet. Therefore at the output wavelength all GST experiences fixed delay and no PDV is introduced (Table in Figure 5.2).

Packet Loss Ratio

The packet loss ratio refers to the ratio of the number of lost packets to the total number of sent packets. In IHON node it happens when traffic load is high and the size of packets in queue are not enough to fit in the gap. Therefore packets loss occur for congestion and blocking.

Here in the simulator, the result shows that GST traffic has zero PLR regardless

[1] RFC 5481, published on 2009; source: https://tools.ietf.org/html/rfc5481



(a) SM Load = 0.1

(b) SM Load = 0.3 and 0.4

Figure 5.3: Average Latency of SM traffic Function of GST Load

of total load and any other changes in input parameters; it means that GST traffic generated at source is received completely at the output port of IHON node. Because GST passes the FDL and this provides gap detector to detect the duration of idle time gaps between GST packets in the channel [VBB+15]. Only the appropriate size SM packets are inserted in the gap without effecting the timing of the packets in the GST stream. Therefore, IHON node avoids losing of GST packets and simulation results PLR as zero.

5.2.2 SM Traffic Performance

In order to measure the performance of SM traffic in IHON, simulation runs by varying GST load (L^{GST}_{10GE}) with fixed SM load (L^{SM}_{1GE})

Average Latency

According to simulation result (showing the graph in Figure 5.3a) When SM load L^{SM}_{1GE} is low like 0.1 and GST load L^{GST}_{10GE} increases from 0.1 to 0.9 with increasing interval of 0.1, average latency increases from 0.67 µsec to 0.037 second.

Furthermore, When the SM load (L^{SM}_{1GE}) increases from 0.1 to 0.3, average latency increased from 1.4 µsec to 0.045 second. Figure 5.3b shows how average latency increases for SM load (L^{SM}_{1GE}) 0.3 and 0.4. Because of increasing SM traffic, system will face buffer overflow from total load 0.89 (for $L^{SM}_{1GE} = 0.3$). This leads the average latency to increase exponentially and causes packet loss as shown in Figure 5.5 . As it can be seen from figure Figure 5.5, when GST load increases it adds more traffic to the output wavelength. It makes the SM packet's waiting time longer at node. As consequence, it will decrease the chance of SM traffic to be inserted in between the gaps of GST traffic. However, the Average latency of SM result gets started increasing from total load (L_{10GE}^{T}) 0.3. As part of software validation (discussed in A.3) the code has compiled with changing parameters in several ways and each time it shows same pattern of result for Average latency of SM.

Packet Delay Variation

The results regarding PDV from simulation shows with increase of GST load (L_{10GE}^{GST}), the value of PDV increases from 29.8 µsec to 405.4 µsec (Figure 5.2). In this simulation, average latency starts increasing from (L_{10GE}^{T}) total load 0.3 and with gradual increase it reaches saturation when total load is high. That's why at the

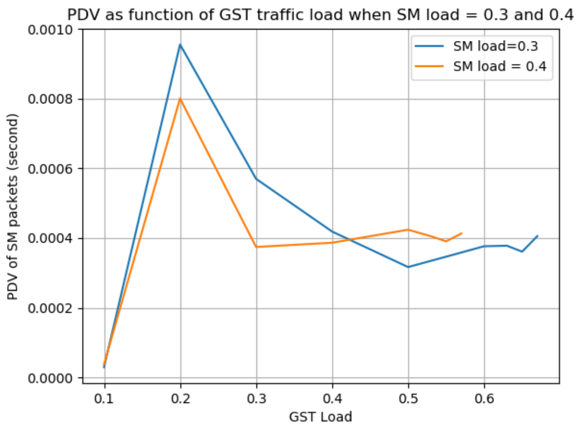
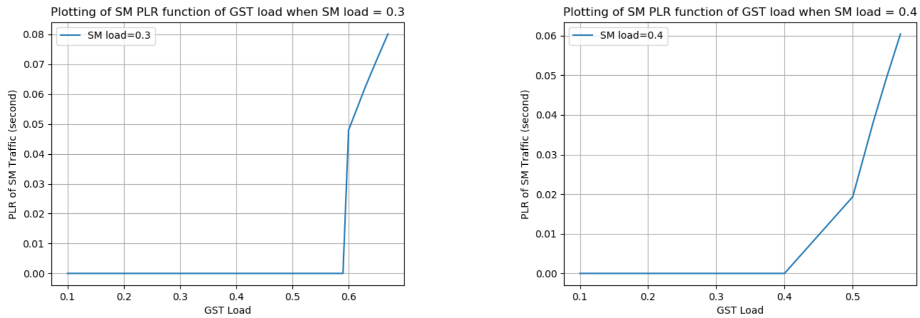


