Planning a C-RAN Deployment for the Next Generation Cellular Networks

by

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Dedicated to

my father, mother, wife, daughter,

son, brothers, sisters and friends.

Declaration

I declare that this thesis is my own work and is submitted for the first time to the Post-Graduate Research Office. The study was originated, composed and reviewed by myself and my supervisors in the Department of Electronic and Computer Engineering, College of Engineering, Design and Physical Sciences, Brunel University London UK. All the information derived from other works has been properly referenced and acknowledged.

SIGNED: .... DATE: ....

by

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Abstract

Over the next decade, it is expected that demand for high data rates will increase dramatically by increasing the connection of smart devices and the introduction of new applications and services. This will lead to increase the complexity of the management and operation of current network. Therefore, Cloud Radio Access Network (C-RAN) architecture has been innovated as one of the Fifth Generation (5G) solutions to simplify the management and control of the future mobile network. This thesis is focused on power consumption model and analysis, saving energy and load balancing in C-RAN. Moreover, this thesis is introduced an approach to solve the network planning issue of the next generation of the cellular network.

A new power consumption model for C-RAN architecture is proposed based on the virtualisation of a Base Band Unit (BBU). A parametrised and minimised linear power model is provided, which covers the individual aspects in a C-RAN system that are relevant to power consumption. Moreover, in this work, an Orchestra Server (OS) is proposed in the BBU pool that hosts an intelligent algorithm to optimise the configuration of the BBUs to the proper Remote Radio Heads (RRHs) in varying traffic load. The scheme is based on the New Minimum Bin Slack (NMBS) algorithm, which aims to find a set of users that fits into the BBU capacity, with load balancing among them as much as possible.

Moreover, a technique is proposed for the network deployment problem which aims to satisfy C-RAN planning by optimizing placement and minimum required number of the BBU pool in the network. The Quasi-Newton Method (QNM) algorithm is proposed to find the optimal BBU pool location in the proposed network. Minimum required number of the BBU pool for the proposed network is determined with respect to the fronthaul size limitations. The Particle Swarm Optimization (PSO) algorithm has been applied for the proposed network to group the RRHs into multiple sub-networks with fair RRHs distributions. Moreover, this work is showed the RRHs coverage area is very considerable value in determining the size of fronthual link and BBU pool position.

Furthermore, an approach for allocating existing 4G installed network radio access nodes to multiple BBU pools, which is proposed to deploy 5G C-RAN and improve the offered Network Quality of Service (NQoS). The proposed approach involves performing four sequent algorithms starting with i) radio access node clustering based on the PSO algorithm then, ii) model selection Bayesian Information Criterion (BIC) through iii) a measure of spread technique then ends by, iv) Voronoi tessellation, which is used to consider a Dynamic C-RAN (DC-RAN) operation, that adaptively adjusts the main RRH coverage range according to the traffic load required as well as providing energy saving.

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List of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
ACK	ACKnowledgement
ADC	Analogue to Digital Conversion
AON	Active Optical Network
AQoS	Application Quality of Service
A-RoF	Analog Radio over Fiber
ARPU	Average Revenue Per User
ARQ	Automatic Repeat reQuest
BBU	Base Band Unit
BF	Best Fit
BFD	Best Fit Decreasing
BIC	Bayesian Information Criterion
BLER	BLock Error Rate
BPM	Bin Packing Method
BPP	Bin Packing Problem
BS	Base Station

CAP	Compression After Precoding
CAPEX	CAPital EXpenditure
CBP	Compression Before Precoding
CN	Core Network
CO	Central Office
CoMP	Coordinated MultiPoint
CPRI	Common Public Radio Interface
CPU	Central Processing Unit
C-RAN	Cloud Radio Access Network
CRE	Coverage Range Extension
DAC	Digital to Analogue Conversion
DC	Data Center
DC-RAN	Dynamic Cloud Radio Access Network
DDC	Digital Down Conversion
DeMux	Demultiplexer
DL	Downlink
DL-SCH	Downlink-Shared CHannel
DRA	Dynamic RRH Assignment
D-RoF	Digital Radio over Fiber
DUC	Digital Up Conversion

E2E	End-to-End
EARTH	Energy Aware Radio and Network TecHnologies
EE	Energy-Efficient
eICIC	Inter-Cell Interference Coordination
eNB	ENodeB
EPON	Ethernet Passive Optical Network
ESS	Electronic Smart Switch
FDX	Full DupleX
FEC	forward error correction
FED	Forward Error Detection
FER	Frame Error Rate
FF	First Fit
FFD	First Fit Decreasing
FFT	Fast Fourier Transform
FH	FrontHaul
FHL	FrontHaul Link
FTTC	Fiber To The Cell
FTTH	Fibre To The Home
GA	Genetic Algorithm
GOPS	Giga Operations Per Second
GPS	Global Positioning System
GSM	Global System for Mobile communications

HARQ	Hybrid Automatic Repeat reQuest
HAS	Heuristic Simulated Annealing
H-CRAN	Heterogeneous Cloud Radio Access Network
HetNet	Heterogeneous Network
HetSNets	Heterogeneous and Small Cell Networks
HPN	High Power Node
HPU	HotsPot of Underlay
ILP	Integer Linear Programming
IoT	Internet of Things
KPI	Key Performance Indicator
LC	Line Card
LDB	Link Delay Budget
LNA	Low Noise Amplifier
LPN	Low Power Node
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
MBS	Macro Base Stations
MIMO	Multiple Input Multiple Output
MMC	Massive Machine Communication
MOPTS	Million Operations Per Time-Slot
MS	Mains Supply

NACK	Non-ACKnowledgement
NF	Next Fit
NFD	Next Fit Decreasing
NGN	Next Generation Network
NIC	Network Interface Card
NMBS	New Minim Bin Slack
NMBS	New Minimum Bin Slack
NQoS	Network Quality of Services
NTx	Number of Antenna
OBSAI	Open Base Station Architecture Initiative
OFN	Optical Fiber Network
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPEX	OPerating EXpenditure
OS	Orchestra Server
PA	Power Amplifier
PDU	Packet Data Unit
PON	Passive Optical Network
PSO	Particle Swarm Optimization
PtP	Point to Point
QNM	Quasi- Newton Method
QoE	Quality of Experience

RAT	Radio Access Technology
RB	Resource Block
RF	Radio Frequency
RLC	Radio Link Controller
RN	Remote Node
RoF	Radio over Fibre
RRH	Remote Radio Head
RRU	Remote Radio Unit
RTT	Round Trip Time
SBS	Small Base Station
SCM	Sub-Carrier-Multiplexing
SDR	Software Defined Radio
SDU	Service Data Unit
SE	Spectral Efficiency
SNR	Signal to Noise Ratio
SON	Self-Organizing Network
Stdv	Standard deviation
TB	Transport Blocks
TCO	Total Cost of Ownership
TCP	Transmission Control Protocol
TrCH	Transport CHannels
TTI	Transmission Time Intervals
TWDM	Time-Wavelength Division Multiplexing
Tx	Transmitted

UE	User Equipment
UL-SCH	Shared CHannel
UMTS	Universal Mobile Telecommunications System
vBBU	virtual BBU
vBS	virtual BS
VC-RAN	Virtual C-RAN
VD	Voronoi Diagram
VM	Virtual Machine
WDM	Wavelength Division Multiplexing
WF	Worst Fit
WTL	Wireless Transmission Link

Chapter 1

Introduction

The next evolution of cellular networks is Fifth Generation (5G) system, it will be towards truly connected world. It is always compared to the Fourth Generation (4G) network. The main goal of 5G is to provide an universal connectivity for any application and kind of device that can use from being connected. 5G network is based on different Radio Access Technology (RAT) used to meet the requirements of future cellular networks. Specification and standardization of 5G network is still in progress such as IMT-2020, which will challenge the current network architecture and especially the Radio Access Network (RAN) [1].

For the next few years, it is expected that data traffic demand will increase a thousand-fold by connecting more than 100 billion devices and all need to share and access data, anytime and anywhere. With increase number of connected devices and demand of higher data rate, several challenges appear which face the current network architecture such as impairing in spectrum utilization, energy efficiency, and cost as well as how to handling the increasing number of the connected devices [2]. Therefore, 5G aims to provide system concepts that support [1, 3]:

1. 1000 times increased data volume per area.
2. 10 to 100 times increased number of connected devices.

3. 10 to 100 times increased typical user data rate.
4. 10 times extended battery life for low power Massive Machine Communication (MMC) devices.
5. 5 times reduced End-to-End (E2E) latency.

To contemplate 5G as a future network, multiple access techniques in the network are required and no needed to change in the wireless setup (i.e. channel connection between the Base Stations (BSs) and User Equipments (UEs)) which comes from First Generation (1G) to 4G. Alternatively, there can be addition of some applications at the current network to satisfy user needs. This will affect the providers to set up a 5G as early as 4G networks [4]. To meet the requires of the user and to overcome the obstacles that have been expected in the 5G network, an extreme change in the scheme of designing the 5G network is required.

Cloud Radio Access Network (C-RAN) is a cost-effective architecture that has been proposed as one of the next generation cellular network solutions to reduce power consumption, enhancing network capacity, reduced system complexity and simplify the network management [5]. C-RAN concept has attracted a lot of attention by industries and researchers in term of solving some problems that relat with this architecture to be more reliable with 5G network. C-RAN architecture has a central Data Center (DC) that consists of the number of Base Band Units (BBUs) which are called BBU pool and remote sites, which are called Remote Radio Heads (RRHs) [6], one BBU can run multiple RRHs.

BBU pooling has a great effect for decreasing the power consumption, as a sharing of collateral subsystems into one place. Differently from traditional distribution BSs, which equipment rooms are separated and so far from each other's, hence not power optimized. BBU pool can be adapted from already deployed telecom offices, taking benefit of existent power management and cooling systems [7]. The reduction of energy consumption is achieved by the pooling concept and based on optimization and resource sharing. For example, when the data traffic demand of some RRHs is low, fewer resources can be shared, this will lead to reduce the energy consumption in the system.

The backhaul interface is used as a medium to connect the BBU pool with the mobile core network in the C-RAN architecture. The fronthaul access is one of the considerable parts in C-RAN ecosystem; it potentially supports the adoption of C-RAN architecture. Fronthaul is the transmission link that provides connectivity between the centralised BBU pool and multiple distributed RRHs. It is very important part in this architecture in terms of providing required data to the RRHs. There are two common types of fronthaul which are wireless and wire links; the optical fibre links is candidate to be used in the Next Generation Network (NGN) [91, 21]. It can meet the increasing demands for high data rate.

1.1 Motivation

Recently, the demand of high data rate has been increased dramatically in mobile network by developing the smart devices and spread of mobile broadband internet that presents a unique opportunity for new services. These increasing will be the reason to consume huge amount of power, which lead to various energy efficiency issues. The RAN is important for mobile network to provide high data rate and services to mobile users. The power consumption of the RAN in cellar network is considerable for operators and cellular network company, because it has heavily effects on OPerating EXpenditure (OPEX). Moreover, it has impact on increasing issues that concern the environment. In sometimes, the power bills may exceed the cost of hardware equipments [5, 8].

Furthermore, network planning and deployment has a significant effect on the network capacity, cellular system management, cost and saving energy. The cost-effective way of minimizing the cost is to reduce the number of cells deployment in network. However, this results in poor Quality of Experience (QoE) and Quality of Service (QoS) in the traditional mobile networks deployment. Future cellular network deployments are predicted to be much denser than current network, in order to face the increasing of required data rates.

Furthermore, increasing the density of cell deployments in the network is improving the system Spectral Efficiency (SE). More cells deployment results in different challenges such as an increase in inter-cell interference, and increase in the number of cells equipment. However, power consumption of radio access node in network varies depending on the radio coverage and type of the cells deployment. Installing of macro-cells in network is easy to configure and cheap cost, but applying a power saving technique for this type is difficult. Switch off some cells which are work with low traffic load and decreases their emission power to save energy have considerable effect on the size of the covered area. However, small cells are more energy efficient and easier to manage, but more expensive in total installing and deployment, because they require many equipments for installation and to guarantee the same level of cell coverage. By using small cell deployment in mobile network increases handover, which raises processing and signaling load on system [9].

