Interplay between capacity and energy consumption in C-RAN transport network design

Huajun Wang
Interplay between capacity and energy consumption in C-RAN transport network design

**Master Student:** Huajun Wang  
**Supervisor:** Dr. Cicek Cavdar, Xinbo Wang  
**Examiner:** Prof. Jens Zander

Master Thesis  
Stockholm, Sweden 2016
Abstract

Current mobile network architecture is facing a big challenge as the traffic demands have been increasing dramatically these years. Explosive mobile data demands are driving a significant growth in energy consumption in mobile networks, as well as the cost and carbon footprints [1]. In 2010, China Mobile Research Institute proposed Cloud Radio Access Network (C-RAN) [2], which has been regarded as one of the most promising architecture to solve the challenge of operators. In C-RAN, the baseband units (BBU) are decoupled from the remote radio units (RRH) and centralized in one or more locations. The feasibility of combination of implementing the very tight radio coordination schemes and sharing baseband processing and cooling system resources proves to be the two main advantages of C-RAN compared to traditional RAN. More importantly, mobile operators can quickly deploy RRHs to expand and make upgrades to their networks. Therefore, the C-RAN has been advocated by both operators and equipment vendors as a means to achieve the significant performance gains required for 5G [3].

However, one of the biggest barriers has shown up in the deployment of C-RAN as the novel architecture imposes very high capacity requirement on the transport network between the RRHs and BBUs, which is been called fronthaul network. With the implementation of 5G wireless system using advanced multi-antenna transmission (MIMO), the capacity requirement would go further up, as well as the power consumption. One solution has been proposed to solve the problem is to have the baseband functions divided, partially staying with RRHs and other functions would be centralized in BBU pool. Different splitting solutions has been proposed in [4] [5] and [6].

In this thesis work, we choose four different splitting solutions to build four C-RAN architecture models. Under one specific case scenario with the fixed number of LTE base stations, we calculate the transport capacity requirement for fronthaul and adopt three different fronthaul technology. The power consumption is calculated by adding up the power utilized by RRHs, fronthaul network and baseband processing. By comparing the numerical results, split 1 and 2 shows the best results while split 2 is more practical for dense cell area, since split 1 requires large fronthaul capacity. The fronthaul transport technology can be decided according to different density of base stations. TWDM-PON shows better energy performance as fronthaul network when the capacity requirement is high, compared to EPON. However, for larger number of BSs, mm-Wave fronthaul is a better solution in terms of energy efficiency, fiber saving and flexibility.

Keywords: C-RAN, Energy Efficiency, Fronthaul, Power Model, Baseband Splits, Fronthaul Network
Acknowledgments

I would like to take this opportunity to express my gratitude to my supervisor Cicek Cavdar and my examiner Jens Zander for giving me the opportunity to work on my master thesis project at the Communication Systems department at KTH. I really appreciate the help I have received from my teachers and colleagues especially from Cicek and Xinbo Wang who has been supervising my work and showing me how to do scientific research and analysing work all the time. I also want to thank my parents who have been supporting my study in Sweden, without whom I could not go this far. All the friends I met in Stockholm, thank you for keeping me company and give me unconditional love and friendship.

This is my first time to live abroad, and first time to explore Europe. I have seen so many different things and people, which enrich my life a lot. I started to learn how to think differently and try new things in life which I would never do before.

For myself: Keep going, don’t settle.
# Table of Contents

List of Acronyms ........................................................................................................... 1

Introduction ...................................................................................................................... 2
  1.1 Background .................................................................................................................. 2
  1.2 Motivation and Problem description .......................................................................... 4
  1.3 Goal ............................................................................................................................. 5
  1.4 Outline ........................................................................................................................ 5

Literature Review ............................................................................................................. 6
  2.1 C-RAN Network Overview ....................................................................................... 6
  2.2 Fronthaul Solutions .................................................................................................. 9
  2.3 Fronthaul Network Technology ................................................................................ 15
    2.3.1 Passive Optical Network ................................................................................... 16
    2.3.2 Millimetre-Wave Wireless Fronthaul Technology ............................................. 18

Methodology ................................................................................................................... 20
  3.1 Case scenario definition ............................................................................................ 21
  3.2 C-RAN architectures under different splitting solutions ........................................... 21
  3.3 Bandwidth Calculation Models ................................................................................. 23
    3.3.1 Split 1 C-RAN Model ....................................................................................... 23
    3.3.2 Split 2 C-RAN Model ....................................................................................... 23
    3.3.3 Split 3 C-RAN Model ....................................................................................... 23
    3.3.4 Split 4 C-RAN Model ....................................................................................... 24
  3.4 Power Consumption Calculation Models .................................................................... 25
    3.4.1 RRHs .................................................................................................................. 26
    3.4.2 PUs ..................................................................................................................... 26
    3.4.3 Transport Network ............................................................................................. 29
  3.5 Summary .................................................................................................................... 32

Numerical Results ........................................................................................................... 33

Conclusion ....................................................................................................................... 39

References ....................................................................................................................... 40
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5G</td>
<td>5th Generation</td>
</tr>
<tr>
<td>RRH</td>
<td>Radio Remote hand</td>
</tr>
<tr>
<td>RAN</td>
<td>Radio Access Network</td>
</tr>
<tr>
<td>SDR</td>
<td>Software Defined Radio</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operating Expense</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expense</td>
</tr>
<tr>
<td>BBU</td>
<td>Baseband Unit</td>
</tr>
<tr>
<td>CPRI</td>
<td>Common Public Radio Interface</td>
</tr>
<tr>
<td>OBSAI</td>
<td>Open Base Station Architecture Initiative</td>
</tr>
<tr>
<td>TDM</td>
<td>Time-Division Multiplexing</td>
</tr>
<tr>
<td>SFP</td>
<td>Small Form-Factor Pluggable</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>TWDM</td>
<td>Time Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multi-Input Multi-Output</td>
</tr>
<tr>
<td>NGFI</td>
<td>Next Generation Fronthaul Interface</td>
</tr>
<tr>
<td>RAU</td>
<td>Radio Aggregate Unit</td>
</tr>
<tr>
<td>PDCP</td>
<td>Packet Data Convergence Protocol</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>MPLS</td>
<td>Multiple Protocol Label Switching</td>
</tr>
<tr>
<td>EPON</td>
<td>Ethernet passive optical network</td>
</tr>
<tr>
<td>OLT</td>
<td>Optical Line Terminal</td>
</tr>
<tr>
<td>RN</td>
<td>Remote Node</td>
</tr>
<tr>
<td>ONU</td>
<td>Optical Network Unit</td>
</tr>
<tr>
<td>PA</td>
<td>Power Amplifier</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background

Nowadays, as mobile phones and Internet applications grow rapidly, the traffic demand from mobile users increases dramatically. According to the CISCO Visual Network Index (VNI) report, the global mobile data traffic will increase 13-fold between 2012 and 2017, growing at a compound annual growth rate of 66%, and reaching 11.2 exabytes per month by 2017 [7]. One of the barriers towards 5G Network is the big gap between the traffic demand and network capacity and the gap is further growing. As a result, operators start adding air interfaces and build more base stations (BS) constantly, to provide better network service. In just five years, China Mobile has doubled their base stations, so as the power consumption [2]. The increasing power consumption causes financial pressure as well as bad environmental influence.

Figure 1 shows the power consumption in radio access network (RAN), where most energy is spent on the BS [2]. Figure 2 shows inside BS, only half of the power is used by the RAN equipment; while the other half is consumed by air conditioners and other facilitate equipment [2].