Figure 5.4: Packet Delay variation of SM traffic as function of GST Load when SM load = 0.3 and 0.4

beginning PDV gets a increase value at total load (L_{10GE}^{T}) 0.3 (Figure 5.4). Because the average latency change is very high from GST load (L_{10GE}^{GST}) 0.1 to 0.2. later on Packet Delay Variation is not that high with load increasing. Therefor it shown in graph (Figure 5.4) slope goes down and afterwards it gets usual changes and finally reaches saturation. Overall data shows PDV is increased when the GST load of the system increases. This proves SM traffic is influenced by traffic load and scheduling algorithm.

Packet Loss Ratio

Packet loss ratio (PLR) is an important factor to analysis the performance of IHON node which is illustrated in . Due to increase of system load packet loss happens. According to simulation result it is illustrated in the Figure 5.5. When total load (L_{10GE}^{T}) reached 0.89, SM traffic starts getting dropped and from that on it goes saturation and packet losses increase exponentially.



(a) SM Load = 0.3

(b) SM Load = 0.4

Figure 5.5: Packet Loss Ratio of SM traffic with Function of GST Load

The utilization of wavelength increases up to 89% because of the SM traffic insertion between the GST gaps when SM load (L_{1GE}^{SM}) is 0.3 without any packet loss.

5.2.3 Overall Observation from the SM and GST traffic

Simulation results confirms that the

1) GST traffic is transported through the network with absolute priority and neither PLR nor delay is affected by the SM insertion. It means that no GST packet losses, and the average GST delay remains constant regardless of the network condition or congestion.

2) Average latency of GST is always 1.2 µsec regardless of the value of SM load; (e.g., setting the parameters of SM load as 0.1, 0.3, 0.4 etc) Figure 5.6 shows the comparison between SM and GST average latency curve.

3) For low or moderate delay (e.g., When total load L_{10GE}^{T} is less than 0.4), average end to end latency of SM is lower than delay of GST traffic.

4) SM insertion increases the 10 GE light-path utilization up to 89% without any losses.

5) When the PLR of SM is $8^{-}2$ (0.08) at total load (L_{10GE}^{T}) 0.99, the network performs as a saturated SM packet network with high utilization while providing a service with circuit QoS properties.

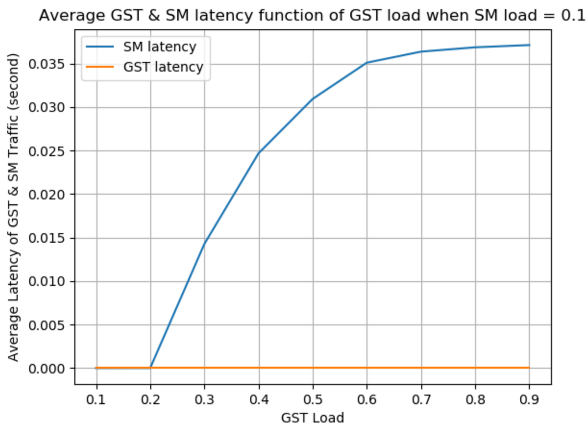


Figure 5.6: Average GST and SM latency with function of GST load when SM load = 0.1

5.2.4 Assessment of IHON in C-RAN Transport

The simulation result shows IHON performance in terms of average latency, PLR and PDV for both SM and GST traffic. Now it is the time to discuss how much this simulation values are in accordance with the fronthaul requirements Section 2.9.2.

In order to measure the performance of IHON node in this simulation work, one 10 GE GST traffic and four 1 GE SM traffics aggregated into a single 10 Gb/s wavelength is considered. The simulation results were validated changing the input parameters A.3.