For this reason, a cost effective scheme for the next generation of the cellular network is required in term of reducing energy consumption, face the increasing of data rate issues and simplify the system management. Therefore, using a heterogeneous C-RAN network deployment for the next generation considers a promising solution, which depends on network and geographical area needs. Moreover, the main advantages of solve C-RAN planning issues are cost, energy saving, increase radio performance, delay and to meet coverage and capacity requirements. Subsequently, this thesis is focused on power consumption model and analysis, saving energy and load balancing in C-RAN. Furthermore, this thesis is introduced an approach for network planning for the next generation of the mobile system.

1.2 Research Challenges

C-RAN architecture provides a reliable interconnection and cooperation among BBUs in the BBU pool, it is based on sharing and scheduling the user data. However, this requires high resilience and security. The interconnection in the BBU pool should support low latency, cost switch network and high bandwidth with flexible interconnecting RRHs to ensure real time cooperative processing. This cooperation in BBU pool capable to save energy in the C-RAN architecture by switching off certain number of BBUs that work with low traffic load and convert their load to others unites.

Energy Aware Radio and Network TecHnologies (EARTH) model of BSs energy consumption [10] has been widely adopted in the previous researches and studies to analyses the energy efficiency and power consumption of cellular systems. However, EARTH model cannot be directly used with next generation of the cellular network (i.e. in the C-RAN architecture that is candidate to use for next generation) for two reasons. Firstly, multiple BBUs exist in one pool, thus the power consumption of BBUs in the pool should be reduced (i.e. switch off BBUs that work with low load and convert their load to others). The second one is a virtualization technology, the BBU computational resources can be dynamically allocated and shared among pool, as well as the BBU application can run when it is needed. However, this model cannot reflect the computational resources variations.

Consequently, a new model for C-RAN architecture based on virtualization technology is required for the cellular network. Therefore, this thesis introduces a new power model for C-RAN based on virtualization as well as linear optimization with special techniques and methods to reduce the power consumption in the proposed system.

In general, network planning and deployment has a significant effect on the network capacity and saving energy. In C-RAN planning, position, and required number of BBU pool, as well as dimension pool area in specific network are significant issues which need be solved. Many parameters required to solve these problems are related to the network deployment such as geographical distribution of RRHs, coverage area of RRHs latency constraints of fronthaul, which increases its complexity and makes the problem difficult to resolve. Moreover, constraints, restrictions and any other requirements must be defined, to guarantee a better network performance in terms of bandwidth speed, transmission delay, reliability, etc.

Although, C-RAN that is proposed by many companies to solve many problems for the next generation cellular network, there are still several issues, such as a managing of traffic load of backhaul. It is expected for the next generation a massive traffic backhaul between BBU pools and Core Network (CN) that needs ultra-high processing capacity for core network. This would result in an increase of CApital EXpenditures (CAPEX) and OPerating EXpenditures (OPEX) when trying to handle the growing signalling overhead.

Moreover, high bandwidth and High cost efficient optical fronthaul has been proposed to use in C-RAN architecture to connect the BBUs by RRHs. However, the major problems with this fronthaul are jitter and latency. The processing delay on a transport network between BBUs and RRHs should be less than 3 ms [11], to meet Hybrid Automatic Repeat reQuest (HARQ) requirements. Due to the HARQ delay, there is a limitation on fronthaul distance between BBU and RRH that should carefully considered this issue in C-RAN design. Therefore, this thesis focuses on fronthaul link restrictions that have a strong effect on C-RAN design in trying to find optimal network configuration.

1.3 Aim and Objectives

The purpose of this thesis to introduce a new power consumption model for the C-RAN architecture, to study and analyses performance, RRH-BBU assignments, load balancing and saving energy of the system. Other aims of this study are to introduce a new approach for the 5G network planning based on heterogeneous dynamic C-RAN. The final output of this approach is to analyses the performance parameters of a C-RAN deployment by optimizing the number, dimensional pool area and BBU pool locations based on minimum fronthaul delay. The following objectives address the research aim;

1. Assessment literature review of C-RAN to understand the network configuration, load balancing, saving energy and network deployment for this architecture.
2. To achieve optimal power consumption for the C-RAN, a unique method or technique to optimise the number of active BBUs. This includes the following sub-objectives:
   - Introducing a new power consumption model for the C-RAN architecture;
   - Introducing optimization algorithm for power consumption in C-RAN by using the Bin Packing Method (BPM);
   - An Orchestra Server (OS) in the BBU pool is proposed to support the C-RAN architecture in terms of energy management and self-organisation by holding the smart algorithms;
   - Reduce the number of active BBUs and achieve load balancing among BBUs in BBU pool.
3. Appling techniques and algorithms for the actual current heterogeneous network to find best locations, optimized number of the BBU pools and connected RRHs to the BBU pools.
4. The Quasi- Newton Method (QNM) algorithm is proposed in this work to estimate the best locations of BBU pools as well as the Particle Swarm Optimization (PSO) used to solve the pooling (clustering concept) problem of network. The position of BBU pool is chosen as a closest location of all RRHs to optimize the latency of the network.
5. Investigate dynamic C-RAN, which adaptively adjusts the main RRHs coverage according to traffic load required in a cellular network.
6. Proposing an approach for allocating the already heterogeneous deployed network radio access nodes to multiple BBU pools to improve the offered Network Quality of Services (NQoS).

1.4 Simulation Methods

The proposed system represents by a mathematical model that uses to introduce and analyse the numerical results. The programming software that chose to build the simulation model is a MATLAB software.

1.5 Thesis Outlines and Contributions

This thesis is organized into six chapters including three main contributions. Each chapter begins with an introduction highlighting the contributions presented in the chapter towards the end of the chapter and a brief conclusion at the end of chapter.

Chapter Two: This chapter introduces a background and overview of C-RAN and describes the evolution of BS architecture in the traditional cellular networks which is essential to this thesis. In addition, the C-RAN is explained in concept in terms of the system principles and the main components in the architecture as well as clarifies types of C-RAN architecture. Moreover, advantages and benefits of virtualization technology of the C-RAN architecture are discussed. Also, this chapter explains some challenges and obstacles of C-RAN deployment. Fronthaul latency requirements and limitations, and clustering techniques in C-RAN are illustrated.

Chapter Three: This chapter proposes a system model and introduces a new power consumption model for C-RAN architecture based on the EARTH model. The main objective of this chapter is to reduce power consumption by switching off the number of BBUs special that works with low traffic demand and convert their load to other BBU units. This model provides the parameters and minimize linear power model which cover the all individual aspects in the C-RAN architecture. This work presents the problem formulation of the system and shows the importance of optimization for reducing power consumption in the system. Moreover, this chapter proposes an OS in the BBU pool that hosts an intelligent algorithm to optimise reconfiguration the BBUs to proper RRHs in a time-varying traffic load. The scheme based on the New Minim Bin Slack (NMBS) algorithm that attempts to find a set of users that fit into BBUs capacity as much as possible with load balancing among them. The simulation results show that the NMBS effectively decreases the number of active BBUs and decrease the power consumption for the C-RAN scheme compared to Best Fit Decreasing (BFD) algorithms and traditional network.

Furthermore, Active Optical Network (AON), Ethernet Passive Optical Network (EPON) and Time and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) are proposed to be used as fronthaul network for the C-RAN. Simulation results have show that TWDM-PON is better than other fronthaul architectures in saving energy by 41% and 7%, when compared to the AON and EPON C-RAN, respectively.

Chapter Four: In this chapter, the planning task of the C-RAN architecture is studied to determine the optimal BBU pool location, and dimension pool area for actual cellular network. A trade-off between fronthaul latency and where to place BBUs is considered carefully. Numerous parameters are considered, which relate to network planning such as a geographical cell distribution, average cells coverage area, and time delay of HARQ. The Quasi-Newton Method (QNM) algorithm is used that satisfies all latency fronthaul constrains to find optimal BBU pool position in the proposed network.

Moreover, this chapter is fund the minim required number of BBU pool in network with respect to the optical fronthaul restrictions. The PSO algorithm is applied on the proposed network to find sub-network configuration with fairness RRHs distribution based on the clustering concept. With the existence of C-RAN, new delay component calculation is added to the fronthaul transmission link. This delay is wireless media delay component between the RRH and UE. This chapter proof the coverage area of RRH which is represented by the wireless delay has a significant effect in determining of maximum optical fibre fronthaul and pool coverage area.

Chapter Five: Heterogeneous Dynamic C-RAN (HDC-RAN) deployment based on a multiple BBU pools approach for 5G Network is adopted in this chapter, new techniques are introduced to optimise the BBU pool number and their position for actual deployed network to improve the offered NQoS. The model takes as input of RRHs positions in the network result as output optimal positions and number of BBU pool in the network based on latency constraints and capacity requirements that represents by number of connections between BBU pool and RRHs to balance the load among BBU pools. Bayesian Information Criterion (BIC) often used as a statistical principle for model selection, so it can be used in solving problem based on number of BBU pools. Conventionally, a correct number of BBU pools can be identified as the local minimum of BIC.
However, in this chapter, the BIC algorithm gives a range of BBU pools that is near to the optimal solution. Therefore, this work is used as statistical analysis to choose optimal pools number for the prosed area network. The PSO algorithm is proposed in this work to estimate the best locations of BBU pools as well as the PSO used to solve the pooling problem of network. The position of BBU pool is chosen as a closest location of all RRHs to optimise the latency of the network. Actual heterogeneous network is used to evaluate these algorithms. Moreover, dynamic C-RAN is proposed in this chapter which based on pooling concept, the purpose of dynamic C-RAN is to balance the traffic load and to reduce the energy consumption.

Chapter Six: Conclusions and future work is provided the summary conclusions of the thesis and presented some suggestions and ideas for future study that were not covered in this thesis.

Chapter 2

Fundamentals and Background

This chapter focuses on background and overview of the Cloud Radio Access Network (C-RAN) architecture as well as what will be the next generation of the mobile network. The evolution of base station architecture of traditional network is discussed. C-RAN architectures classified into three types according to the distribution functions of base band processing unit between Remote Radio Heads (RRHs) and Base Band Unit (BBU) pool, these types have been explained in detail.

Numerous components of C-RAN such as RRH, BBU, and optical fibre fronthaul network are described. In addition, advantages and challenges of C-RAN architecture are discussed. Importance and benefits of virtualization technology for the C-RAN architecture in context of resource sharing and reducing power consumption are illustrated. Moreover, some challenges and obstacles that face mobile operators before commercial deployment are explained. The requirements of the C-RAN deployment are clarified; moreover this chapter presents the maximum fronthaul latency and clustering technique in C-RAN.

2.1 Introduction

In recent years, cellular networks are facing extreme traffic loads because of sharp increasing in connected smart devices (e.g., smart phone, tablet, Internet of Things (IoT) devices, etc.) and the introduction of new applications and services. This increasing is a considerable challenge for the mobile network that will lead to increase the complexity of management and operation of network, as well as high upgrade costs, and slow time-to-market for new innovations and services [12]. With respect to the Cisco VNI Global Mobile Data Traffic Forecast, 2015 - 2020 mobile data transmission volume is continuously rising as shown in Fig. 2.1 [13]. Where 1 Exabyte= 1018 bytes.