For mobile operators, they have a big dilemma in hands: on the one hand, rapid traffic growth urges them to deploy more base stations and upgrade their radio access network; on the other hand, the cost of those changes, maintenance and power consumptions cannot be covered by the revenue increased by the traffic growth. In a word, the margin becomes smaller and smaller. In order to deduce the cost of new network deployment and improve customers’ experience at the same time, a lot operators started to review the current network architecture and implementation, in order to find new solutions and opportunities.
In 2010, China Mobile announced a centralized radio access network architecture, namely C-RAN, which incorporates centralized baseband pool processing, cooperative radio with distributed antennas equipped with remote radio heads (RRHs), and real-time cloud infrastructures. C-RAN represents Cloud, Centralized processing, Cooperative radio, Clean radio access network, and has been seen as one of the most promising architecture solution for 5G network deployment. Recent study shows that C-RAN implementation on a macro-cell based RAN can lead to valuable energy savings (up to 40–50%), which even just rely on the current infrastructure [19].

However, with the deployment of C-RAN promoted in a larger scalability, more small cells are connected with BBU pool through fronthaul network, there are some barriers showing up on the way, one of which is that C-RAN architectures impose very strict capacity requirement, as well as the high power consumption of fronthaul network. One way proposed is to divide the BBU functions, and partially centralize them in BBU pool while leaving some functions with RRHs, so that the required transport capacity can be reduced. Under this methodology, several new architectures with different splitting solutions have been proposed. Shown as figure 3, the baseband function chain has been split in 4 methods: split 1, 2, 3 and 4. The part before split would be deployed in central office while the functions that after split are deployed at small cells.
On the other hand, traditional C-RAN uses fiber links as fronthaul such as Passive Optical Network (PON) due to its big capacity and low delay advantages [10]. With the densification of small cells, this approach becomes very impractical since the cost is very high, when every cell needs a fiber connection.

Recently, DTU researchers proposed a very promising approach using millimetre wave (mm-Wave) wireless connection as fronthaul solution [28]. In this approach, each small cell is connected with an aggregate point via mm-Wave, and only the aggregate points connect with BBU pool through optical fibers, which is called midhaul network. In that case, the small cells could be placed at anywhere with flexibility and not worrying about the cost of fiber and its reachability. However, in this new method, the high capacity requirement for midhaul, namely between aggregate points and central office, still limits the deployment with same problem.

There are some researches about exploring the possibility and performance of different function splits, such as comparing the bandwidth requirement, delay analysis such as [4], [5], [6]. Very few of them have concentrated on the energy performance of different splits, especially combining different fronthaul technology.

1.2 Motivation and Problem description

C-RAN has been regarded as one of the most promising architecture for future 5G network. One of its greatest advantages comes from the fact that centralization of baseband processing can improve the energy efficiency of mobile network by sharing processing resources and the cooling systems. This is significant for saving cost for mobile operators and also have positive impact on environmental problem considering Carbon footprint of ICT is approximately 2% to total human footprint [20].

In 5G wireless system, advanced massive multi-antenna will be widely adopted as well as wider wireless bandwidth. With mobile traffic increasing further, and densified network deployment, one of the barriers shows up and might jeopardize the advantages of C-RAN. The requirement for transport network between RRHs and BBUs, i.e. fronthaul network, becomes very strict. High bandwidth and low delay requirement directly limit the practicality under current CPRI interface, and even with the help of WDM (Wavelength-Division Multiplexing) technology, the equipment cost and power consumption can be intolerable for operators. Even though the wireless fronthaul has been proposed as mentioned in 1.1, the problem of excessive bandwidth requirement for the midhaul still exists.

In order to solve those barriers of C-RAN mentioned above, in this project, we want to answer two questions:
- Which splits should be deployed?
- Which fronthaul technology should be adopted?
We will do the quantitative analysis for C-RAN architectures. Each architecture will deploy one splitting solution and one fronthaul technology. We will evaluate their feasibility by giving the cost and power comparison. The cost is displayed by the number of devices, components and fiber of each architecture model, and the power is calculated by the total power consumption of all network parts.

For mobile operators, it is very important to have a comprehensive view of power division in mobile network and understand which splitting solutions are more practical. They also should be aware of the cost for deploying a new architecture of RAN. In addition, environmental influence should be taken into account when we are thinking about power consumption and consequently carbon emissions caused through producing electricity.

1.3 Goal
In this thesis project, we review C-RAN Network Architecture, and build different C-RAN architecture models with different splitting solutions and calculate their bandwidth requirements. We also introduce and choose different fronthaul transport technology as our case architectures. Under one specific case scenario with fixed end traffic, we do quantitative cost and power consumption analysis for C-RAN mobile network architectures, which adopts different level of baseband centralization and fronthaul solutions. By giving the overview of network cost and energy consumption, the aim is to understand comprehensively about the deployment cost and energy performance of each network and which C-RAN architecture yields the best overall energy performance, to drive the future choices in splitting solutions and fronthaul transport technology for mobile operators. In addition, the methodology we develop in this project also can be widely used in other architectures as a framework.

1.4 Outline
The content of this thesis is organized as follows. In Chapter 2, the related literatures are reviewed. We present general idea about C-RAN architecture including its benefits and barriers, current progress on baseband splitting solutions, fronthaul solutions and analysis results about those solutions. Methodology regarding establishing power consumption model and transport capacity model would be introduced in Chapter 3. We decide the case scenario we use in the models, and the parameters assumed in this scenario. The calculation of power consumption has been divided into three parts: RRHs at small cell, fronthaul network and baseband processing power. Chapter 4 presents the numerical results, calculated by the models displayed in Chapter 3. Chapter 5 provides the conclusions of this thesis and some suggestions for the future work.
Chapter 2

Literature Review

2.1 C-RAN Network Overview

C-RAN represents Cloud, Centralized processing, Cooperative radio, Clean radio access network [2]. In short, Centralized baseband processing greatly reduces the number of sites equipment room needed to cover the same areas; Cooperative radio with distributed antenna equipped by Remote Radio Head provides higher spectrum efficiency; real-time Cloud infrastructure based on open platform and BS virtualization enables processing aggregation and dynamic allocation, reducing the power consumption and increasing the infrastructure utilization rate. Gather all baseband units and keep all of them cool in a single location would make it greener in terms of energy savings. Compared to traditional radio access network, the proposed C-RAN architecture emphasizes the use of cloud, service-oriented resource scheduling and management, thus it facilitates the utilization of current and even future communication and computer techniques [17]. C-RAN provides an innovative approach to enable the operators to not only meet the requirements but advance the network to provide better coverage, new services, and lower support costs. From the economic point of view, its benefits generally can be divided into three categories: site simplification benefits, load-balancing benefits, and CoMP-related benefits [21].

C-RAN reviews the components of current BS, which are baseband unit (BBU) and remote radio head (RRH). C-RAN tries to re-design the functions architecture between BBU and RRH, so that more processing work and functions can be done together with centralized platform. In the original white paper of China Mobile [2], C-RAN solutions have two architectures: one is called “full centralization”, where layer 1 (physical layer), layer 2 (data link layer) and layer 3 (network layer) functions are all located in BBU; the other is called “partial centralization”, where the RRH integrates not only the radio function but also some baseband function (i.e. layer 1), while all other higher layer functions are still located in BBU.

Figure 4. Two solutions in C-RAN [2]
Based on the Figure 4 and discussion above, the architecture for two solutions both has three parts:

1. Remote radio heads and antennas which are located at remote sites;
2. The BBU pool composed of high-performance programmable processors and real-time virtualization technology;
3. High bandwidth and low latency optical transport links which connect RRHs and BBU pool.

Figure 5 shows the C-RAN solution 1 architecture, “full centralization”. The advantage of this solution is that it is very easy to upgrade and expand the network coverage. The operator only needs to install new RRHs at remote cell sites and connect them to the BBU pool to expand the network coverage or split the cell to improve capacity. If the network load continues growing and stress the processing capacity in central office, the operator only needs to upgrade the BBU pool’s hardware to accommodate the increased processing capacity. In combination with open platform and general purpose processors, (who?) will provide an easy way to develop and deploy software defined radio (SDR) which enables upgrading of air interface standards by software only, and makes it easier to upgrade RAN and support multi-standard operation. In addition, it’s more convenient for supporting multi-cell collaborative signal processing. This means that there is no fixed connections between RRHs and BBUs, and the BBUs can proceed (process?) any RRH radio signals, due to the virtualization technology, maximizing the flexibility of the whole system.