– **Average Latency** According to IEE-802.1CM-2018 the maximum end to end one-way latency for fonthaul data between RRH and BBU is 100 μs. Taking into account propagation delay of fiber 5 μs/km, if fiber is used in the path as transmission media, the maximum transmission distance (link length) will be less than 20 km to meet up the 100 μs maximum end-to-end one-way delay requirement [Net14].

  According to simulation result, latency of GST traffic (Fronthaul traffic) for each node is 1.2 μs. To calculate link length For a numerical example, considering four (4) nodes in the network and 1.2 μs latency applied on each node. For this network, the total delay added by nodes to the longest path crossing all nodes is (1.2 x 4) = 4.8 μs. Therefor, remains budget for fiber transmission is (100 - 4.8) still 95.20 μs. As per kilometer delay is 5 μs, therefore maximum transmission distance that can still meet the delay requirements is then be at most 95.20/ 5 = 19.04 km. The higher number of nodes lower the transmission length. .

Therefore, it is proved that IHON node has the capability of carrying radio signal over packet based fronthaul network maintaining the fronthual requirement. It enables transmission of backhaul traffic (SM) alongside fronthaul (GST) traffic without any impact on the performance of fronthaul traffic.

– **Packet Delay Variation** PDV is a significant performance metrics for evaluating IHON performance in fronthaul network. GST traffic shows zero PDV and this highly in accordance with fronthaul requirements. Therefore backhaul traffic (SM) can be easily transmitted between GST traffic without effecting the QoS. Though PDV for SM traffic is not straight forward from simulation result as SM latency depends on various factors like GST load, buffer size, number of packets etc.

– **Packet Loss Ratio** Fronthaul network has very strict requirements in PLR which should be in the interval of [10^{-6} to 10^{-7}] [IEE14b]. The maximum tolerable PLR between edge ports of a fronthaul bridged network for a User Plane data flow is 10^{-7} and for Control and Management data is 10^{-6}. According to simulation result, GST traffic has no packet loss regardless of the network congestion for higher traffic load. This also shows promising output for SM as up to total load (L^{T}_{10GE}) 0.89 there is no packet loss with SM load ($L^{S}_{1GE}M$) is 0.3. Therefore, IHON node can increase the wavelength utilization up to 89% by providing deterministic priority means transferring backhaul traffic in between the gap of fronthaul traffic .

5.2.5 IHON aggregation mechanism towards using fewer or only one wavelength

The mechanism of IHON node aggregation is briefly described in Section 3.4. This mechanism preserves the packet gaps between the packets of individual GST stream being aggregated on a single wavelength during the transmission across a network and deaggregation at output channel [VBB+15].

Usually in optical circuit switching, each path contains separate wavelength where aggregation mechanism of IHON enables transferring GST stream through single wavelength channel. Different packet streams being aggregated at the client side and passed through virtual containers,at the end again aggregated at the line side [BCV18].

Virtual containers preserve the exact size of packet and gaps between packet during aggregation process. For example, if aggregated 5x1 Gb/s input streams transferred into a 10 Gb/s link, a cycle consisting of five virtual containers of length

2 x 1500 Byte may be used. The large virtual container provides space for both packets and packet gaps. Transferring GST packet through the virtual container allows the stream to be reconstructed at the de-aggregation side. As the gap between packets are preserved at output port that means PDV is zero what is also proved here in simulation work.

Therefore, IHON node aggregation enables transferring several fronthaul streams through a single channel using different time slot.

IHON would be an efficient solution in 5G transport network by enabling services (low and fixed delay, zero PDV for fronthaul traffic, implying static multiplexing for backhaul traffic and aggregation of frotnhaul traffic towards utilizing wavelength) that is not specified by current RoE standardization or eCPRI specification.

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Chapter 6
Conclusion

Traditional RAN architecture needs to be improved because of the enormous data need from the customers' side and the increasing of falling ARPU by introducing multiple service from the MNOs' side. C-RAN is the newest idea to overcome the challenges by easing the transport network architecture and to upgrade the network architecture in accordance with the requirements of 5G. However existing architecture of C-RAN is not compatible with fronthaul requirements when it talks about very low latency 100 µsec, low packet loss and very low PDV.

Transpacket, a start-up company invented an IHON based node called 'Fusion' to improve the C-RAN architecture towards achieving the requirements of 5G transport network for both fronthaul and backhaul traffic. In this thesis the focus was to improve the C-RAN architecture by using IHON node.