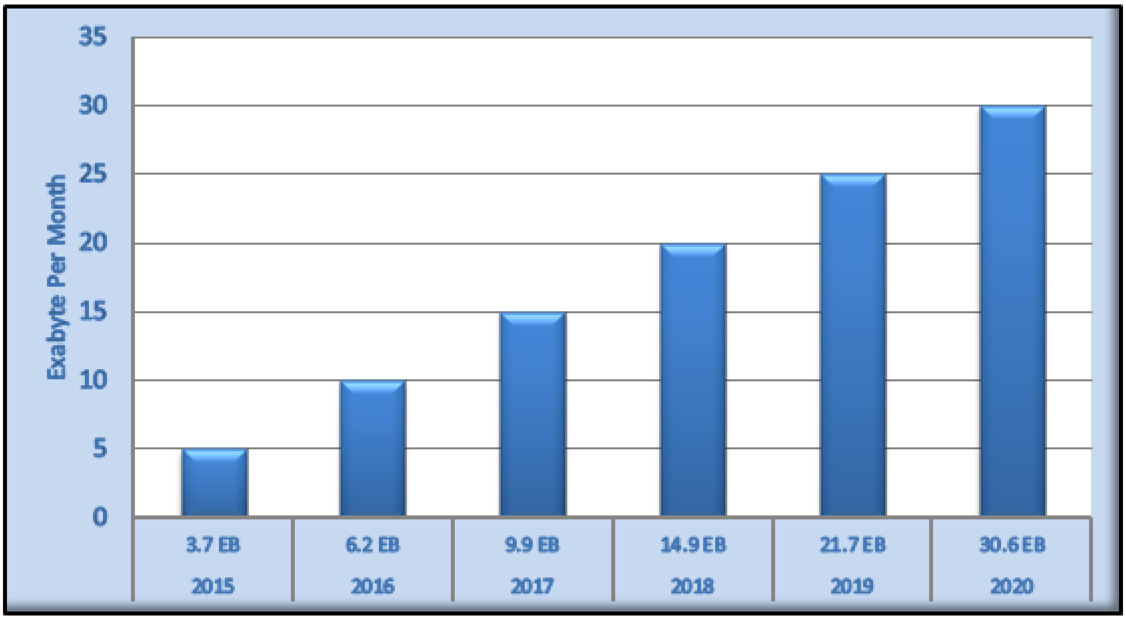


Fig. 2.1 Global mobile data traffic growth from 2015-2020

[12]

Therefore, the cellular companies should increase the network capacity to meet the demand of growing user data rate. Furthermore, Long Term Evolution (LTE) is used as an approache to increase network capacity by either, creating a complex structure of Heterogeneous and Small Cell Networks (HetSNets), adding more cells or by implementing techniques such as multi user Multiple Input Multiple Output (MIMO) and 3D Massive MIMO [14–16]. Total Cost of Ownership (TCO) in mobile cellular networks comprises of CAPital EXpenditure (CAPEX) and OPerating EXpenditure (OPEX) as shown in the eq. 2.1:

$$TCO = CAPEX + OPEX \tag{2.1}$$

CAPEX can be defined as expenditure relevant to network construction which includes Radio Frequency (RF) hardware, software licenses, baseband hardware, installation, building cost and site support like cooling. However, OPEX refers to the cost required to operate the cellular network such as leased line, site rental, electricity, maintenance and operation [17]. Generally, CAPEX and OPEX are increasing with more base stations. Therefore, cellular network operators need to cover these costs for maintenance, network construction, and operation while the Average Revenue Per User (ARPU) approximately stays at the same range. Typically, the user needs more and more services and data, but expects to pay less for usage [18].

Traditional and LTE networks deployment become too expensive for mobile operators in term of OPEX and CAPEX to keep competitive. Moreover, all these needs will increase the load on Central Office (CO) and increase energy efficiency issues. However, Base Stations (BSs) in a traditional configuration consume a huge amount of power because BSs serve individual cells [19]. As result, these networks deployment will become unsuitable for the next generation of the mobile communication system. Consequently, new architectures deployments become a necessity in the field of cellular network. The 5th Generation (5G) of the mobile network is proposed to face these challenges [20]. The 5G should meet the following requirements [21]:

1. Reduced power consumption,
2. Reduced CAPEX and OPEX values,

3. Provide a platform for additional revenue generating services,
4. High spectral efficiency,
5. Support multiple standards.

C-RAN architecture is developed as one of the 5G solutions to simplify the management and control of the mobile network [5, 8].

C-RAN architecture is preferred by many mobile network operators, such as Nokia Siemens Networks [17], IBM [22], China Mobile Research Institute [5], Alcatel-Lucent [23], Intel [24], ZTE, and Huawei [25]. Moreover, C-RAN considers a significant architecture to support green technologies in the 5G cellular network in the year 2020 [26].

In C-RAN, Base Band Unit (BBU) is centralized in a BBU pool and connected to the RRHs. Therefore, few BBUs are needed in C-RAN compared to the traditional architecture. C-RAN has ability to decrease the cost of network operation and power consumption compared to the traditional architecture. A new architecture can be upgraded easily, that lead to improving the scalability also enabling network maintenance easy.

Recently, virtualization technology is used in the BBU pool to decrease power consumption. Generally, it consists of two parts; physical servers working with a set of hardware components, and software platform applied by the operating system. Virtualized BBU pool can be shared the resources, as well as can be shared by different network operators by letting them rent Radio Access Network (RAN) as a cloud service. For example, BBUs from different operators are placed in one cloud service. They can interact with increased spectral efficiency, lower delays, and throughput. Furthermore, the performance of the network is improved, by reducing handover delay during intra-BBU pool. Additionally, the virtualization technology has many benefits in C-RAN architecture, such as reducing costs, minimizing the investment capital, reducing power consumption as well as more reliability and flexibility in utilizing the server/network resource [8].

2.2 C-RAN Overview and Base Station Architecture Evolution

C-RAN architecture can be defined as centralized different BBUs of deployed traditional BSs together to form of a single pool. Therefore, they can be managed and dynamically share resources on demand among all BBUs. C-RANs have many benefits over traditional cellular networks, such as low power consumption, increased resource utilization efficiency, better hardware utilization and light interference.

Centralized processing has many methods and technology to turn RRHs on/off in the in a time-varying data traffic in different scenarios. However, this section explains the basic concept of C-RAN as well as the traditional BS evolution. The BS functions can be divided into radio functionalities and baseband processing. Furthermore, the baseband processing functions are Modulation, Coding, Mapping, Fast Fourier Transform (FFT), etc. However, the radio unit is the response to frequency, digital processing, and power amplification.

2.2.1 Traditional Cellular Network Architecture

In the traditional architecture as shown in Fig. 2.2, the functions of the radio and BBU processing are co-located in BS (i.e. in the same cell site). Generally, the antenna is located near to the radio unit, the coaxial cables are used to connect the antenna with radio unit. Furthermore, X2 interface and S1 are used between BSs and connect the BSs to the mobile core network, respectively. This architecture is used for Second Generation (2G) of cellular networks [8].

2.2.2 C-RAN Architecture

In this context, the BS is separated into two parts; a baseband signal processing unit and a radio unit, as shown in Fig. 2.3. The radio unit is called an RRH, and it has many functions

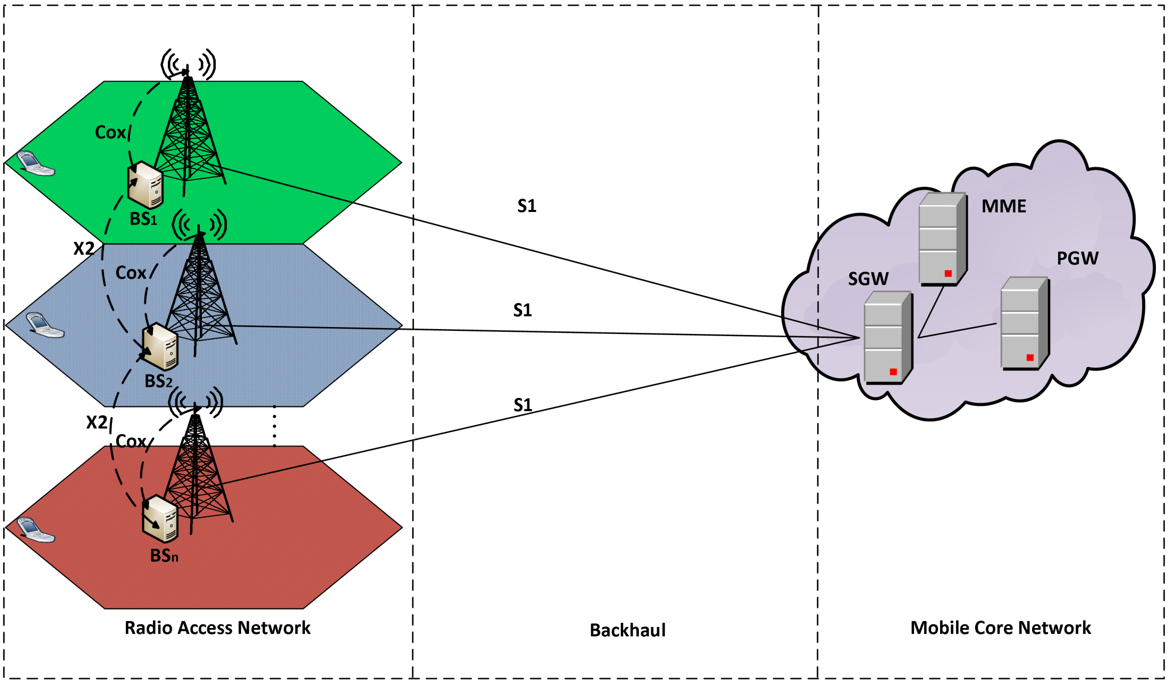


Fig. 2.2 Traditional architecture of cellular network

such as Digital to Analogue Conversion (DAC), Analogue to Digital Conversion (ADC), digital processing, filtering, power amplification and interface to the fibre [27]. The baseband signal processing is called a BBU, which is located in a central unit called BBU pool. The Interconnection and split function between the BBU and RRH depend on type of the network deployment.

The distance between an RRH and a BBU pool is up to 40 km [28], distance limitation is coming from the propagation delay of fibre and processing signal in BBU. However, a fronthaul can be optical fibre or microwave. Generally, the optical fibre is a candidate to be used in the next generation to meet the requirements of data rate demands. Moreover, RRHs designed to be small and light, so easy to install on poles or rooftops with very efficient cooling. Open Base Station Architecture Initiative (OBSAI) [29] and Common Public Radio Interface (CPRI) [30] are the radio interface candidate protocols to use between RRHs and BBUs.

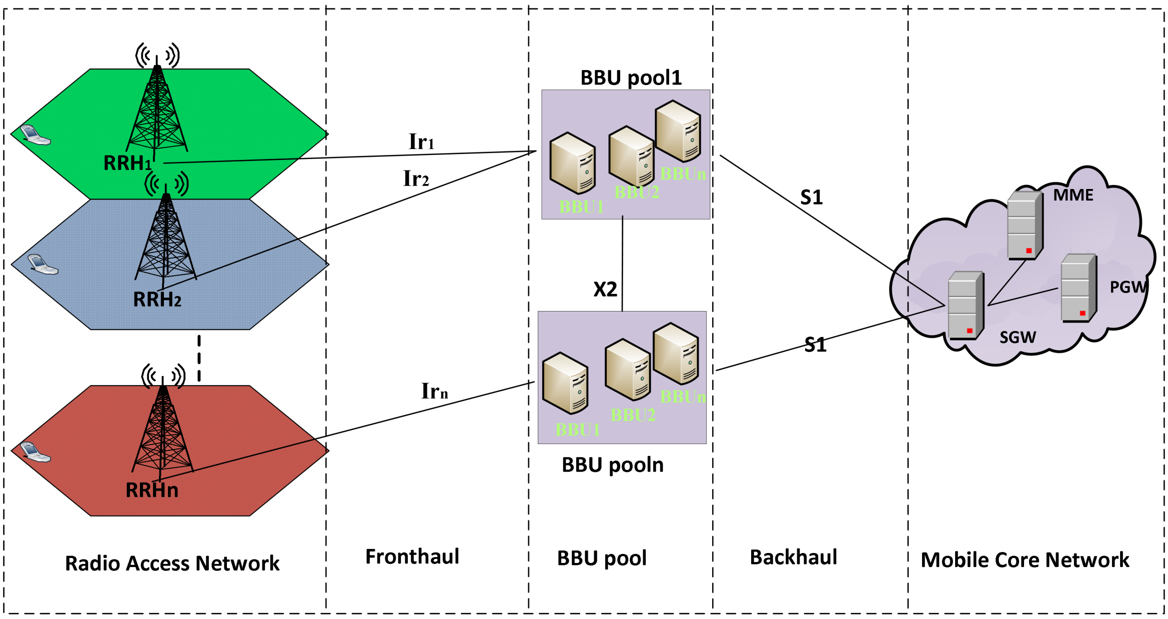


Fig. 2.3 C-RAN architecture

2.2.3 C-RAN Architecture based on Virtualization

In C-RAN, the BBUs are centralized into one place that is called a BBU pool to optimize BBU utilization between light and heavy data traffic demand to save energy. In this architecture, virtualization technology is used, where the BBU's functions installed as software on the physical servers called the virtual BS as shown Fig. 2.4.