The biggest problem for this solution is that this architecture requires very large transport bandwidth between RRHs and BBUs to carry the baseband I/Q signals, especially when the traffic demand by end user equipment exceeds certain level. For example, in the extreme scenario, a TD-LTE 8-antenna with 20MHz bandwidth will need almost 10Gpbs transmission rate [5], which gives big pressure on the implementation of transport network.

To mitigate this challenge mentioned in solution 1, Figure 6 shows the C-RAN solution 2 architecture, “Partial centralization”, which requires much lower transmission bandwidth between BBU and RRH, by separating the baseband layer 1 processing from BBU and integrating it into RRH. Compared with the solution 1, the BBU-RRH transmission links only need to carry demodulated data, which is only 1/20~1/50 of the original baseband I/Q sample data [5]. It helps with the transport pressure, however, when it comes to upgrades and multi-cell collaborative signal processing, solution 2 is not very flexible since it integrates baseband functions into RRHs.
The splits among functions are not only limited to only excluding Layer 1 processing, but in a deeper and more specific function segmentation way inside baseband processing chain. We will discuss the details in the following section, fronthaul solution.
2.2 Fronthaul Solutions
Currently in the deploying C-RAN network, the CPRI (Common Public Radio Interface) or OBSAI (Open Base Station Architecture Initiative) transmission interface is adopted by existing BBUs and RRHs. This is a fixed-rate fronthaul interface based on the TDM (time-division multiplexing) protocol, which transport CPRI/OBSAI streams even without traffic load and thus could not fulfil the efficiency vision of 5G. Also it has very strict requirement for the bandwidth and delay, standing on the way of scalable deployment.

For example, data rate between BBU and RRH using CPRI is as high as 9.83 Gbps for 8-antenna TD-LTE, requiring 4 fibres for each carrier with 6G SFP [5]. More examples of specific date rate requirements show in Table 1 as followed. Other constrains are latency, symmetry, jitters, which come from the need for transport time synchronization [3]. Even though we can use active or passive WDM to save fibre and solve the problem, additional equipment of WDM system is needed to support, increasing the cost very much, which is not a fundamental solution for large-scale RAN deployment.

<table>
<thead>
<tr>
<th>Antenna configuration</th>
<th>10 MHz</th>
<th>20 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2 MIMO</td>
<td>1.2288 Gbps (IP rate 75Mbps)</td>
<td>2.4576 Gbps (IP rate 150Mbps)</td>
</tr>
<tr>
<td>4x2 (4x4) MIMO</td>
<td>2.4576 Gbps (IP rate 150Mbps)</td>
<td>4.9152 Gbps (IP rate 300Mbps)</td>
</tr>
<tr>
<td>8x2 (8x4, 8x8) MIMO</td>
<td>4.9152 Gbps (IP rate 300Mbps)</td>
<td>9.8304 Gbps (IP rate 600Mbps)</td>
</tr>
</tbody>
</table>

Table 1: CPRI data rates in function of radio technologies [8]

![Figure 7. C-RAN Network Segmentation](image)

Figure 7 shows the whole picture of current C-RAN network, and in this section, we will mainly discuss the radio access network part in this thesis work.

In order to solve the challenges mentioned above, the white paper [5] presented by China Mobile set out a vision for “Next Generation Fronthaul Interface.
(NGFI)”, which redefines the functions of baseband units (BBUs) and remote radio heads (RRHs). Some BBU processing functions are shifted to the RRH, which leads to a change in BBU and RRH architecture.

This NGFI Interface needs to fulfill some technical requirements:
(1) Multipoint to multipoint;
(2) Packet based exchange protocol;
(3) Adaptive bandwidth changes responsive to statistical multiplexing and payload;
(4) Optimization of RRHs and BBUs connections.

In this white paper, authors mentioned several different splitting methods, which have introduced different scheme designs. The main part is to move some baseband functions from BBUs to RRHs, which consist of protocol functional layers, including a physical layer, a second layer (MAC, RLC, PDCP sub layer, etc.) and a third layer (e.g. RRC). In different wireless network architectures, these functional layers may be distributed over different physical devices and physical entities. It needs to meet wireless network performance requirements and take into account about pressure on the fronthaul network. It is also necessary to determine how the packaged wireless loads are carried based on the characteristics of each carrier network technology (Ethernet switching, MPLS-TP switching, IP routing, L2/L3 MPLS switching and so on)

The potential functional divisions are showed in Figure 8. The different scheme designs formed by those divisions are showed in Table 2.

What should be noticed is that the Scheme 5 is actually CPRI interface which is currently accepted by most operators who have been developing C-RAN, exposing more and more limits now.

In this white paper, parameters were assumed as follows:
20M LTE carrier waves
2 terminals
8 antennas
Downlink spectrum efficiency: 2 b/s/Hz,
Downlink/Uplink: 64 QAM/16 QAM
Maximum number of users: 100

The bandwidth calculation presented is for cell bandwidth per sector per carrier wave. It does not include synchronization data or Ethernet headers. The additional load created by Ethernet headers will vary depending on the length of the Ethernet packets. In our study we will use bandwidth requirement to choose and select our transport technology so here we only take bandwidth into account.
Figure 8. Potential Functions Division in NGFI [5]

<table>
<thead>
<tr>
<th>Scheme 1</th>
<th>High-Mac and Low-Mac division</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme 2</td>
<td>Division between MAC/PHY</td>
</tr>
<tr>
<td>Scheme 3</td>
<td>Bit-level/Symbol-level Division</td>
</tr>
<tr>
<td>Scheme 4</td>
<td>Bit-level/Symbol-level Division</td>
</tr>
<tr>
<td>Scheme 5</td>
<td>Baseband/RF Division (CPRI)</td>
</tr>
</tbody>
</table>

Table 2: Schemes for different splitting methods
In the Table 3, Ratio indicates the ratio of front-end transmission bandwidth to backhaul bandwidth. The bandwidth of interfaces 1, 2, 3, and 4 is the maximum or peak bandwidth, and the bandwidth of interface 5 is fixed.

<table>
<thead>
<tr>
<th>Schemes</th>
<th>DL bandwidth</th>
<th>Ratio</th>
<th>UL bandwidth</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme 1</td>
<td>174 Mbps</td>
<td>1</td>
<td>99 Mbps</td>
<td>1</td>
</tr>
<tr>
<td>Scheme 2</td>
<td>179.2 Mbps</td>
<td>1</td>
<td>78.6 Mbps</td>
<td>1</td>
</tr>
<tr>
<td>Scheme 3</td>
<td>125.2 Mbps</td>
<td>1</td>
<td>464.8 Mbps</td>
<td>6</td>
</tr>
<tr>
<td>Scheme 4</td>
<td>498 Mbps</td>
<td>3</td>
<td>2,689.2 Mbps</td>
<td>36</td>
</tr>
<tr>
<td>Scheme 5</td>
<td>9,830.4 Mbps</td>
<td>66</td>
<td>9,830.4 Mbps</td>
<td>131</td>
</tr>
</tbody>
</table>

Table 3: Maximum interface bandwidth

The study has shown that current deployment of CPRI has really high demand bandwidth and been the bottleneck of C-RAN building to large scale. Other interfaces might have lower bandwidth requirement but still impose challenges such as transmission delay, jitter, and Synchronization etc.

With many further studies focusing on function splits of baseband functions, more splitting methods have been analysed with their compatibility and practicality. In [6], Small Cell Forum has proposed more specific splits solutions and use fronthaul transport latency and bandwidths requirements as key differentiator for them.

As Figure 9 shows, functions to the left of the split are centralized, while functions to the right reside in the remote hand unit. The use cases are presented from left to right as gradually more centralization of baseband processing. For the MAC and PHY use cases exist where the functionality is divided between the central and remote units, to represent this they are divided into upper and lower components, in these split cases the upper portion resides in the central BBU pool and the lower part in the remote hand sites.