Before going deep details into IHON, research on C-RAN has performed focusing on the topics related to C-RAN component, fronthaul architecture (comprises of full, partial and hybrid centralization), several transport options, functional splitting and frontahul requirements in terms of delay, PLR and PDV from plenty of scholarly literature and ITU-T and IEEE standardization.

Considering several transport options for C-RAN e.g. point to point optical fiber, PON, OTN, there is a finding every option has the capability to meet the fronthaul requirement from specific angle but not capable of showing performance in all sector of QoS. For example, because of deploying dedicated wavelength to each access point, WDM-PON may meet the delay requirement for fronthaul. However it costs huge bandwidth because there is no option for sharing wavelength. OTN is an ITU-T G.709 standard designed for delivering Guaranteed Service Transport (GST) in the network [Sch18] and TDM based technology enables OTN to provide zero packet loss, low delay and delay variation. Nevertheless , OTN does not support Static Multiplexing (SM) and it's circuit switching principal capacity can not allow to combine fronthaul and backhaul traffic in same wavelength with low cost.

On the contrary of transport option PON and OTN, Ethernet transport enables a more dynamic bandwidth allocation since statistical traffic variations in the fronthaul traffic can be utilized by the backhaul traffic. Taking into consideration Ethernet as promising option for mobile transport there are several standardization (IEEE 1914.3, IEEE 802.1CM-2018, eCPRI specification etc.) in the industry to make this compatible with time sensitive application. However there is some drawback in transferring radio data over Ethernet. To smooth out burst traffic, buffer is used at output channel that leads to create PDV. Preemption property (IEEE Qbu) of Ethernet transport outcomes as PLR if the traffic load is high. In addition, Ethernet traffic does not arrive synchronously, means that there is no deterministic approach of serving a packet after being served of current one. Therefore it needs to introduce an additional scheduling mechanisms in order to support a deterministic Ethernet-based network for fronthaul. IHON based noble technology 'Fusion' can enable packet switched nodes to transport both GST and SM traffic classes which can add deterministic scheduling in Ethernet transport.

The focus of the IHON technology is to minimize the packet delay and delay variation even in the presence of multiple traffic sources [VBB13], these are prime requirements in 5G mobile fronthaul. This can be performed by aggregating several fronthaul streams with low and fixed delay (Deterministic aggregation) and by the statistically multiplex lower priority traffic, e.g. backhaul traffic, with no impact on fronthaul streams.

Therefore the thesis goal was to investigate how this 'Fusion' node based on IHON technology can improve the performance of C-RAN. Pursuit of reaching the goal two research questions were set at the very beginning followed by few objectives. Below the discussion is a summing up to present the answer of those research questions.

Research Question:1 How IHON can improve the performance in terms of latency in 5G mobile transport network (i.e. the fronthaul and backhaul networks)?

In order to discover this research question based on relevant literature, standardization, specification; a numerical analysis (for finding the way of calculating one way end to end latency, maximum separation distance between RRH and BBU for different transport medium) and a simulation work with object oriented programming language 'Simula' have performed. The goal is to measure the performance of IHON in terms of average latency, PDV and PLR.

In simulation model, one 10GE GST stream and four 1GE sub-wavelength SM (inserted on the left over capacity of GST) is considered.

GST traffic is transported through the network with absolute priority and simulation result shows neither packet loss nor delay is affected for GST traffic by the SM insertion.This traffic type has no packet losses, no PDV and the average delay remains constant at 1.2 µsec regardless of the network condition or congestion.

SM traffic gets low latency when there is low load and with the increasing of traffic load, latency gets higher value. There is no packet loss in SM up to total traffic (GST and SM) load 0.89; means SM insertion increases the 10GE light-path utilization up to 89% without any losses. The network starts performing as a saturated SM with PLR 0.08 at total traffic load 0.99.

According to simulation results it is proved IHON shows better performance for GST traffic in PDV and PLR than what is recommended in IEEE-802.1CM-2018. As PDV and PLR for fronthaul traffic is zero from simulation output. SM traffic (backhaul) can be transmitted with GST (fronthaul) stream with no impact on fronthaul stream. This is the principal of deterministic priority of 'Fusion' node. Therefore, in this way IHON can improve C-RAN architecture in terms of latency in 5G mobile transport network.