Furthermore, the fronthaul interface is used as a medium to connect the RRHs with the BBU pool within high-performance processors, low latency, and high bandwidth optical fibre medium. The backhaul interface is used as a medium to connect the BBU pool with the mobile core network [6].

2.3 C-RAN Components

In general C-RAN architecture comprises of three main parts, namely (i) BBU pool which consists of a large number of BBUs with centralized processors located at the CO, (ii) RRHs with antennas system located at the cell sites, and (iii) fronthaul transport link which connects

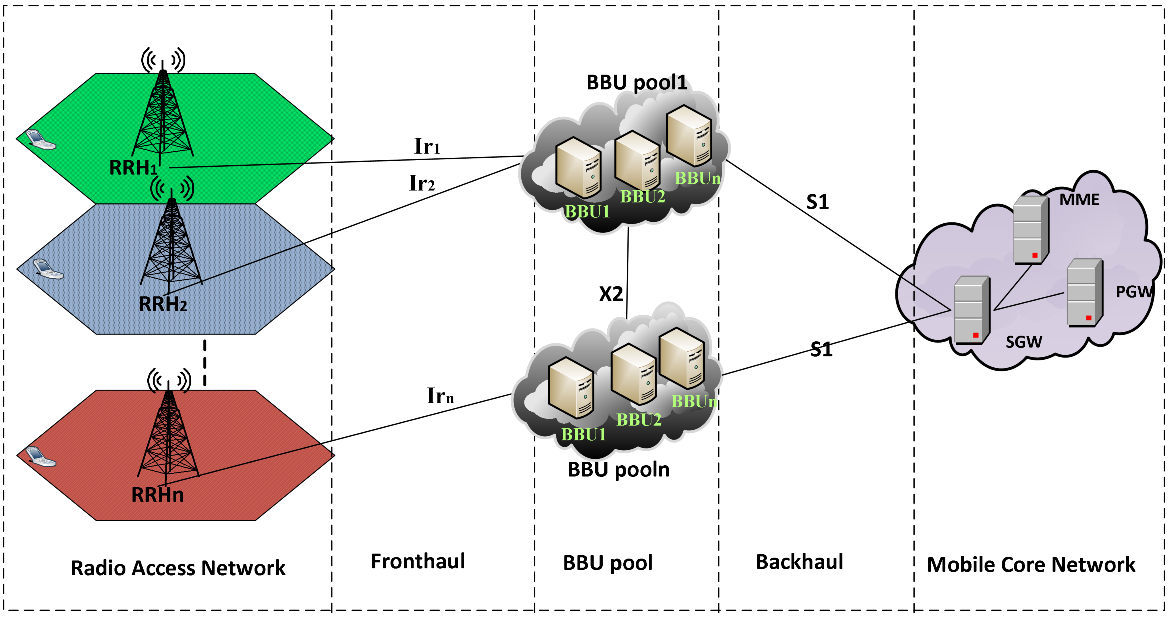


Fig. 2.4 C-RAN architecture based on virtualization

the BBU pool to the RRHs and needs low latency and high bandwidth to meet the 5G requirements.

2.3.1 Base Band Unit Pool

BBU pool consists of multiple BBUs in a form of a cloud, each capable to serve many RRHs. BBUs can be located at Central Office (CO) or Data Centres (DCs) of system. BBUs operate as virtual base stations which comprise of parts that process and schedule the incoming signals from different RRHs and optimizing radio resource allocation [8]. BBUs are responsible for functions from layer 1 to layer 3 depending on functional split between the BBUs and RRHs that used in level of C-RAN architecture [6, 31, 32].

Based on data traffic demand and time varying environment, the signal processing radio resources can be fully shared among different BBUs in the BBU pool. The BBU pool is connected by optical fibre to RRHs using Radio over Fibre (RoF) technology. In term of power consumption in the BBU pool, the power consumption model for the BBU pool is calculated as a sum of the active BBUs. Computing resources and processing of the BBU can be measured in by Million Operations Per Time-Slot (MOPTS) [33] or Giga Operations Per Second (GOPS) [34] translated into power figures. Many components and functions in BBU have significant effect in power consumption calculation such as the frequency and time domain processing, central processing units (CPU), Forward Error Correction (FEC) and processing related to CPRI [35].

2.3.2 Remote Radio Head

RRH is located at the cell site, it provides the wireless signal coverage for the cell site area and comprises of Analogue to Digital Conversion (ADC) and Digital to Analogue Conversion (DCA), Power Amplifier (PA), antennas system, interface adaptation, voltage suppliers and Low Noise Amplifier (LNA) as shown in Fig. 2.5. By moving most of the baseband processing from cell site to BBU pool to reduce both CAPEX and OPEX, which allows a more optimized energy consumption as well as less complexity and of course lowers their price.

Therefore, RRH can significantly help cellular network operators to resolve performance, cost, and efficiency challenges when deploying new base stations in 5G networks. Moreover, RRHs distributed in certain areas such as urban areas with high traffic loads offer efficient cost. They are located at the cell sites and used to transmit the RF signals to users and forward the baseband signals from the users to the BBU pool [6, 36].

2.3.3 Fronthaul Network

It can be defined as a connection between RRHs and BBUs to provide low latency and high capacity [28, 37]. C-RAN fronthaul is realized by different technologies such as wireless, and wire represented by optical fibre networks. Generally, Wireless fronthaul link are cheaper and faster to deploy than optical fiber fronthaul links. Wireless fronthaul typically operates on the licensed spectrum. Wireless operates with carrier frequencies 5-40GHz. However,

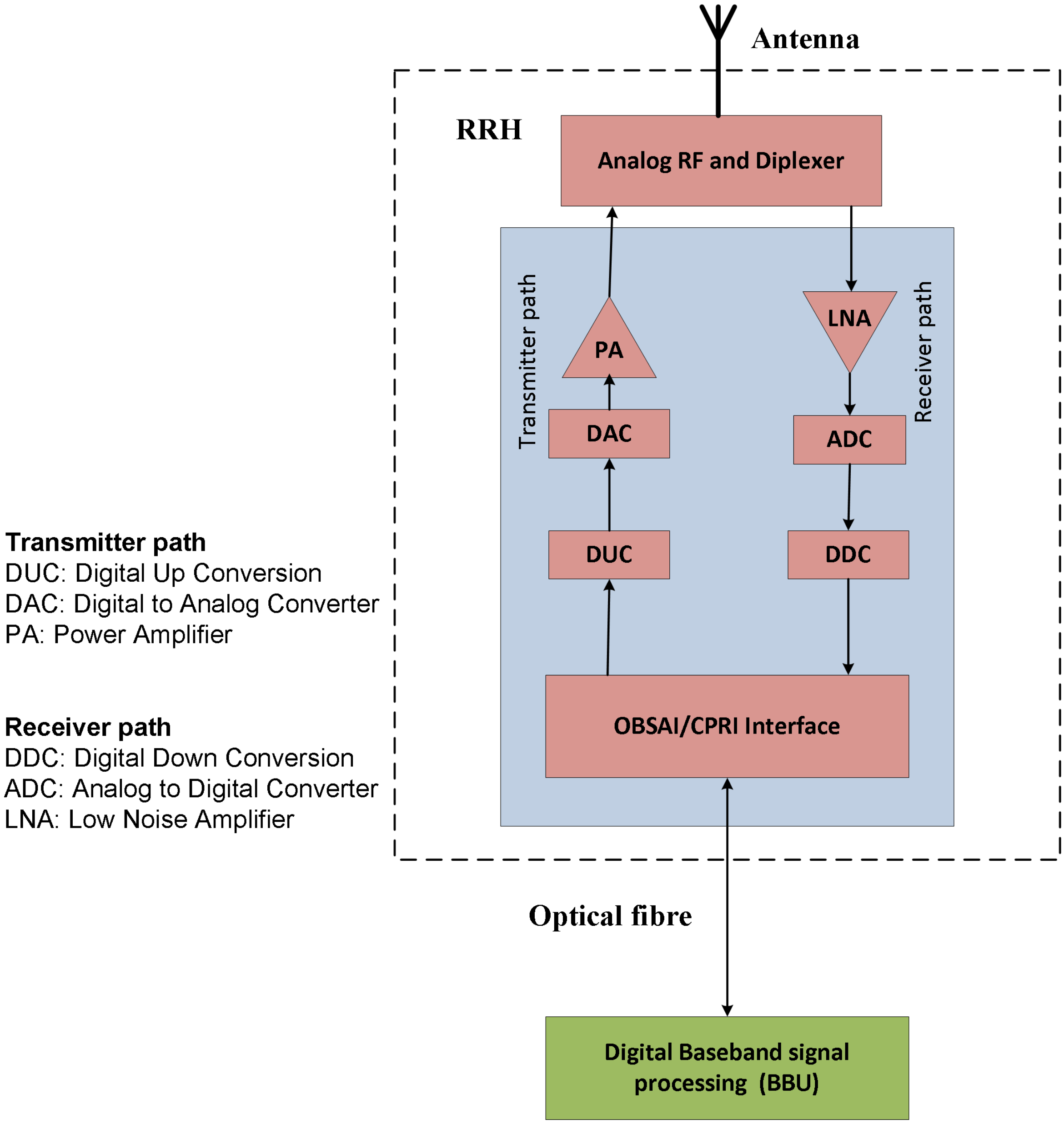


Fig. 2.5 RRH components in C-RAN architecture [36].

they can provide only a few hundred Mbps of data rates due to the limitation of bandwidth at these frequencies [6].

Therefore, optical fibre network is considered fronthaul link for the next generation of the cellular network to provide the data rate requirements [38, 39]. By using the optical fibre fronthaul link, two different protocols can be used; CPRI [30] and OBSAI [29]. However, many operators and cellular companies face difficulty to deploy new optical network fronthaul link for the next generation.

Therefore, they see more economy to use the infrastructure of optical fibre as a fronthaul for the next generation. The Radio over Fibre (RoF) is a technology for of integration of optical fiber and wireless access network where two type of RoF candidate to use in C-RAN, Digital (D-RoF) [35] and Analog (A-RoF) [40], which are compatible with CPRI and OBSAI protocols.

2.4 C-RAN Architecture Types

In general, there are three different types of C-RAN architectures according to the split function options of base band processing unit between RRHs and BBU pool. There are full centralization, partial centralization and hybrid centralization. This section shows these three types in detail.