Figure 9. Splits case architectures [6]
The use cases result has been showed in Table 4 with the comparison of bandwidth requirements and transport delay. Calculations are based on the parameters showed as following:

**General parameters:**
1 user per TTI  
20MHz channel bandwidth  
1 carrier component  
UE IP MTU 1500 bytes

**Parameters for Downlink:**
64 QAM  
2x2 MIMO  
100 RBs for data (PDSCH)  
MCS 28  
2 transport blocks of 75376 bits per sub-frame  
CFI = 1  
1 DCI 2a and 1 DCI 0 (PDCCH)  
1 HARQ (PHICH)

**Parameters for Uplink:**
16 QAM  
1x2 SIMO  
96 RBs for data (PUSCH)  
MCS 23  
1 transport block of 48936 bits per sub-frame  
4 RBs for control (PUCCH)  
1 CQI and 1 HARQ received on PUCCH

<table>
<thead>
<tr>
<th>Splits Point</th>
<th>One way latency</th>
<th>DL bandwidth</th>
<th>UL bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRC-PDCP</td>
<td>Non Ideal – 30ms</td>
<td>151Mbps</td>
<td>48Mbps</td>
</tr>
<tr>
<td>PDCP-RLC</td>
<td>Non Ideal – 30ms</td>
<td>151Mbps</td>
<td>48Mbps</td>
</tr>
<tr>
<td>RLC-MAC</td>
<td>Sub Ideal – 6ms</td>
<td>151Mbps</td>
<td>48Mbps</td>
</tr>
<tr>
<td>Split MAC</td>
<td>Sub Ideal – 6ms</td>
<td>151Mbps</td>
<td>49Mbps</td>
</tr>
<tr>
<td>MAC-PHY</td>
<td>Ideal – 250μs</td>
<td>152Mbps</td>
<td>49Mbps</td>
</tr>
<tr>
<td>Split PHY</td>
<td>Ideal – 250μs</td>
<td>1075Mbps</td>
<td>922Mbps</td>
</tr>
<tr>
<td>CPRI</td>
<td>Ideal – 250μs</td>
<td>2457.6Mbps</td>
<td>2457.6Mbps</td>
</tr>
</tbody>
</table>

Table 4: splits case analysis results

For transport bandwidth requirement, the splits beyond physical layer showed very similar results, while for splits in and after physical layer it increased
significantly. Concerning latency part, the splits RLC-MAC, Split MAC, MAC-PHY and Split PHY showed ideal possibility in future deployment.
2.3 Fronthaul Network Technology

One of the biggest barrier for conventional C-RAN where all the BBU functions would be centralized in the central office is that fronthaul bandwidth between RRHs and BBUs would be extremely high, requiring large transport capacity and jeopardizing the advantage of cost saving identity of C-RAN. In addition, the transmission time ideally for the user is limited to less than 4 ms [22], yielding very strict delay requirement for fronthaul network.

![Table 5: Different Fronthaul Technology [26]](image)

Table 5 shows the possible fronthaul technology with their latency, throughput and topology. In this thesis work, we will basically use the capacity requirement calculated in each split, combined with delay requirement (less than 4ms) to determine which fronthaul technology we are going to implement in the architecture. In our assumption for configuration of RRHs in small cells, namely 20-MHz, 2x2 MIMO, 64-QAM, coding rate 1, 100%-time domain and frequency-domain duty-cycling, the largest transport capacity is not bigger than 2.5 Gbps. This fact leads us to the further selection and discussion in the following sections.
2.3.1 Passive Optical Network

Low-cost passive optical network technologies that depend on passive components that do not consume electrical power therefore become the prevalent optical access network technology [10] promoted nowadays. Passive Optical Networks (PONs) recently have been regarded as a feasible transport solution with the advantages of unpowered passive devices and high speed fibre which enables a point to multi-point architecture. Additionally, less than 1ms-delay proves to be very ideal as a fronthaul. In this thesis, we mainly use TWDM-PON (time-wavelength division multiplexing PON) [23] and EPON (Ethernet PON) as our optical fronthaul network in the case architecture discussed.

![Figure 10. 10G-PON transport network](image)

TWDM-PON is a combination of TDM (time-wavelength division multiplexing) PON and WDM technology. WDM system is very expensive and TDM-PON is lacking in bandwidth efficiency, which lead the TWDM-PON solution. As transport network, when ONUs (Optical Network Units) receive traffic from RRHs, ONUs can share the same wavelength and transport data to the OLT (Optical Line Terminal) of PON, every wavelength is served by a line card (LC) (i.e., transceiver) in OLT. In that case, one LC can serve several ONUs in different small cells. Not only to a large degree, extend the capacity of transport network, but also save the energy by sharing LCs. Also it is very easy for operators to upgrade the system capacity by adding new wavelengths into one single fiber.
There are many advantages by using EPON technology. First of all, compared to active optical network, passive optical network cost significantly less than active components. Also, EPON is fully compatible with other Ethernet standards, so no conversion or encapsulation is necessary when connecting to Ethernet-based networks on either end. Since Ethernet is the primary networking technology used in local-area networks (LANs) and now in metro-area networks (MANs), and has been dominant transport technology due to its flexibility, simplicity, and economies of scale that have naturally driven down
its cost compared to alternatives in the marketplace. These same technical capabilities and market dynamics will continue to give EPON a total cost of ownership advantage. There are also OLT (Optical Network Units), splitter and ONU (Optical Network Units) associated in EPON system. However, for EPON, each one can only carry one single wavelength. When in dense small cells scenario, with large traffic to transport, we need multiple EPONs and that can be very expensive.

2.3.2 Millimetre-Wave Wireless Fronthaul Technology

Compared to fibre enabled fronthaul optical network, wireless fronthaul is more cost efficient and flexible. As carrier frequency moves to millimetre-wave (mm-Wave) band range, large bandwidth is available for wireless communication nowadays which can even reach fibre capacity. In 2011, Ericsson demonstrated the world’s first CPRI transmission link over 2.5 Gbps E-band (70/80 GHz) radio link between a LTE BBU and RRH [27].

However, usually for mm-Wave link, the distance between transmitter and receiver is up to 200 meters. While usually for RRHs and BBU pool, the distance can be 20km to 40km. Connecting RRHs and BBU pool through mm-Wave links is not very practical for currently CRAN network architecture. In [28], a Millimetre-Wave fronthaul network has been proposed keep the advantages of both high rate mm-Wave links and cost-efficient C-RAN architecture. A typical mm-Wave fronthaul is deployed in dense urban area, where one aggregating point (AP) is associated with multiple small cell RRHs. As shown in Figure 11, Users’ equipment connects with small cell RRHs and small cell RRHs transmit I/Q traffic to aggregating point over mm-Wave links. A switch is integrated in aggregating point to direct the traffic between BBU and aggregating point. The distance between aggregating point and small cell RRHs are limited to 200 meters so it can satisfy the requirement for mm-Wave communication. While the distance between aggregating points is set for 500 meters. Between aggregating points and BBU in central office, we can use TWDM-PON as midhaul network.

According to [28], the processing time in small cell RRH is around 0.02 to 0.04 ms, processing time in aggregating point is around 0.01 to 0.02 ms and processing fronthaul is 0.01 to 0.02 ms. Local switch processing is around 0.005 to 0.01 ms. In that case, before long distance transmitting, the maximum delay for this wireless fronthaul part is 0.09 ms which is good enough to fulfil the delay requirement.

However, the proposed mm-Wave fronthaul still faces the same problem of high capacity requirement for the midhaul. Even though we can use optical methods, the traffic aggregated in the AP can be very large and impose the pressure on the midhaul transmission.
Figure 13. mm-Wave C-RAN architecture
Chapter 3

Methodology

Figure 14. Model overview

Figure 14 shows the overall methodology overview of models we are using in this project. Three models are developed and they are models of LTE small picocell network, fronthaul network and baseband processing units. The input of three models are baseband splits models, configuration of small cells, and number of small cells. The output of three models are the cost, which is represented by the number of devices, components and fiber, and power, which is represented by the power consumption of RRHs, fronthaul network and baseband processing units.