Research Question:2 How IHON can be applied in the mobile transport network containing only a few, or only a single wavelength channel?

In order to discover this research question, deterministic aggregation (Section 2.7) of IHON has analysed. IHON based 'Fusion' has the capability to aggregate several fronthaul streams in low and fixed delay. Simulation result also proofs the fixed delay of fronthaul traffic which is very low. Aggregation principal introduces a concept of virtual container in where aggregated packet (from client side) are divided up before being aggregated again at the output (line side). Bit rate of line side is larger than the the some of the bit rate of the client side. Packet gaps are preserved in each virtual container and static multiplexing is performed. At the deaggregation side, each of the containers is deaggregated by forwarding its packets to an interface dedicated to each stream without adding PDV [BCV18]. Usually in optical circuit switching, each path contains separate wavelength where IHON aggregation mechanism enables of transferring GST stream through single wavelength channel. Therefor IHON node aggregation mechanism would able to reduce the number of wavelength channel in mobile transport network.

Chapter 7
Future Work

This chapter presents some suggestions to consider and to investigate further as part of future work. Here is the few points those can be conducted to measure the IHON performance more details towards improve C-RAN architecture.

1. In the simulation work of this thesis to measure the performance of IHON, average latency, PDV and PLR are considered. However, packet synchronization has not been considered in the simulation. Time and phase synchronization is important mechanism such as IEEE 1588 or Precision Time Protocol is required to achieve synchronized packets through the exchange of time-stamped packet [IEE08]. It can be added in future work.

2. Current research work in TDMA-PON such as GPON is highlighted as one of the alternatives for fronthaul networks. Reusing of the infrastructure for mobile fronthaul is key concept and it is already widely deployed in Fiber To The Home (FTTH) and fibre to the premises networks. There has been demonstration by mobile equipment vendor Company Nokia showing the possibility to use a commercial NG-PON to transport ultra-low latency CPRI streams via a standard single fiber running between the BBU and RRH [Nok17]. IHON based 'Fusion' also has the capability to perform in very low latency. There would be a comparison work between NG-PON and IHON in future.

3. Functional splitting of C-RAN fronthaul proposes for reducing the asymmetry between RRH and BBU function. Low layer splitting requires very strict latency and creates pressure on BBU as BBU is responsible for all Layer-1,2 and 3 activities. There are few proposals [IEE14b] related to transferring some task of centralize unit to RRH for improving the conventional architecture towards deployment of 5G. Specially option 6 for MAC/PHY split and Option 7 for intra-PHY (intra-physical layer) split (with three different variants 7-1, 7-2, 7-3) is thought to be significant to meet the fronthaul requirements in terms of

latency. This would be a new turn to future work towards improving C-RAN architecture.

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Chapter A
Simulation of IHON

A.1 IHON Source Code

Source Code is uploaded in separate file (IH.sim) along with thesis pdf file. The logic of 'SMPacket' and 'SM_Packet_Scheduler' entity is reused with some changes from a previous simulator provided by supervisor.

A.2 IHON input and Output File

All the input parameters (e.g., capacity of link, SM & GST traffic load, minimum and maximum packet length of SM, length of GST packet, the number of buffers, buffer size) needed for the simulator are inserted through an input file. That is convenient to run the simulation codes by changing the relevant parameters without changing the code. The contains of input file is described in 5.1 and also is uploaded as separate file (IH_input.txt) with thesis.

In the simulator Ten output files are generated After implementation of IHON node. These output files keep the results of all performance metric to be measured. These oputput files are described below:-

– Avg_latency_GST_out.txt file presents the GST latency of the simulator for different GST load.

– Avg_latency_SM_out.txt file presents the SM latency of the simulator for different GST load.

– PDV_GST_out.txt file presents the GST PDV of the simulator for different GST load.

– PDV_SM_out.txt file presents the SM PDV of the simulator for different GST load.

- PLR_SM_out.txt file presents the PLR of SM of the simulator for different GST load.
- Conf_Int95_latency_gst.txt file presents the 95% confidence interval of GST latency results for different GST load.
- Conf_Int95_latency_sm.txt file presents the 95% confidence interval of SM latency results for different GST load.
- Conf_Int95_PDV_gST.txt file presents the 95% confidence interval of PDV results for different GST load.
- Conf_Int95_PDV_sm.txt file presents the 95% confidence interval of SM latency results for different GST load.
- Conf_Int95_PLR_SM.txt file presents the 95% confidence interval of SM traffic for different GST load.