1. **Full Centralization**: In this architecture type, the baseband processing functions (i.e., physical layer, the Medium Access Control (MAC) and the network layer) move to the BBU pool. In this case, the BBU demonstrates all managing and processing functions of the traditional BS. This architecture makes the system simpler and clear in the context of maintenance and operation, as well as it has capabilities to support multi-standards in the system. However, the RRH deals with up/down conversions,

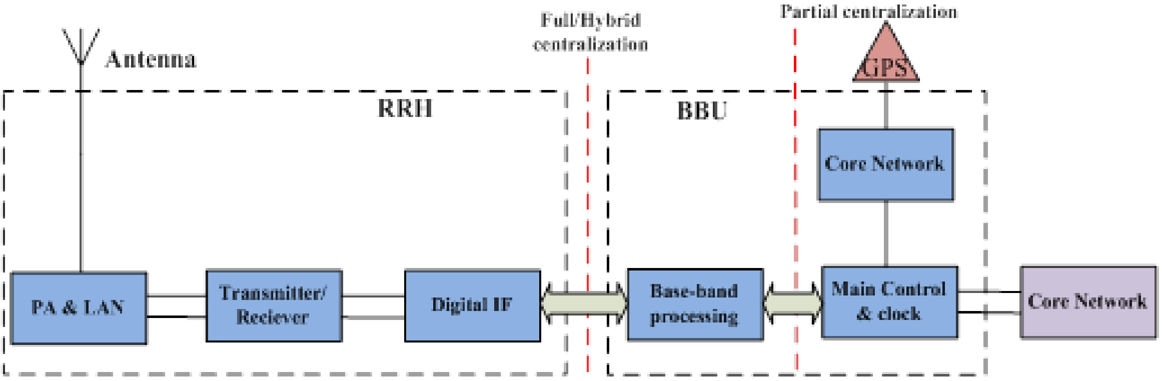


Fig. 2.6 Options of split functions between the RRH and BBU in C-RAN architecture

filtering, amplification of RF signals, and interface adaptions [21]. In general, this architecture suffers from a high burden on fronthaul.

2. **Partial Centralization**: In this structure, the RRH is responsible for the baseband processing that related to RF function. However, BBU is responsible for baseband processing that related to all functions of layer one and the upper layer. This structure reduces the RRH-BBU overhead and burden of fronthaul as shown in [6]. The structure of this type is shown in Fig. 2.6

3. **Hybrid Centralization**: Some functions of layer one such as the user specific functions and the cell-specific signal processing are removed from BBU to a separate unit. This unit may be part of the BBU pool or not [6]. This architecture can be as a special case of full centralization that has some advantages such as reducing energy consumption in BBUs. The structure of this type is shown in Fig. 2.6.

All above architectures are under evaluation and development. They can be applied in different schemes depending on the situation and requirements of the network.

2.5 Benefits of C-RAN

C letter in C-RAN has several features such as Centralization, Cloud computing, Cooperative radio, and Clean system. Therefore, functions in a C-RAN architecture should include receiving, resource control and sharing, virtualization and co-operative transmission in order to permit managed execution of multi-RATs support, multiple workloads independent of underlying hardware platform, network sharing especially active RAN sharing, reliability and common O&M. This section shows the major advantages of C-RAN architecture [5, 41, 42].

1. **Energy Efficient/Green Infrastructure**: C-RAN is an eco-friendly system. By centralizing processing (i.e. BBU pool), the number of BS equipment's can be largely reduced that leads to reduce power consumption in the network. That is due to sharing number of BBUs in the BBU pool the same equipment such as shelter, cooling system and utilization of processing resources. Virtualization can be used in C-RAN which has a significant effect in reduce energy consumption.

   Furthermore, due to the shared resource among virtual BSs in BBU pool, the power can be reduced by using several mechanisms related with this concept such as active-sleep mode technology. For example, an idle BBU can turn off without affecting the service, especially at the low traffic load, to reduce the processing power. Small cells configuration, which is candidate to deploy in C-RAN, can use lower transmission power to serve users while the quality of network is not affected. That leads to reduce energy of signal transmission, which is supportive for the decrease of energy consumption in the User Equipment (UE) battery and RAN.

2. **Cost-saving on CAPEX & OPEX**: Due to the site equipment and BBUs of BSs are gathered in one CO, makes the system simpler for centralized management, as well as saving Operation and Maintenance (O & M) cost associated with a traditional RAN network. The RRHs in a C-RAN architecture have a simpler functions, power

consumption and size are reduced and they can be located on poles or building roofs with minimum site support and management. However, network operators can subcontract third-party hosts' servers in one place to share applications and resources.

3. **Co-operative Transmission and Receiving**: Coordinated multipoint (CoMP) considers a type of Coordination techniques is known as an efficient means to increase the high data rates coverage, the cell-edge throughput and/or to increase system throughput and mitigate interference between cells.
   In C-RAN architecture, the joint processing in the BBU pool becomes easier due to centralized processing. The joint processing includes addition to CoMP, joint interference alignment/cancellation, joint scheduling, and others technologies that could support by C-RAN architecture.

4. **Non-uniform Traffic** In term of user's movement, the traffic load provided by the RRH dynamically changes, while the BBU is still in the same BBU pool. The non-uniform traffic generated from the user can be distributed in BBUs of the same BBU pool due to the coverage area of BBU pool. The BBU pool considers larger coverage area than the traditional BS. Therefore, the distributed BBU pool has capability of load balancing to the dynamic traffic change.

5. **Multi-RAT Support**: C-RAN can support multiple access technologies such as LTE, Universal Mobile Telecommunications System (UMTS) and Global System for Mobile communications (GSM) in the same BBU cloud infrastructure. Nevertheless, these technologies differ in their function and the BBU should be designed to integrate them into one device for multiple technologies. Therefore, Software Defined Radio (SDR) considers one of the significant schemes to process any protocols for multiple access technologies.

6. **Virtualization**: Virtualisation technology proposed for C-RAN leads to Virtual C-RAN (VC-RAN). This technology consists of two parts: a) physical servers that include the Network Interface Card (NIC), memory, Central Processing Unit (CPU) and a storage unit called physical BBU, BBU or server. b) Software platform that is applied by an operating system called a VM, virtual BBU (vBBU), or virtual BS (vBS). With this technology, VM can as an independent operating environment with I/O resource, and virtually independent CPU.
   Furthermore, virtualisation produces weighty benefits in C-RAN by enabling virtual machine migration to balance the loads across the BBU pools. The biggest benefit of engaging the virtualisation technique in C-RAN is the flexibility of sharing the physical resources of the servers and saving energy.

7. **Migration of Virtual Machines**: One of the key features of C-RAN for cost and power saving is migration of Virtual Machines (VMs). Migration gives the ability for VMs to move from one physical BBU to another continuously and seamlessly running. The VMs migration technique consolidates the VMs, which are installed on different physical BBUs onto one physical BBU. Growing of utilizing the VMs for that reasons:

   - Sophisticated technology of processors, which helps to accept the overhead of VMs.
   - Maintenance: in the case of the source server required to be decommissioned due to urgently required maintenance.
   - Load balancing, there might be servers experiencing heavy load due to their position in a dense area or the type of service they run. In this case, it is wiser to distribute the load amongst other servers in the network while proportionally considering their processing usage and without degrading the performance of the participants [33].

- Offloading, when the traffic in the network is in a low state, some servers are chosen to be switched off to save energy so as the energy efficiency is increased. In this case, live migrating the VMs from the chosen servers to other active ones is the solution.
- Minimizing power consumption in a C-RAN environment, live migration technology is employed to combine VMs host in multiple under-utilized servers onto a single server. Therefore, the servers who migrate the VMs can be switched off.

2.6 Challenges of C-RAN

The C-RAN has many advantages in cost, saving energy and flexibility over traditional network. However, it has some challenges and obstacles that should be solved by mobile operators before the commercial deployment. This section explains some of these challenges.

1. **Latency of Transport Network**: The optical fibre fronthaul link has been proposed to use between BBU pool and RRHs, it has high bandwidth. The transport link in cellular network not only requires to support cost efficiency and high bandwidth, but also requires supporting jitter and latency. The processing delay on a transport network between BBUs and RRHs should be less than 3 ms, to meet HARQ requirements. Because of the delay Hybrid Automatic Repeat reQuest (HARQ) requirements, the maximum fronthaul link distance between BBU and RRH must not exceed 40 km [5].
2. **Advanced Cooperative Transmission**: Interconnection and cooperation between vBSs in the BBU pool is achieved by CoMP concept based on sharing and scheduling the user data. Combining of many BBUs in one BBU pool needs special resilience and security mechanisms. The interconnection between vBSs in the BBU pool to exchange the information should support low latency, cost switch network and high bandwidth flexibly interconnecting RRHs to ensure real time cooperative processing.

C-RAN can provide reliability for interconnection between the BSs better than traditional network. BBU pool is capable to support RRHs from different areas such as residential or office. To achieve optimal way to save energy in the C-RAN architecture, the system shall optimize the active number of BBUs based on active sleep mode technology [43, 8].

3. **Base Station Virtualization Technology**: After the BBUs of cells have been moved to a centralized BBU pool, it is necessary to use virtualization technologies for the physical BBUs to be as a vBBUs which are implemented in physical severs. The main challenges of virtualization are:, virtualization of the baseband processing pool, real-time processing algorithm execution and dynamic processing allocation to deal with the dynamic RRHs load in network [8].

2.7 Virtualisation Concept in C-RAN

Virtualization can be defined as a technology that has an ability to create a logical, isolated entity from a physical entity. It can be shared in a flexible and dynamic way. Furthermore, virtualization technology is used for many years for desktop virtualization, network virtualization data, and storage virtualization. Network virtualization is a significant technique for the C-RAN architecture. It comprises a number of virtual links and virtual nodes. Virtual networks are used in the heterogeneous network that will provide low cost, flexible control, diversified applications and efficient resource usage [44].

The important keys required for network virtualization are efficient resource utilization, customization and isolation [45]. In the terms of BBU pooling, the BBU pool operates over a set of hardware platforms such as a Network Interface Card (NIC), memory and CPU. Moreover, the virtualization technology is implemented in C-RAN by operating systems such as a Linux. The BSs functions are simulated as software, called the vBSs. The requirements of virtualization are customization, efficient resource utilization, and isolation [45]. However, there are following motivations using virtualization in C-RAN:

- Reduced the investment capital,
- Provide different services with different authentication mechanisms,
- Minimize cost and reduce time consumption for testbed setting,
- Reduced power consumption.
- Provide reliability and flexibility in terms of being able to add or remove virtual operators.

Moreover, a C-RAN system can run multiple independent vBBUs at the same time on one physical server, which has many benefits such as, hardware resources saving, effective server integration and cost reduction. Multiple vBBUs can share the common resources, involving hardware and software systems, which provides effective and flexible utilisation. Within the vBBUs, many operators can share programming, network environments and IT platforms [8]. Moreover, vBBUs with low traffic can be centralised onto fewer physical servers through a live migration technique. Finally, by shutting down the idle servers, the overall system power consumption can be reduced.

2.8 C-RAN Deployment

C-RAN is a candidate architecture to implement for next generation of cellular network instead of traditional cellular network like LTE Advanced (LTE-A), LTE and UMTS. In C-RAN architecture, BSs can be implemented by separating BBUs and RRHs, and baseband processing resources for multiple BBUs in a CO can be scheduled in carrier level. Easy to deploy the RRHs due to they are light weight and small size. RRHs transmit and receive radio signals from and to the BBUs via optical fiber fronthaul links. RRHs can be installed in cell sites far from the BBU pool (e.g. 1- 40 km) [38]. The fronthaul network between BBUs and RRHs can be standardized like CPRI or OBRI. The centralized BBUs should have a low latency, high bandwidth, corresponding protocol and switch matrix to support the effective cooperation among multiple BBUs in BBU pool.