Based on the input of baseband splits, small cell configurations, and number of small cells, we can calculate the cost and power for small cells, and also the fronthaul bandwidth for fronthaul network. Based on the bandwidth calculation, we choose different fronthaul technology, and in result, we can have the number and power consumption of ONUss, OLTs, switch, fiber and so on. Based on the baseband split methods, we can calculate the power of different baseband functions, and also their overhead power according to their locations.
3.1 Case scenario definition
In this project, we assume an industrial area with many buildings and offices as our case scenario, where most traffic is generated indoor. Users are served by LTE cell-based C-RAN.

To specify the definition, we choose a 1x1 km² Kista area as our case scenario. Kista is located in northern part of Stockholm, Sweden, occupied with many ICT companies and research centers. According to [9], there are around 20 to 50 base station sites per km² in the industrial area of Stockholm. We define the following 1 km² area, shown in figure 10, is served by 32 LTE small cells, which are located at rooftop of buildings. The configuration of RRH is 20-MHz, 2x2 MIMO, 64-QAM, coding rate 1, 100%-time domain and frequency-domain duty-cycling.

![Figure 15. 1 km² case scenario area in Kista, Stockholm](image)

In the architectures we discuss in this scenario, baseband processing functions can either be placed at small cells, or the BBU pool in central office. We assume all the equipment and systems are working at full load and the transport distance is less than 40 km to satisfy the requirement for delay [2].

3.2 C-RAN architectures under different splitting solutions
In this section, we will define the splits that used as our case architectures and discuss each architecture in detail
Figure 3 presents the baseband processing chain, and four possible different function splits.

**Split 1:** The RRH includes only time-domain RF while the BBU includes all other functions. This is the standard split considered in C-RAN, conventional C-RAN. Consequently, the transport network is in charge of carrying the digitalized time-domain I/Q data generated by RRHs, using standard protocols such as CPRI.

**Split 2:** The FFT function is included in RRH, transforming samples from the time to the frequency domain. As a result, the transport network is in charge of carrying the frequency-domain I/Q data.

**Split 3:** Channel estimation based on control and data reference signal (RS) symbols is performed and the estimation result is then applied for equalization at RRH. Afterwards, it applies IDFT and demodulation outputs the log-likelihood ratio (LLR) of each bit to BBU through transport network [11].

**Split 4:** The RRHs will take all Layer 1 functions in baseband processing, further performing bit-rate processing, including de-scrambling, de-rate matching, channel decoding and CRC check. The BBU will receive whole transport block in bits for higher layer processing.

In order to differentiate the concept of BBU and the sub-components after we split the BBU functions, in this project, we call the function sub-components Processing Units (PU). To simplify, each PU can represent a baseband function. The relation between BBU and PU can be illustrated as Figure 16. Under this assumption, when we choose different splitting solution, we can simply consider moving different PUs to small cell.

![Figure 16. Relation between BBU and PU](image)

According to [12] split that goes beyond split 4 to higher layer is not very meaningful, since very little benefits from centralization would remain. Different splits would cause different bandwidth requirement on the transport network part, which could be translated to different levels of power
consumption. In next section, we will discuss about bandwidth calculation models in order to get the transmission bandwidth requirements for different split architectures under our case scenario.

### 3.3 Bandwidth Calculation Models

Because usually downlink bandwidth is more than uplink, thus we choose downlink bandwidth requirement as the basis of defining transport network capacity. The basic description of the chosen scenario is 1 user per Transmission Time Interval (TTI) with 150Mbps Downlink, since this is the only possible method to achieve maximum throughput in the field, as more users per TTI are implemented the overall throughput quickly decreases [6].

#### 3.3.1 Split 1 C-RAN Model

M1 is the conventional C-RAN architecture where all the baseband functions are located at BBU pool. According to [6], corresponding fronthaul transport bandwidth can be denoted as:

\[
C_1 = f_s \times N_{Ant} \times N_{CPRI} \times \frac{10}{8}
\]

Where \(f_s\) is the sampling rate, \(N_{Ant}\) is the number of antennas.

#### 3.3.2 Split 2 C-RAN Model

M2 puts the split inside the physical layer and its front-haul bandwidth can be denoted as [6]:

\[
C_2 = \frac{N_{RB}^{RB} \times N_{RB} \times N_{Ant} \times N_{IQ} \times 1000}{1000000}
\]

Where \(N_{RB}\) is number of resource blocks per user, \(N_{RB}^{RB}\) is the number of subcarriers per resource block, and \(N_{Ant}\) is number of antennas.

#### 3.3.3 Split 3 C-RAN Model

In M3 more physical layer functions have been placed at RRHs, and its front-haul bandwidth can be denoted as [6]:

\[
C_3 = \frac{(N_{UE} \times PDSCH_{RES} \times Qm_{PDSCH} \times Layers_{DL} + (PCFICH_{RES} \times Qm_{PCFICH}) + (PHICH_{RES} + PDCCH_{RES} \times Qm_{PDCCH})) \times 1000}{1000000}
\]

Where \(N_{UE}\) is the number of user equipment per TTI. PDSCH presents Physical Downlink Shared Channel and \(PDSCH_{RES}\) means number of PDSCH Resource Element per UE. 16 QAM modulation used for PUSCH. PCFICH means Physical Control Format Indicator channel, one of the physical control channel in LTE.
PCFICH<sub>Res</sub> represents number of PCFICH Resource Element per UE. QPSK modulation used for PCFICH. PDCCH means Physical Downlink Control Channel and QPSK modulation used for PDCCH. Layers<sub>DL</sub> is the number of Downlink layers. PHICH stands for Physical Channel Hybrid-ARQ Indicator Channel.

### 3.3.4 Split 4 C-RAN Model

All Layer 1 physical functions would be performed at RRHs, thus transport network would carry the user data as IP datagrams, with relevant lower layer headers added as appropriate. The front-haul bandwidth can be denoted as [6]:

\[
c_4 = \frac{IP_{TTI}^{DL} \times (IP_{pkt} + Hdr_{PDCP} + Hdr_{RLC} + Hdr_{MAC}) \times N_{DL}^{TBS} \times 8 \times 1000}{1000000} + FAPI_{DL}
\]

Where \(Hdr_{RLC}\) is PDCP header in bytes, \(Hdr_{RLC}\) is the RLC header in bytes and \(Hdr_{MAC}\) is the MAC header in bytes, \(IP_{pkt}\) is the IP packet size in bytes, \(IP_{TTI}^{DL}\) is the number of IP packets per transport block, \(N_{DL}^{TBS}\) is the downlink transport block number per TTI and \(FAPI_{DL}\) means downlink FAPI overhead per UE in Mbps. All the parameters involved in our calculation are set as shown in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_s)</td>
<td>30.72 Mbps</td>
</tr>
<tr>
<td>(N_{Ant})</td>
<td>2</td>
</tr>
<tr>
<td>(N_{CPR1})</td>
<td>32</td>
</tr>
<tr>
<td>(N_{SC})</td>
<td>12</td>
</tr>
<tr>
<td>(N_{RB})</td>
<td>100</td>
</tr>
<tr>
<td>(N_{IQ})</td>
<td>32</td>
</tr>
<tr>
<td>(N_{UE})</td>
<td>1</td>
</tr>
<tr>
<td>PDSCH&lt;sub&gt;RES&lt;/sub&gt;</td>
<td>14400</td>
</tr>
<tr>
<td>(Qm_{PDCSCH})</td>
<td>6</td>
</tr>
<tr>
<td>Layers&lt;sub&gt;DL&lt;/sub&gt;</td>
<td>2</td>
</tr>
<tr>
<td>PCFICH&lt;sub&gt;RES&lt;/sub&gt;</td>
<td>16</td>
</tr>
<tr>
<td>(Qm_{PCFICH})</td>
<td>2</td>
</tr>
<tr>
<td>PHICH&lt;sub&gt;RES&lt;/sub&gt;</td>
<td>12</td>
</tr>
<tr>
<td>PDCCH&lt;sub&gt;RES&lt;/sub&gt;</td>
<td>144</td>
</tr>
<tr>
<td>(Qm_{PDCCH})</td>
<td>2</td>
</tr>
<tr>
<td>(IP_{TTI}^{DL})</td>
<td>6,244</td>
</tr>
<tr>
<td>(IP_{pkt})</td>
<td>1500</td>
</tr>
<tr>
<td>(Hdr_{PDCP})</td>
<td>2</td>
</tr>
<tr>
<td>(Hdr_{RLC})</td>
<td>5</td>
</tr>
<tr>
<td>(Hdr_{MAC})</td>
<td>2</td>
</tr>
<tr>
<td>(N_{DL}^{TBS})</td>
<td>2</td>
</tr>
<tr>
<td>(FAPI_{DL})</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 6: Parameters and values for bandwidth calculations
3.4 Power Consumption Calculation Models