A.3 Simulator validation

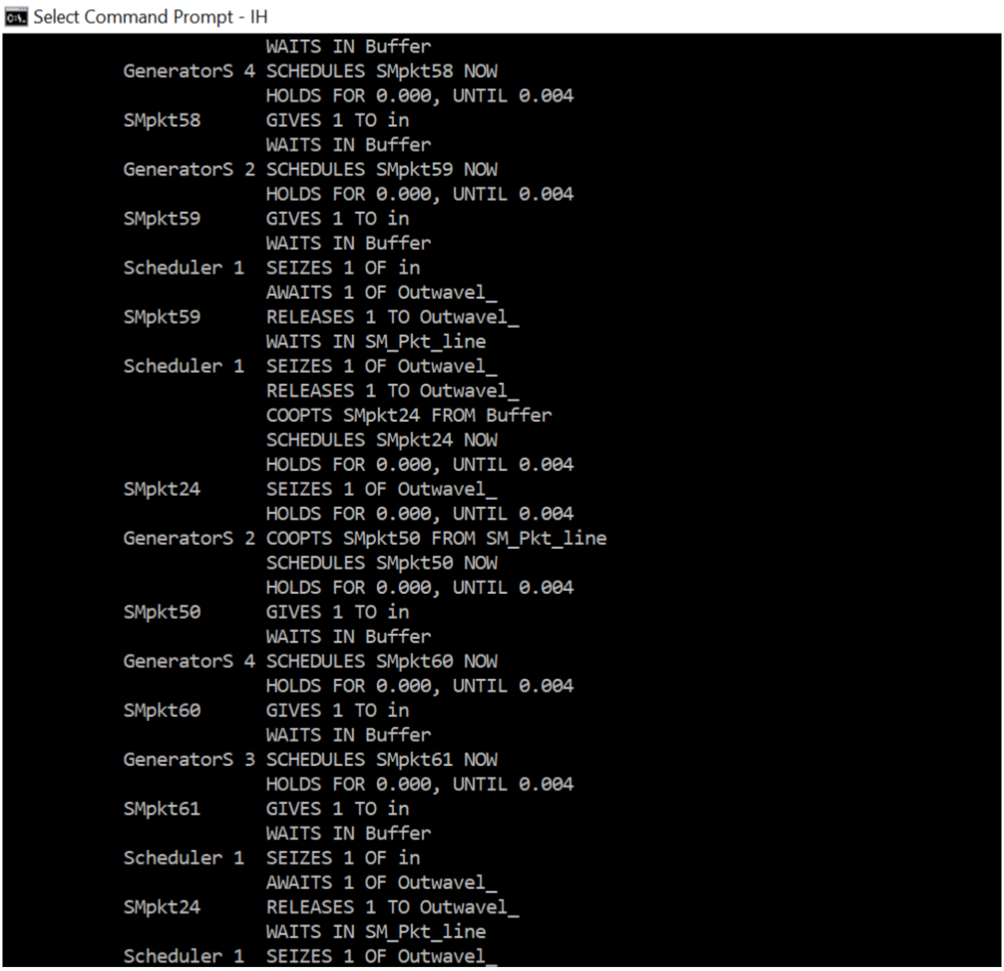
The validation of simulator is conducted in two ways. First approach is to trace the output of simulation for each event with the DEMOS built-in library function called 'trace'. The output after trace command shows the behavior of entities and it is in accordance with the logic set for each entities, resources and bin. A screenshot of trace oputput shown in Figure A.1.

Another way of validation is to run the simulation with change the input parameters ; such as buffer size is changed to 16 Mb, changes the SM packet distribution from uniform to constant (fixed SM size 64 MB), considering only SM packets. The simulation output patterns are same regardless of changes occur in input parameters.

A.4 Formula for calculating 95% Confidence Interval

The results presented in Chapter 5 are calculated with 95% confidence interval accuracy level. This confidence interval is performed with the formula (Figure A.2) described in Textbook for TTM 4110 'Dependability and Performance with Discrete Event Simulation' [EHHP99].