The radio signals from deployed RRHs can be switched to any BBU in the BBU pool. Thus, the centralized concepts can use load balance technique to avoid overloading in some BBUs during peak hours while some BBUs operate in low load. This can reduce power consumption, improve the usage efficiency of devices, and improve system reliability. Deployment of C-RAN will be an unique scenarios for micro, macro, picocell, and indoor as well as the deployment candidate to be a heterogeneous arrangement. Generally, C-RAN supports many significant scenarios such as greenfield deployments [46], C-RAN for capacity boosting [47] and different stages of C-RAN deployment [48]. C-RAN deployment still is limited by the maximum distance between RRH and BBU (up to 40 km) due to propagation signals in fronthaul link and processing delays in BBU [38]. The path towards complete C-RAN deployment, where BBUs are pooled to support RRHs, and how many pool needed to serve specific network becomes required. Multiple BBU pools may be needed to serve a metropolitan area.

- **Green Field Deployment**: In term of this field, the placement of the RRH and BBU pool is subjected to network planning. The transport solution and physical medium can be designed with respect to C-RAN architecture requirements. In general, the main aim of the network deployment is to reduce cost of deployment and minimize Total Cost of Ownership (TCO) a ratio with high system performance [49]. However, C-RAN architecture is promising for small scale deployments for metropolitan areas with high density RRHs.

- **Small Cell Deployment**: A small coverage area cells are most likely for C-RAN architecture for capacity boosting. Release 13 of cellular network standards provide enhancement of small cell deployment [50]. Adding new small cells to cellular network is promising to increase network capacity. Small cell deployment scenarios are candidate to be used with C-RAN. It also supports both user deployed cells and operator, co-existence operators, Self-Organizing Networks (SONs) mechanisms, and networking between different RATs.

  The small cells deployment scenario with C-RAN reduces signalling resources because they are supported by one central BBU pool, not many BSs as in tradition network [47]. In future cellular networks many small cells can be deployed to improvements network capacity and quality in offices, public spaces and homes. When a user will move out from small cell to the other, the system needs to handover the user to the new small cell. In this case, the system needs a special coordination technique between small cells.

2.9 Heterogeneous Network

A Heterogeneous Network (HetNet) can have multiple types of radio access nodes in a cellular network, e.g., the macro, pico, femto, and relay which are designed to meet the increasing traffic demand in broadband wireless networks. In HetNet, the macro ensures the coverage to meet the demands of low speed services, while the coverage capacity of hotspots enhanced by small cell such as pico and femto by deploying under the underlay of macro cells. The reduced coverage area of small cells means that the number of users sharing the same cell is lower compared to macro cells, giving users more freedom of using the bandwidth with lower transmission power [51].

2.9.1 Access Node in HetNet

There are many types of access nodes in HetNet depending on the coverage area; this section explains the details of these types as follow:

- **Macro/Micro Cells**: The distance between two macro or micro cells is usually no less than 500 meters, which can provide a ubiquitous coverage for users in a wide range of area, and support high mobility users by minimizing the handover frequency. However, due to factors such as channel fading and traffic congestion, the connectivity between users and macrocell has relatively low data rate and is unstable [51].

- **Small Cells**: It has a range of 10 meters to a few kilometers and works in licensed and unlicensed spectrum. The wireless backhaul traffic of small cells is transmitted to the macrocell by millimetre wave communication links, and then the aggregated backhaul traffic at the macrocell is forwarded to the core network. Since smart mobile devices and cloud applications are hungry for a high-speed and stable connectivity to the cloud, the small cells become a better choice [52].

- **Pico Cells**: that have a coverage range of about 200 meters or less are used to provide hotspot coverage in malls, airports or stadiums. It is considered low-powered radio access nodes, and their access is open to all cellular users [52].

- **Femto Cells**; it has coverage range less than 100 meters typically designed for mobile devises in a home or small business Similar to WiFi, it is considered low power base station.

- **Relay Nodes**: The relay nodes are low power base stations that can provide coverage and capacity enhancement to macro cells at the cell edge [51].

2.10 Heterogeneous Cloud Radio Access Network

The HetNets technology is proposed as a solution to satisfy the increasing of high capacity and high traffic demand in cellular network. High Power Node (HPN) (e.g. macrocell) deployed to extend the coverage area and high mobility support while the Low Power Node (LPN) (e.g. small cell) help to achieve high data rate for hotspot of underlay HPN [53]. Unfortunately, an underlay structure in which Macro Base Stations (MBSs) and Small Base Stations (SBSs) reuse the same spectral resources could lead to severe inter-tier interference. Hence, it is difficult to conquer interference through advanced signal processing techniques, such as adopting the advanced Coordinated Multi-Point (CoMP) transmission and reception technique to suppress both intra-tier and inter-tier interference [54].

HetNets compatible with C-RAN architecture candidates to use as a solution for the next generation of cellular networks. That has the ability to increase capacity, low power consumption and cooperative processing technique between RRHs and between BBUs because that are centralized and shared within the BBU pool. However, the fronthaul have great impact on the performance of the C-RAN. By combining C-RAN and HetNets to introduce new technology called a Heterogeneous Cloud Radio Access Network (HC-RAN) overcome the challenges in C-RAN and HetNets.

The motivation of HC-RANs is to embed the cloud computing technology into HetNets to realize the large-scale cooperative signal processing and networking functionalities, and thus SE and EE performances are substantially improved beyond the existing HetNets and the C-RANs. HC-RAN has capabilities to provide high data rate service to the desired User Equipment (UE) by helping of heterogeneous MBSs and SBSs [55, 56].

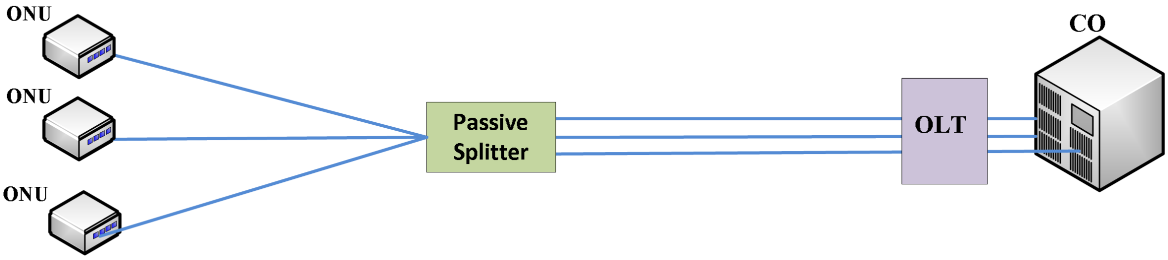


Fig. 2.7 Passive optical network architecture

2.11 Fronthaul Networks for C-RAN

In C-RAN architecture, the fronthaul link can be wireless or wire, It is expected that future wireless fronthauled by wireless links cannot meet the demands of increasing of data rate. Therefore, High optical fiber fronthaul link is proposed instead of wireless fronhaul to provide the required data rate for the next generation cellular network [57].

The optical fiber network is divided into three main parts: Optical Line Terminal (OLT) that represents signal generation and modulation techniques optical amplifier & filters located at the BBU pool; Optical Fiber Network (OFN) that own optical fiber characteristics and Optical Network Unit (ONU) that the function of signal detection such as photodiode as a receiver, electronic amplifiers and filters located near the RRHs [58, 59].

A passive optical network (PON) is a network operating by optical passive components that do not need power to operate; this is very useful to save energy and reduce costs.

The OLT is responsible to control the bidirectional flow of information. In the downstream direction the function of an OLT is to take in information from the BBU pool to ONU through passive splitters that allow communication between the OLT and their respective ONU, and passive splitters located at the near ONUs. In the reverse direction (upstream), OLT accepts and distributes all the traffic from the network RRHs [60]. This architecture shown in Fig. 2.7.

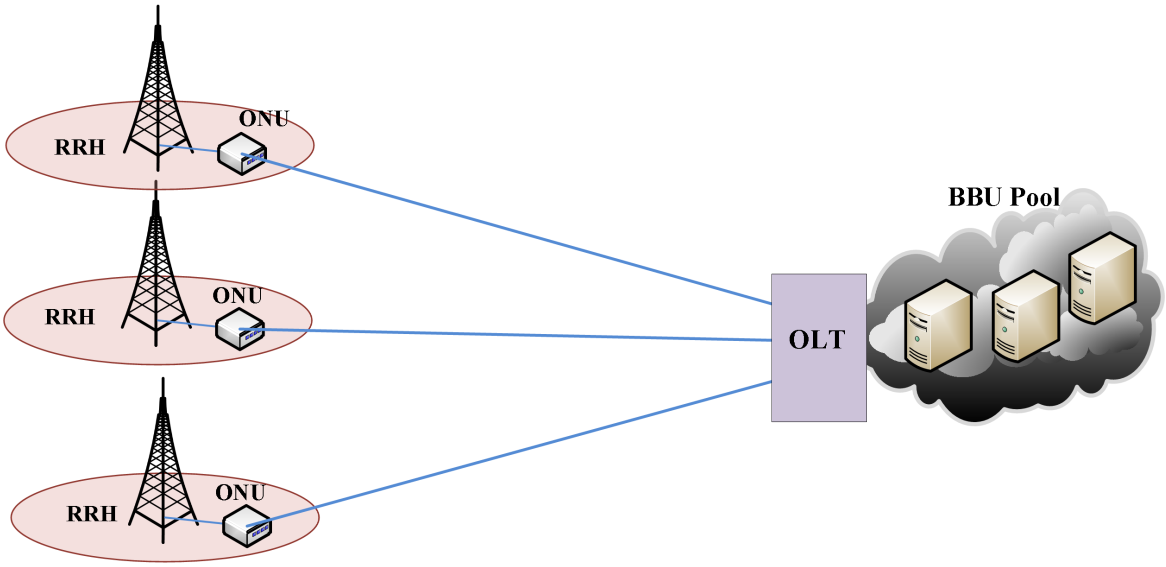


Fig. 2.8 C-RAN Point to Point (PtP) fronthaul architecture

2.12 Types of Fronthaul Networks

The are many types of optical fiber network, which can be used as a fronthaul for the next generation of cellular networks such as the Point to Point (PtP) Options, Active Optical Network (AON) and Wavelength Division Multiplexing (WDM) fronthaul architecture. The following subsections explain the fronthaul networks types, which are potential candidates for C-RAN architecture.

- **PtP Fronthaul Architecture**: Each BBU is connected to the RRH over a pair or a single fiber for bidirectional optical fibers, as shown in Fig. 2.8. PtP fronthaul is not practical for the C-RAN deployments because of the cost associated with their deployment compared to others [61].

- **WDM Fronthaul Architecture**: The main component of this type is WDM; it is a technology where multiple optical channels can be simultaneously transmitted at different wavelengths through a single optical fiber [62]. WDM considers one of the most promising concepts for high capacity communication systems. Each channel is allocated a communication system with different wavelengths and can be multiplexed

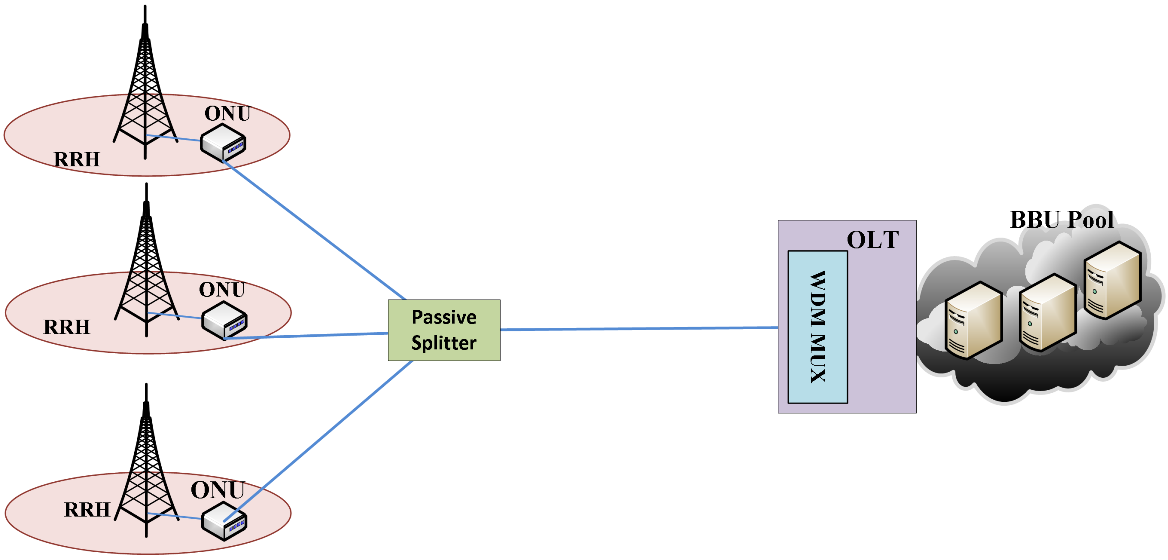


Fig. 2.9 C-RAN WDM fronthaul architecture

by using Multiplexer (Mux) onto a single fiber. At the destination, wavelengths are separated to different receiver locations by using a Demultiplexer (DeMux) or by using optical splitter as a shown in Fig. 2.9.