In the traditional C-RAN network, power model includes three parts, i.e., RRHs, BBUs processing and overhead power such as power systems and cooling, and fronthaul network. In our model, RRHs and BBUs power consumption are still existing in C-RAN architecture as RRHs remain almost the same and BBU processing power consumption is depending on the splitting solution. As for the overhead power consumption for cooling and supporting BBU processing in small cells, only in fully centralized case can they be neglected. When we move part of processing functions to small cell, overhead power is needed. We will discuss each model specifically with its splitting solution regarding how the power consumption is influenced.

This section explains the power models utilized for the four different-splitting C-RAN architectures. The power model breakdown is shown as Figure 17. First we discuss the methodology for calculating the power consumption of each network part, namely RRHs, PUs, and fronthaul network. The power consumption for PUs has been divided into two parts. PU_CO presents the PUs which are placed in central office, and PU_SC presents the PUs which are placed at small cells. The total power consumption is the sum of power consumed by RRH, PU, and fronthaul network, which consists of optical equipment and switching.

![Figure 17. General power model breakdown](image)
3.4.1 RRHs

For the power consumption of RRHs, which consists of a power amplifier (PA) and a radio frequency (RF) small-signal transceiver module. According to [13], the power consumption can be denoted as:

\[ P_{\text{RRH}} = N_{\text{Ant}} \times (P_{\text{RF}} + P_{\text{PA}}) \]

Where \( P_{\text{RF}} \) and \( P_{\text{PA}} \) are the power consumption of RF and PA in a RRH, \( N_{\text{Ant}} \) is the number of antennas employed.

However in mm-Wave fronthaul case, the power consumption for small RRHs have been given in [29], where 2 antenna-MIMO system is adopted, same configuration as our assumption.

3.4.2 PUs

We already know power consumption for one BBU, used in case LTE small cell. However, when splitting the processing functions into two locations, it is important to know how the power is consumed in each part.

So here we introduce a concept named complexity figures (GOPS or Giga Operations Per Second) that can be translated into power figures depending on the intrinsic efficiency of the selected technology (GOPS/W). This method has been proposed in [18] to present a framework about how to calculate a LTE base station’s power consumption flexibly. Although this is a crude approximation, this is the only one compatible with the simplicity and flexibility of the model presented in that paper. The power numbers obtained from this estimation have been benchmarked to actual values in existing base stations in order to validate the approach and ensure meaningful results [18].

Basically speaking, the BBU components have been divided into several sub-components, when each sub-component represents one specific function of BBU. Different sub-components have different GOPS to show their variety in power consumption. [18] has given a reference LTE Base station power, which we can use to calculate power consumption of any LTE BSs BBU and their sub-components.

Table 7 shows the GOPS of each sub-component for a LTE small cell.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Downlink GOPS</th>
<th>Uplink GOPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter</td>
<td>120</td>
<td>160</td>
</tr>
<tr>
<td>OFDM</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>FD (linear)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>FD (non-linear)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>FEC</td>
<td>20</td>
<td>120</td>
</tr>
<tr>
<td>CPU</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 7. Complexity of baseband functions in BS
The baseband processing complexity is split into a number of sub-components:

- Filter: up/down-sampling and filtering
- OFDM: FFT and OFDM-specific processing
- FD: Frequency-Domain processing (mapping/de-mapping, MIMO equalization); it is split into two parts, scaling linearly and non-linearly with the number of antennas
- FEC: Forward Error Correction
- CPU: platform control processor

The baseband processing is modelled based on estimated complexity in GOPS, multiplied by a technology-dependent factor expressing the number of operations that can be performed per second and per Watt. This factor is 40 GOPS/W for the reference case. The power consumption of BBU can be denoted as the sum of the power consumption of all functions in the table above. According to the power value of reference LTE configuration and method to change value for any configurations in [18], we can get the power for our LTE BBU sub-components, namely PUs in our definition, shown in Table 8.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Downlink power</th>
<th>Uplink power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter</td>
<td>6 W</td>
<td>8 W</td>
</tr>
<tr>
<td>OFDM</td>
<td>3.5 W</td>
<td>4 W</td>
</tr>
<tr>
<td>FD (linear)</td>
<td>1 W</td>
<td>2 W</td>
</tr>
<tr>
<td>FD (non-linear)</td>
<td>13.5 W</td>
<td>21.5 W</td>
</tr>
<tr>
<td>FEC</td>
<td>1 W</td>
<td>6 W</td>
</tr>
<tr>
<td>CPU</td>
<td>1.5 W</td>
<td>1.5 W</td>
</tr>
</tbody>
</table>

Table 8. Power consumption of baseband functions in BS

However, when we consider processing power, we need to take the housing power into account which is not used directly related to processing but this part of the consumption cannot be neglected.

In order to make our models less complicated, we introduce another concept PUE (Power Usefulness Effectiveness), which has been widely used for determining the power efficiency of data centres [32]. The definition of PUE shows as following:

\[
PUE = \frac{\text{Total Power}}{\text{Power used by IT}}
\]

We can tell from the formula, when the PUE is small, meaning the power usage is more efficient. On average, the PUE of datacentres in Europe is 2. In our models, the value of PUE is different from location to location. There will only be three locations that PUs would be placed: small cells, aggregating points and central office. For example, because of the resource sharing and virtualization technology and so on, central office would have very low PUE, i.e. 1.12, as Google Data Centres [31]. Aggregating points would have average value, i.e. 2,
and for small cell, which is considered to be the least energy efficient, the PUE would be set as 2.5.

In our model, we will integrate this overhead power into PU power consumption, which can be denoted as:

\[
\begin{align*}
    P_{PU,SC} &= P_{Units} \times PUE_{SC} \\
    P_{PU,AP} &= P_{Units} \times PUE_{AP} \\
    P_{PU,CO} &= P_{Units} \times PUE_{CO}
\end{align*}
\]

Here, \( P_{PU,SC} \) presents the power consumption of PUs in small cell, and \( PUE_{SC} \) is the corresponding PUE value; \( P_{PU,AP} \) presents the power consumption of PUs in aggregating point, and \( PUE_{AP} \) is the corresponding PUE value; \( P_{PU,CO} \) presents the power consumption of PUs in central office, and \( PUE_{CO} \) is the corresponding PUE value. \( P_{Units} \) in all cases means the power consumption of functions processing at that location.
3.4.3 Transport Network

There are three transport technology we are using as our fronthaul network, namely TWDM-PON, EPON, and millimetre wave fronthaul network (mm-Wave). In this section, we discuss power models for three of them separately.