To calculate the $\alpha/2$ quantile value (or Z value), we have to sbutract 1 from sample size (n). here sample size n is 10. So, it becomes (n-1)= (10-1)= 9. This gives degree of freedom. Then to get the value of α, have to subtract the confident level from one and divide by two, So it becomes (1-0.95)/2 = 0.025. Using T-distribution table, for 9 degrees of freedom and α = 0.025, quantile or Z value is 2.262. This value is used in simulation to calculate the confidence interval.



```
Select Command Prompt - IH
                WAITS IN Buffer
GeneratorS 4 SCHEDULES SMpkt58 NOW
                HOLDS FOR 0.000, UNTIL 0.004
SMpkt58         GIVES 1 TO in
                WAITS IN Buffer
GeneratorS 2 SCHEDULES SMpkt59 NOW
                HOLDS FOR 0.000, UNTIL 0.004
SMpkt59         GIVES 1 TO in
                WAITS IN Buffer
Scheduler 1     SEIZES 1 OF in
                AWAITS 1 OF Outwavel_
SMpkt59         RELEASES 1 TO Outwavel_
                WAITS IN SM_Pkt_line
Scheduler 1     SEIZES 1 OF Outwavel_
                RELEASES 1 TO Outwavel_
                COOPTS SMpkt24 FROM Buffer
                SCHEDULES SMpkt24 NOW
                HOLDS FOR 0.000, UNTIL 0.004
SMpkt24         SEIZES 1 OF Outwavel_
                HOLDS FOR 0.000, UNTIL 0.004
GeneratorS 2 COOPTS SMpkt50 FROM SM_Pkt_line
                SCHEDULES SMpkt50 NOW
                HOLDS FOR 0.000, UNTIL 0.004
SMpkt50         GIVES 1 TO in
                WAITS IN Buffer
GeneratorS 4 SCHEDULES SMpkt60 NOW
                HOLDS FOR 0.000, UNTIL 0.004
SMpkt60         GIVES 1 TO in
                WAITS IN Buffer
GeneratorS 3 SCHEDULES SMpkt61 NOW
                HOLDS FOR 0.000, UNTIL 0.004
SMpkt61         GIVES 1 TO in
                WAITS IN Buffer
Scheduler 1     SEIZES 1 OF in
                AWAITS 1 OF Outwavel_
SMpkt24         RELEASES 1 TO Outwavel_
                WAITS IN SM_Pkt_line
Scheduler 1     SEIZES 1 OF Outwavel_
```

Figure A.1: Simulation output Tracing by DEMOS library function 'Trace'

Estimators

Let Θ be an *unbiased* and *consistent estimator* of a *parameter* ξ, i.e. $\mathrm{E}(\Theta) = \xi$ and $\mathrm{Var}(\Theta(n)) \to 0$ when $n \to \infty$. Let $X_1, X_2, \cdots, X_n$ be n independent and identically distributed observations, and $\mathrm{E}(X_i) = \xi$ and $\mathrm{Var}(X_i) = \sigma^2$, $i = 1, 2, \cdots, n$.

Time average

$$\bar{X} = \frac{1}{T}\int_0^T X(t)\,\mathrm{d}t \tag{63}$$

Sample mean

$$\hat{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{64}$$

Sample variance

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - \hat{X})^2 = \frac{1}{n-1}\sum_{i=1}^{n} X_i^2 - \frac{n}{n-1}\hat{X}^2 \tag{65}$$

Variance of the sample mean

$$S_{\hat{X}}^2 = \frac{S^2}{n} \tag{66}$$

Standard error of the sample mean

$$S_{\hat{X}} = \frac{S}{\sqrt{n}} \tag{67}$$

$1-\alpha$ **confidence interval** for $\hat{X}$ (with unknown variance)

$$\left(\hat{X} - t_{\alpha/2,n-1}\frac{S}{\sqrt{n}}, \hat{X} + t_{\alpha/2,n-1}\frac{S}{\sqrt{n}}\right) \tag{68}$$

($t_{\alpha/2,n-1}$ is the $\alpha/2$-quantile of the Student's t-distribution with $n-1$ degrees of freedom.)

Figure A.2: formula for calculating confidence interval