In addition, the WDM is a suitable solution for the heterogeneous network to limit fibre resource. The WDM technology enabled the C-RAN to improve the bandwidth link between the BBU and RRH, where multi wavelengths (40-80) can be transmitted in a single mode optical fibre; therefore a large number of RRH can be supported with single optical fiber [8].

- **AON Fronthaul Architecture**: Remote Node (RN) switches (active components) are between the the ONUs and OLT [63], as illustrated in Fig 2.10. Generally, this type is also not useful to use with the C-RAN architecture because it consumes more power compared to other types.

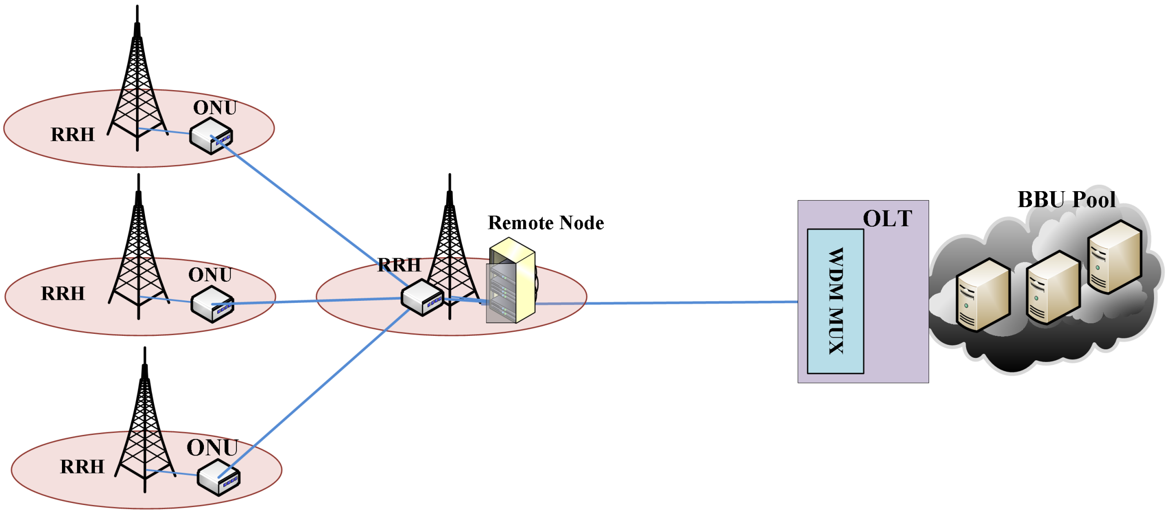


Fig. 2.10 C-RAN AON fronthaul architecture

2.13 Maximum Fronthaul Latency

C-RAN fronthaul dimension plays a significant role to meet the QoS of the mobile network. Fronthaul dimension for C-RAN depends on separation distance between the BBU and RRH. The latency which occurs in fronthaul must be carfully considered, as well as the actual timing performance to be accurately determined. Fronthaul latency considers one of the main essential restrictions for BBU pooling, because it provides the maximum distance between BBU pool position and RRHs location. The latency in C-RAN architecture can be categorized into two parts:

1. Latency due to the propagation signal during fronthaul between the BBU and RRH which can be caused by protocols used such as CPRI or OBSI and type of optical components in the fronthaul. Moreover, the radio interface link between the RRH and US, which can be caused by the coverage area of cells.
2. Latency due to the radio signal processing; the delays of both RRH and BBU depends on the specific hardware and software implementation.

To show some numerical fronthaul latency values calculation in network, the maximum latency and the maximum distance between BBU pool and RRHs in C-RAN are due to the timing of the synchronous uplink Hybrid Automatic Repeat ReQuest (HARQ), which is a proposed protocol 5G. Specifically, uplink data is received the radio frame number i, the BBU in the BBU pool should send back the Acknowledgement (ACK)/Non-acknowledgement (NACK) notification at frame number (i+3). For this process, the latency budget for the BBU-RRH round trip time must be less than 3 ms [64].

2.14 Clustering Techniques in C-RAN

Clustering concept in C-RAN can be defined as a controlling number of RRHs in one group; this concept has the ability to bind the computational complexity and estimation overhead to a low level, which leads to low capacity requirements on the fronthaul link. However, large-scale cooperative processing gains of the C-RAN inevitably s reduced by this technique and reduces the C-RAN capacity.

The centralized concept is not fully exploited by limiting the scale of coordinated RRHs within a small group. The cluster size considers a critical parameter in planning C-RAN architecture. To calculate the optimal dimensioning of the cluster, it is necessary to know some information about the network such as the number of RRHs, the processing capacity of BBU pool, and RRHs coverage area. Three components are involved in determining the clustering [65]:

1. A technique to cluster the required data (normally through a feature vector),
2. A dimension measurement (to determine the performance and quality of the clustering), and
3. Algorithm to solve clustering problem.

2.15 Summary

This chapter discusses the evolution of the base station architecture of a tradational network and explains the concepts of the C-RAN architecture. The BS functions that divided into radio functionalities and baseband processing are explained. Furthermore, it details the C-RAN architecture classified into three types; full centralization, hybrid centralization and partial centralization. Moreover, this chapter describes the main components used in C-RAN architecture; RRH, BBU and optical fibre fronthaul network.

Advantages, challenges and benefits of C-RAN architecture are explained. Furthermore, it is showed how C-RAN deployment is important to apply for 5G instead of traditional cellular network. Virtualization technology is clarified in term of saving energy and resource sharing in the C-RAN. Furthermore, latency due to fronthaul and clustering concept in C-RAN architecture are introduced in this chapter.

Chapter 3

Modelling Power Consumption Model and Optimisation for a Cloud Radio Access Network

The main contribution of this chapter is to introduce a cost effective scheme for Cloud Radio Access Network (C-RAN) by dynamically changing the connection among Base Band Units (BBUs) in the BBU pool, with respect to the data traffic demand of the Remote Radio Heads (RRHs). The number of operating BBUs has been minimised to provide energy saving by sleeping certain BBUs experiencing low traffic load at particular times of the day.

Furthermore, this work introduces Orchestra Server (OS) to switch on/off the BBUs and reconfiguration of fronthaul with respect to the data traffic demand. Reconfiguration between the BBUs and RRH is achieved by a switching system. This switch takes the decision from the OS that knows everything about network status and traffic load demand in the RRHs as well as, it holds the intelligent algorithm. Moreover, an internal switch in Layer-2 is proposed to redirect the traffic load among the BBUs, in response to OS commands. In addition, a power model for C-RAN architecture based on the BBU pool virtualisation scheme is put forward.

The virtualisation technique is used to enable the BBUs to share resources, thereby minimising power consumption in the BBU pool. Each BBU is represented as a bin for processing traffic load and expressed in Giga Operations Per Second (GOPS). The dynamic traffic load of the RRHs is the number of users that are required to be packed into the bins. The bins can be reduced by switching off a certain number of BBUs at low traffic load and routing the users' traffic to the others BBUs with respect their available capacity. There are many algorithms to solve this optimisation problem, such as the Next Fit (NF), First Fit (FF) and First Fit Decreasing (FFD) algorithm.

A combination of Bin Packing Methods (BPMs) and the New Minimum Bin Slack (NMBS) algorithm are proposed to solve this optimisation problem. The NMBS algorithm is a modification of the Minimum Bin Slack (MBS) algorithm. It tries to minimise the number of bins by matching the right number of users' load as much as possible with the BBU processing load with load balancing among all the BBUs.

Moreover, there are three common types of optional fibre network, namely, Point To Point (PTP), Active Optical Network (AON) and Passive Optical Network (PON). These types of network are proposed to be used as an optical fibre front-haul for C-RAN architecture.

3.1 Introduction

In recent years, the demand for traffic data in cellular networks has been steadily increasing due to the development of smart devices and the vast spreading internet with new applications [66]. These challenges will increase the load on the Central Office (CO), which will increase the power consumption in the system as well as raise some serious energy efficiency issues. Hence, the cellular network companies need to provide possible solutions to meet these challenges and the 5th Generation (5G) of the mobile network has been proposed to do so [20].

The main part of power consumption in the traditional cellular network is Base Stations (BSs) that will lead to an increased Operating Expenditure (OPEX) [67, 19]. C-RAN architecture is presented as one of the 5G solutions for saving energy, simplifying the management and control of mobile networks [5, 68]. The most significant aspect of C-RAN to provide data requirements is the Radio Access Network (RAN) [8, 69]. It is anticipated that the RAN, as represented by the microwave back-haul link, cannot meet the demand for increasing data rates. Hence, high capacity optical fibre is proposed to replace the microwave back-haul to provide these needs. The optical fibre is used as a fronthaul to connect the BBUs from the BBU pool to the RRHs. The distance between an RRH and a BBU pool is up to 40 km. The distance limitation is due to the propagation delay of fibre and signal processing in BBU [8]. Recently, virtualisation technology has been used in the BBU pool to decrease costs and power consumption. Generally, it consists of two parts, physical servers that work with a set of hardware components, and a software platform that is applied by an operating system. The virtualisation technology has many benefits in C-RAN architecture, such as reducing costs, minimising investment capital, reducing power consumptions well as providing more reliability and flexibility in utilising the server/network resource [8].

The traffic data vary depending on geographical area and time during the 24 hours, i.e. a huge amount of energy is wasted in the area that users have moved [70]. To achieve an optimal solution to saving energy in C-RAN, the number of active/sleep RRHs/BBUs with respect to the traffic demand needs to be optimised. C-RAN gives high reliability of dynamically sharing BBUs in the BBU pool, whereby it can run multiple RRHs using one specialised BBU at low data rate demand.

3.2 Related Work

Fronthaul with BBU-RRH connections is becoming an important feature of reconfigurable techniques. Many studies have focused on the cooperation of the BBUs and reconfiguration of optical fibre fronthaul to save energy and load balancing in C-RAN. The authors of

[71] proposed a technique to reduce energy in C-RAN architecture based on BBU workload consolidation by reducing the number of BBU servers used. The technique involves switching off idle BBUs to reduce the energy consumption in the system. The authors of [72] introduced a switching technique in C-RAN with cooperative BBUs-RRHs to save energy. In this work, the power consumption in the BBU pool was reduced by 47% and 26% for adaptive and semi-static schemes, respectively, when compared to the conventional RAN network.

The authors of [73] proposed a scheme to associate BBUs and RRHs based on a graphical method to reduce the power consumption in the BBU pool. Simulation results showed that the algorithm minimises power consumption by about 20%.