**TWDM-PON**

According to the energy model for Passive Optical Network in [24], the whole network which utilize TWDM-PON can be illustrated as Figure 14. Each site is using one ONU. With the help of splitter, multiple ONUs are connected with OLT through fibres. Several ONUs can share a same wavelength to transfer traffic, due to the high capacity of 10G wavelength channel. At OLT site, after combining through a wavelength division multiplexer, every wavelength is served by one Line Card. In Figure 18, same colour of ONUs and LC mean they are working with one specific wavelength traffic. After processing in LCs, traffic is navigated to an internal switch which transfer traffic to each BBU port for further processing. Compared to TWDM-PON, EPON cannot share wavelength for different ONUs, and each PON have only one wavelength and cannot transfer much traffic for one single link. To put it another way, TWDM-PON can help to save fibres and number of active OLTs using.

![Figure 18. TWDM-PON enabled C-RAN](image)

For TWDM-PON scenario, the power consumption of transport network can be denoted as:

\[
P_{TWDM-PON,FH} = N_{ONU} \cdot P_{ONU} + N_{LC} \cdot P_{LC} + m \cdot P_{Switch,P} + P_{Switch,baseline}
\]
Here, \( N_{ONU} \) denotes the number of ONUs in the whole fronthaul network, \( N_{LC} \) denotes number of active LCs, and \( m \) means the number of switching ports are using, and \( P_{ONU}, P_{LC}, P_{Switch,p} \) are the power consumption of each one component, respectively. \( P_{Switch,baseline} \) is the baseline power consumption of internal switch in central office.

In our case, we will employ a typical 10G-PON in our calculations, so as EPON we will discuss next. The maximum traffic one wavelength can handle is 10 Gbps, so as each line card. The number of ONUs, LCs and switching ports are depending on transport capacity requirements of different models.

**EPON**

Transport network adapting EPON technology has been demonstrated in [15], combining which with our deploying scenario, and we can get following Figure 19. Each link can only carry one wavelength and this means we need multiple EPON and fibre links between central office and small cells.

![EPON enabled C-RAN](image)

**Figure 19. EPON enabled C-RAN**

For EPON scenario, the power consumption of transport network can be denoted as:

\[
P_{EPON,FH} = N_{ONU} \cdot P_{ONU} + N_{OLT} \cdot P_{OLT} + m \cdot P_{Switch,p} + P_{Switch,baseline}
\]

Here, \( N_{ONU} \) denotes the number of ONUs in the whole fronthaul network, \( N_{OLT} \) denotes number of active OLTs, and \( m \) gives the number of switching ports used, and \( P_{ONU}, P_{OLT}, P_{Switch,p} \) are the power consumptions of each one component.
component, respectively. $P_{\text{Switch \_baseline}}$ is the baseline power consumption of internal switch in central office.

**mm-Wave Fronthaul**

For mm-Wave fronthaul, the fronthaul network usually can be divided in two parts, the wireless connection over mm-Wave links between small cell RRHs and aggregating points, and links between aggregating points (APs) and central office (midhaul). For midhaul we choose TWDM-PON in our discussion. We can consider the APs here as a gateway, collecting signals from all the small cells associated with it. Also in order to solve the capacity limitation on midhaul, baseband function splitting happens in APs. Here all the mm-Wave small cell RRHs also have 2 antennas, with bandwidth in 80 Ghz.

![Diagram](Image)

**Figure 20. mm-Wave enabled C-RAN**

For mm-Wave scenario, the power consumption of transport network can be denoted as:

$$P_{\text{HetNet} \_FH} = N_{\text{ONU}} \cdot P_{\text{ONU}} + N_{\text{LC}} \cdot P_{\text{LC}} + m \cdot P_{\text{Switch\_P}} + P_{\text{Switch\_baseline}} + n \cdot P_{\text{Local\_Switch}}$$

Here, $N_{\text{ONU}}$ denotes the number of ONUs in the whole fronthaul network, $N_{\text{LC}}$ denotes number of active LCs, and $m$ gives the number of switching ports used, and $P_{\text{ONU}}, P_{\text{LC}}, P_{\text{Switch\_P}}$ are the power consumption of each one component, respectively. $P_{\text{Switch\_baseline}}$ is the baseline power consumption of internal switch in central office. $P_{\text{Local\_Switch}}$ is the power consumption of local switch associated with macro cell and $n$ is the number of them.
3.5 Summary

To sum up, there are three types of C-RAN under discussion, which are TWDM-PON C-RAN, EPON C-RAN and mm-Wave C-RAN. In each type, we calculate the power consumption of C-RAN under different splitting solutions in BBU. The total power consumption is made of three parts. First, the power consumption of RRHs at small cells. Then, the baseband processing power which is divided into the power consumed at small cells and central office, when baseband functions split. What should be noticed is that overhead power for supporting baseband processing is also included in this part. The last part is fronthaul network which consists of the internal switching and optical terminals power consumption. Particularly for mm-Wave fronthaul, calculation also includes the power of local switching. In order to see their energy performance equally and quantitatively, the number of base stations, and their parameters are fixed. We assume they are at full load.

To sum up, we have 2 variables here: three fronthaul technology, and four splitting solutions. This give us 12 architectures in total. We will compare those architectures in terms of bandwidth requirement, namely how many fibre and optical equipment needed, and their power consumption. This comparison gives operators an idea, regarding the cost to deploy them (CAPEX) and power cost after deployment (OPEX).
Chapter 4

Numerical Results

In this section, we discuss the calculation results regarding the bandwidth requirements and power consumption of each case architectures.

<table>
<thead>
<tr>
<th>Architecture Model</th>
<th>Bandwidth requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split 1</td>
<td>2.4 Gbps=2457.6 Mbps</td>
</tr>
<tr>
<td>Split 2</td>
<td>1.05 Gbps=1075 Mbps</td>
</tr>
<tr>
<td>Split 3</td>
<td>173.2 Mbps</td>
</tr>
<tr>
<td>Split 4</td>
<td>152.2 Mbps</td>
</tr>
</tbody>
</table>

Table 9: Fronthaul capacity requirement

Table 9 presents the transport bandwidth requirement for one LTE base station in each splitting model discussed in chapter 3. Compared to Model 1, Model 2, Model 3 and Model 4 have reduced very large amount of transport data by leaving layer 1 functions in small cells. When more physical processing functions stay in small cells, less bandwidth is required for transmission.

According to Table 5, all bandwidth requirements above can be covered by passive optical networks (PONs) as well as mm-Wave fronthaul, which means our architectures for transport network is suitable under our scenario definition.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Value</th>
<th>Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption of RF</td>
<td>$P_{RF}$</td>
<td>0.8W</td>
<td>[18]</td>
</tr>
<tr>
<td>Power consumption of PA</td>
<td>$P_{PA}$</td>
<td>16.5W</td>
<td>[18]</td>
</tr>
<tr>
<td>Power consumption of BBU</td>
<td>$P_{BBU}$</td>
<td>35W</td>
<td>[18]</td>
</tr>
<tr>
<td>Power consumption per port of Switch</td>
<td>$P_{SP}$</td>
<td>15W</td>
<td>[24]</td>
</tr>
<tr>
<td>Baseline power consumption of Switch</td>
<td>$P_{S, baseline}$</td>
<td>50 W</td>
<td>[24]</td>
</tr>
<tr>
<td>Power consumption of ONU</td>
<td>$P_{ONU}$</td>
<td>10.5W</td>
<td>[15]</td>
</tr>
<tr>
<td>Power consumption of LC</td>
<td>$P_{LC}$</td>
<td>5W</td>
<td>[24]</td>
</tr>
<tr>
<td>Power consumption of OLT</td>
<td>$P_{OLT}$</td>
<td>84W</td>
<td>[15]</td>
</tr>
<tr>
<td>Power consumption of mm-Wave receiver</td>
<td>$P_{mmw, receiver}$</td>
<td>181 mW</td>
<td>[29]</td>
</tr>
<tr>
<td>Power consumption of mm-Wave transmitter</td>
<td>$P_{mmw, transmitter}$</td>
<td>145 mW</td>
<td>[29]</td>
</tr>
<tr>
<td>Power consumption of local switch</td>
<td>$P_{Local,Switch}$</td>
<td>50W</td>
<td>[15]</td>
</tr>
</tbody>
</table>

Table 10: Power model parameters
Table 10 shows the parameter we use to calculate and their resources.

<table>
<thead>
<tr>
<th>Split 1</th>
<th>Split 2</th>
<th>Split 3</th>
<th>Split 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONU</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Splitter</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fibre links</td>
<td>33</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>LC</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Switch port</td>
<td>16</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 11: Number of equipment in TWDM-PON enabled C-RAN

<table>
<thead>
<tr>
<th>Split 1</th>
<th>Split 2</th>
<th>Split 3</th>
<th>Split 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONU</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Splitter</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Fibre link</td>
<td>40</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>OLT</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Switch port</td>
<td>16</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 12: Number of equipment in EPON enabled C-RAN

<table>
<thead>
<tr>
<th>Split 1</th>
<th>Split 2</th>
<th>Split 3</th>
<th>Split 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONU</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Local switch</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Splitter</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fibre link</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>LC</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Switch port</td>
<td>16</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 13: Number of equipment in mm-Wave enabled C-RAN

Table 11, 12 and 13 present the number of equipment needed for the three types of C-RAN we discussed. The numbers above are calculated according to the capacity requirement calculated by each splitting models. Those number present the cost of each architecture model.

For PON-enabled C-RAN, each ONU is associated with one small cell so the number of ONUs are fixed as 32. The number of splitters in 10G-EPON are decided by the capacity requirement for each BS. For example, when the capacity requirement is 2.4 Gbps, namely CPRI bandwidth, one splitter can gather traffic from 4 BSs, total 9.6 Gbps. In that case we need 8 splitters, and also 8 fibre links. With the help of TWDM-PON, we can see, under the same circumstance that the fibre link and splitter can be saved to a very large degree, only 1 fibre needed with 8 wavelength transmitting together.

For mm-Wave fronthaul, in our defined case, we need 4 aggregating points (APs) to connect 32 small cells, which communicate with central office. Each AP is associated with one ONU with multiple transceivers since the traffic aggregated here can be very large.
The number comparison of fiber links are shown in Figure 21. Compared to PON fronthaul, mm-Wave fronthaul saved large amount of fiber links because of the wireless connection in the first part transmission. The fiber links only connect central office with aggregation points (AP). Regarding EPON and TWDM-PON fronthaul, there is no significant difference between them since each ONU at small cell has to be connected with fiber, which is the same for both FH. The difference comes from the multiplexing to central office, where TWDM-PON can share a single fiber with different wavelengths.

As presented in Figure 22, the power consumption of all fronthaul technology is decreasing when more PUs move to small cell, which lead to lower transport
bandwidth requirements. Among all four split models, mm-Wave fronthaul shows the lowest power consumption. This is due to the fact that mm-Wave fronthaul uses less amount of ONUs, which saves much power consumption.

The advantage of TWDM-PON, compared to EPON, is more noticeable in split model 1, when fronthaul traffic is large, which is almost half of the latter. As transport capacity increasing, EPON fronthaul has to add multiple EPON system while TWDM-PON only needs to add more wavelengths into the fiber. With more processing functions moving to small cells, the transport capacity requirement become less, so as the number of EPONs needed. When total capacity is less than 10G, there is no difference of the physical setting between EPON and TWDM-PON, so the power consumption is the same in split model 3 and 4.

Considering mm-Wave CRAN is using TWDM-PON as midhaul, so the pattern shows similar tendency to TWDM-PON but less power consumption.

![Figure 23. Processing Units Consumption in Each Architecture](image)

With more processing units move to small cell, the total power consumption of PU is increasing, shown in Figure 23. Also here mm-Wave CRAN shows the least power consumption considering less power-efficient small cells don't have any processing units at all and splitting happens in aggregating point, with better PUE. In two PON-based CRANs, split model 4 almost consume similar amount of power as DRAN. Because we keep layer 2 and beyond functions at central site but move all the layer 1 processing functions to small cell, which are the most power-consuming parts of a base station. This indicates that functional splits beyond layer 1 cannot achieve meaningful power saving compared to DRAN.
We take a detailed breakdown of power consumption of PUs, which consist of functions at Central Office (CO) and functions at Small Cell (SC) of EPON-based CRAN. The PU consumption at CO is decreasing when more PUs are moved to small cells. While at the same time, PU power consumption at small cells increases considerably, leading to similar power consumption of DRAN in model 4.

The total power consumption includes the power consumed by RRH, Processing Units and Fronthaul Network. The total power consumption are
increasing when more PUs are moved to small cells. However, EPON-CRAN achieves the lowest power consumption in Model 2. This is because when all PUs are placed at central office, fronthaul network needs to provide huge amount of bandwidth to transport traffic without baseband processing, and this incurs high power consumption of fronthaul network, which counteracts the power saving of centralizing PUs. So there exists a trade-off between the power consumption of fronthaul and PUs. Model 3 and 4 consume even higher power than DRAN, so they are not suitable functional splits for saving power. This is because we assume the additional power consumption from central office and fronthaul for CRAN, which are not considered in DRAN. But mm-Wave CRAN achieves lower power consumption than DRAN in all split models.

The mm-Wave CRAN shows the most power efficient architecture in our study. Figure 26 presents its power breakdown into power consumed by RRH, PU and fronthaul (FH). The RRH power is the same for four split models. When more PUs move to small cell, the PU power increases a lot. Even with the reduction of transport power, the total amount of power consumption is still increasing.

![Figure 26. Total Power Breakdown for mm-Wave C-RAN](image-url)

Figure 26. Total Power Breakdown for mm-Wave C-RAN
Chapter 5

Conclusion

In this thesis work, we present four C-RAN split models with different fronthaul network. We present the model in the real case scenario, with the fixed number of LTE small cells and UE per TTI, and assume that all RRHs are active. For each model, we calculate the transport capacity requirement per small cell and the mobile network power consumption, including the RRHs, baseband processing, fronthaul network and total mobile network.

The numerical results showed that when more baseband functions are centralized in central office, the less power consumption is needed. At the same time, we came to a conclusion that split 1 become less practical, as a result of high capacity transport network required to be implemented and huge cost of power consumption is driven in turn. Even TWDM PON and mm-Wave fronthaul show considerable reduction in transport power, the cost of implementing TWDM system can be very expensive to deploy. Split 2, 3 and 4 separate some baseband functions with RRHs at the small cells. Split 2 can not only reduce the transport capacity requirement significantly but also keep a certain level of centralization advantage in power savings. While split 3 and 4 show much more power consumption, which is even comparable to DRAN.

With the introduction of mm-Wave fronthaul, the cost and power consumption has been reduced a lot as a result of much less fiber and ONUs used in mm-Wave. Additionally, small cells placement and upgrade is very flexible and convenient in mm-Wave with its wireless identity, so the mm-Wave fronthaul is most promising fronthaul solution in our study.

In the future work, we can explore more splitting methods inside Layer 1 baseband processing functions (such as Split 2) and their corresponding interface standards like CPRI. For optical transport network, by comparing the energy consumed in EPON and TWDM-PON, and also taking the deployment cost into account, TWDM-PON is more suitable for larger density of base stations to save energy compare to EPON. As the network expanding further in next decade, mm-Wave fronthaul have great advantage in flexibility and efficiency of C-RAN deployment. However, one limitation of our study is that the power efficiency advantage for mm-Wave C-RAN is highly technology dependent, which means low power mm-Wave system is a crucial part in our calculation. Higher power consumption of mm-Wave system might result in different conclusion for power comparison but still mm-Wave can save large amount of fiber links.
References


[15] Zhongwei Tan, Chuanchuan Yang, Jingjing Song, Yu Liu, and Ziyu Wang, “Energy consumption analysis of C-RAN architecture based on 10G EPON front-haul with daily user behaviour,” 14th International Conference on Optical Communications and Networks (ICOCN) @ Nanjing, China, 2015.