The authors in [46] proposed a C-RAN scheme based on virtualisation technology that reduces power consumption in the BBU pool. The scheme uses a bin packing algorithm with the Heuristic Simulated Annealing (HSA) algorithm, which decreases the power consumption of the system when compared to standard approaches. The authors of [70] proposed RAN architecture for deploying a small celled Colony-RAN. It has the ability to change connections of BBUs in the BBU pool dynamically with respect to the data traffic demand of the RRHs. This process can reduce the number active BBUs due to the statistical multiplexing effect, thereby saving energy in proposed scenario. The authors of [74] focused on the BBU pool power consumption under a tidal traffic scenario and BBU aggregation energy-efficient was proposed by dynamically waking and sleeping BBU cards. They proposed a 2D bin-packing method for solving the transferring load problem among the BBUs and the number of active BBU cards is minimised by the development of heuristic algorithms.

In terms of the reducing number of used bins, the author of [75] introduced four heuristics: constructive, FF, FFD and local search through the deployment of greedy packing, a Genetic Algorithm (GA) and HSA to minimise number of bins by using the Bin Packing Problem (BPP) technique. The authors in [76] analysed the power consumption of the whole C-RAN and then, proposed a technique that made the C-RAN architecture work in the most energy-efficient way considering the Quality of Service (QoS).

The authors in [77] proposed a Dynamic RRH Assignment (DRA) algorithm to evaluate the system. The results showed that DRA is better than FFD in terms of consumption of time and reduction in the number of active BBUs. In [78], an Energy-Efficient (EE) for a downlink C-RAN based on a Compression Before Precoding (CBP) strategy as well as Compression After Precoding (CAP) one was investigated. The numerical results showed that the proposed system outperforms the other conventional systems with the Energy Efficiency (EE) criterion.

3.3 Proposed System

For the current work, an Orchestra Server (OS) is proposed as a server in the BBU pool to support the C-RAN architecture in terms of energy management and self-organisation, as shown in Fig. 3.1. The OS hosts a proposed algorithm to find the proper network configuration setting dynamically. It recognises the network status and instantaneous data traffic demand for each RRH to produce a decision to switch to making reconfiguration of the BBUs-RRHs. An internal switch in Layer-2, behind the BBU pool, is responsible for redirecting traffic from overloaded BBUs to others. That is, this switch response to the OS commands is to reduce the number of BBUs in the context of energy management and saving energy.

However, the switching system is considered a significant challenge in C-RAN architecture. The main challenges and possible solutions for fronthaul reconfiguration in C-RAN are explained in [79]. Moreover, this architecture consists a set of RRHs $\mathscr{H} : \{RRH_i, i = 1,2,...,H\}$, where H denotes the number of RRHs which are connected with high speed optical fibre fronthaul links to the associated BBUs in BBU pool. Generally, optical fibres are the candidates to use in the next generation of cellular networks to meet the requirements of data rate demand [5].

Furthermore, there is a set of BBUs in the BBU pool $\mathscr{M} : \{M_j, j = 1,2,...,M\}$, where M

is the number of BBUs in BBU pool for processing the baseband signals of the RRHs. In this architecture, virtualisation technology is used, with the BBUs' functions being installed as software on the servers. A set of users served by RRH_i can be represented as $\mathscr{U} : \{U_u, u = 1, 2, ..., U\}$, where U denotes their number.

In this work, it is proposed that the user can be processed either by its BBU or other BBUs to achieve load balancing and save energy in the BBU pool. Each RRH in C-RAN architecture is associated to a BBU in the BBU pool to perform the PHYcell functions of RRHs. An OS in BBU pool decides to which BBU a newly arriving user is assigned to. In the case of overload or want to achieve energy saving, the OS allows for the reallocation of a user to a different BBU.

In this architecture, the Optical Line Terminal (OLT) is co-located with the BBU pool and Optical Network Units (ONUs) are co-located with the RRHs at cell sites. In the BBU pool, each BBU is associated with one Line Card (LC), and provides baseband processing functions for all the associated RRHs (one BBU can serve multiple RRHs).

In addition, Electronic Smart Switch (ESS) is proposed to be between the BBU pool and OLT to convert the traffic load from the BBUs to the correct LC after switching off a specified number of BBUs under load balancing technology. The ESS is designed to support the dynamic reconfiguration concept for the system which is demonstrated by OS.

The ESS routes the traffic load from the BBUs to the LC by Radio Frequencies (RFs) generated by BBUs and each RF is specified to RRH, where one wavelength can carry multi RFs by using Sub-Carrier-Multiplexing (SCM) techniques [79]. Moreover, the RRHs can separate the undesirable frequencies by filters. By using ESS, the system can be a reconfiguration as one to one, one to many, many to many, and many to one.

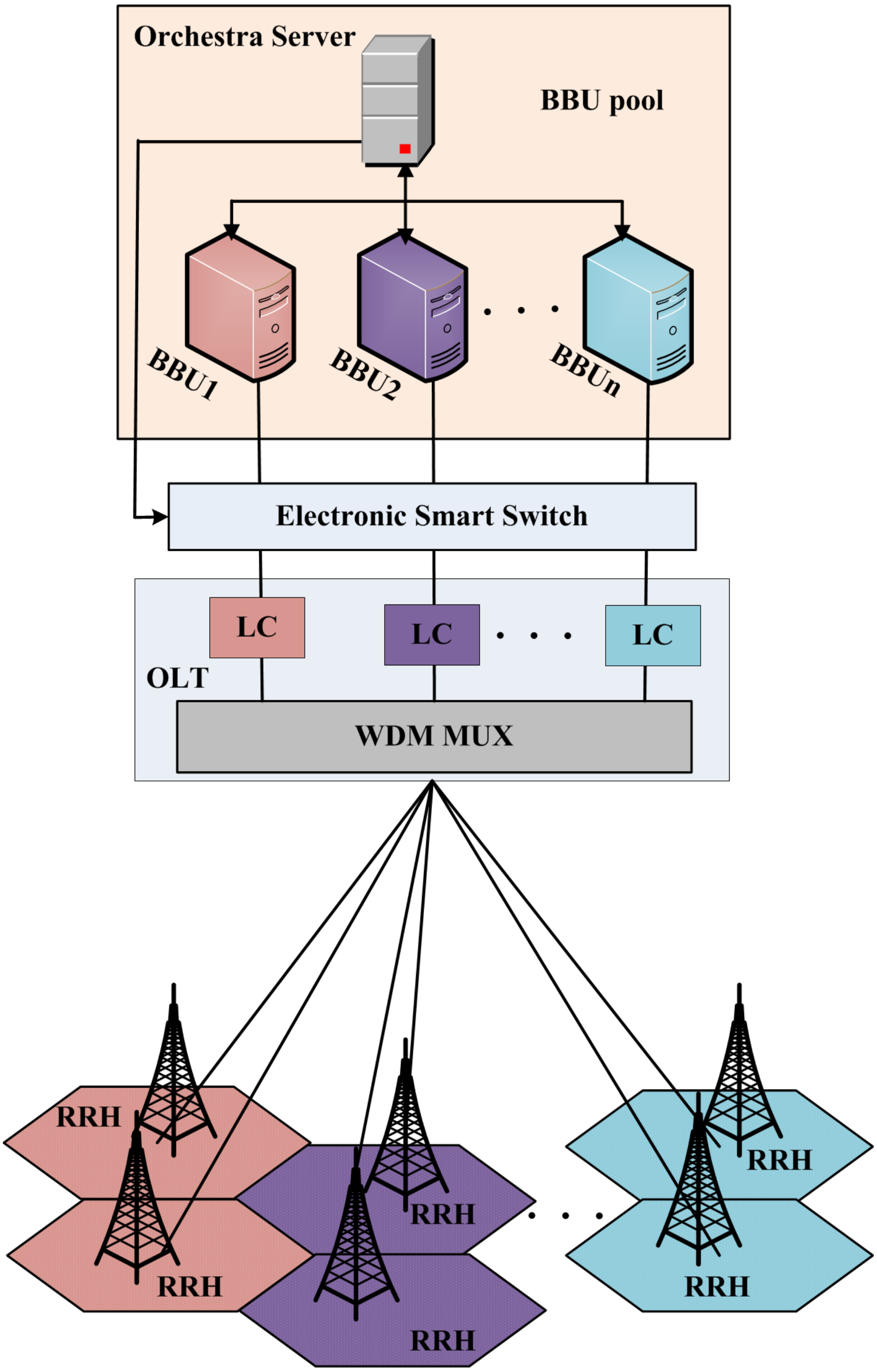


Fig. 3.1 Proposed C-RAN architecture represented by an Orchestra Server

3.4 Computational Resources

In the proposed work knowing the computing resource per user U_u in RRH_i is essential in order to calculate the energy consumption model for the C-RAN architecture. The baseband processing procedure of each RRH in the BBUs is measured in Giga Operation Per Second (GOPS) [34]. Each BBU has maximum capacity G GOPS. eq. 3.1 describes the fraction of Resource Blocks (RBs) allocated to user U_u by RRH_i [80]:

$$R_{i,u}^{REQ} = \frac{r_i}{R_{i,u}} \tag{3.1}$$

where r_i is the data rate demand of user U_u, $R_{i,u}$ is the achievable data rate for user u when it is associated with RRH i and R_i represents load of RRH_i. To obtain $R_{i,u}$, the Signal to Noise Ratio (SNR) of user u associated with RRH_i can model as follows:

$$\gamma_{i,u} = \frac{p_i h_{i,u}}{\sum\limits_{k \in H \setminus \{i\}} p_k R_k h_{k,h} + \sigma^2} \tag{3.2}$$

where $h_{i,u}$ is the channel gain between RRH_i and user U_u, p_i is wireless transmission power of RRH_i, and σ^2 represents average noise power. Based on the Shannon capacity theorem, $R_{i,u}$ can be calculated as follows:

$$R_{i,u} = W log_2(1 + \gamma_{i,u}) \tag{3.3}$$

The computer resource load of RRH_i at the BBU_j can be obtained by summing the resource usage fractions over all the users in RRH_i, which is represented as follows:

$$R_{j,i}^{BBU} = \sum_{u=1}^{U} R_{i,u} = \sum_{u=1}^{U} W log_2(1 + \gamma_{i,u}) \tag{3.4}$$

where, $0 \leq R_{j,i}^{BBU} \leq 1$.

3.5 LTE Power Model

Fig. 3.2 illustrates a block diagram of a BS that can be considered as being representative of all BS types, including micro, macro, femto and pico. A BS comprises several parts of power consuming equipment: a number of antenna (NTx), RF, a Power Amplifier (PA), a baseband engine, a DC-DC power supply, a cooling system, Low Nosie Amplifier (LNA), ADC/DAC, Digital Up Conversion (DUC), Digital Down Conversion (DDC), Mains Supply (MS) and an AC-DC unit [10]. The BS power consumption per sector can be mathematically expressed as follows [81]:

$$P_{in} = \frac{P_{PA} + P_{RF} + P_{BB}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{3.5}$$

where, P_{PA}, P_{RF} and P_{BB} denote the PA, RF, and Base Band unit (BB), respectively. σ_{DC}, σ_{MS} and σ_{cool} denote the losses accrued by the DC converter, MS, and active cooling, respectively, which are scaled linearly with the power consumption of the other components. The output of PA is a linear function of the BS transmission power and is expressed as [10]:

$$P_{PA} = \frac{P_{out}}{\eta_{AP}(1-\sigma_{feed})} \tag{3.6}$$

where, η_{PA} denotes PA efficiency, the σ_{feed} and P_{out} represent feeder loss and output power, respectively. BS power consumption is breakdown at maximum load, where $P_{out} = P_{max}$, yields:

$$P_{in} = \frac{\frac{P_{out}}{\eta_{AP}(1-\sigma_{feed})} + P_{RF} + P_{BB}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{3.7}$$

where, the efficiency can be defined as:$\eta = \frac{P_{out}}{P_{in}}$, and the loss factor can be defined as: $\sigma = 1 - \eta$. The output power of RF per transmit antenna P_{out}, can be measured at the input of the antenna. Consequently, the losses that are caused at the antenna interface are not included in the power breakdown. The P_{BB} and P_{RF} are scaled linearly with bandwidth W

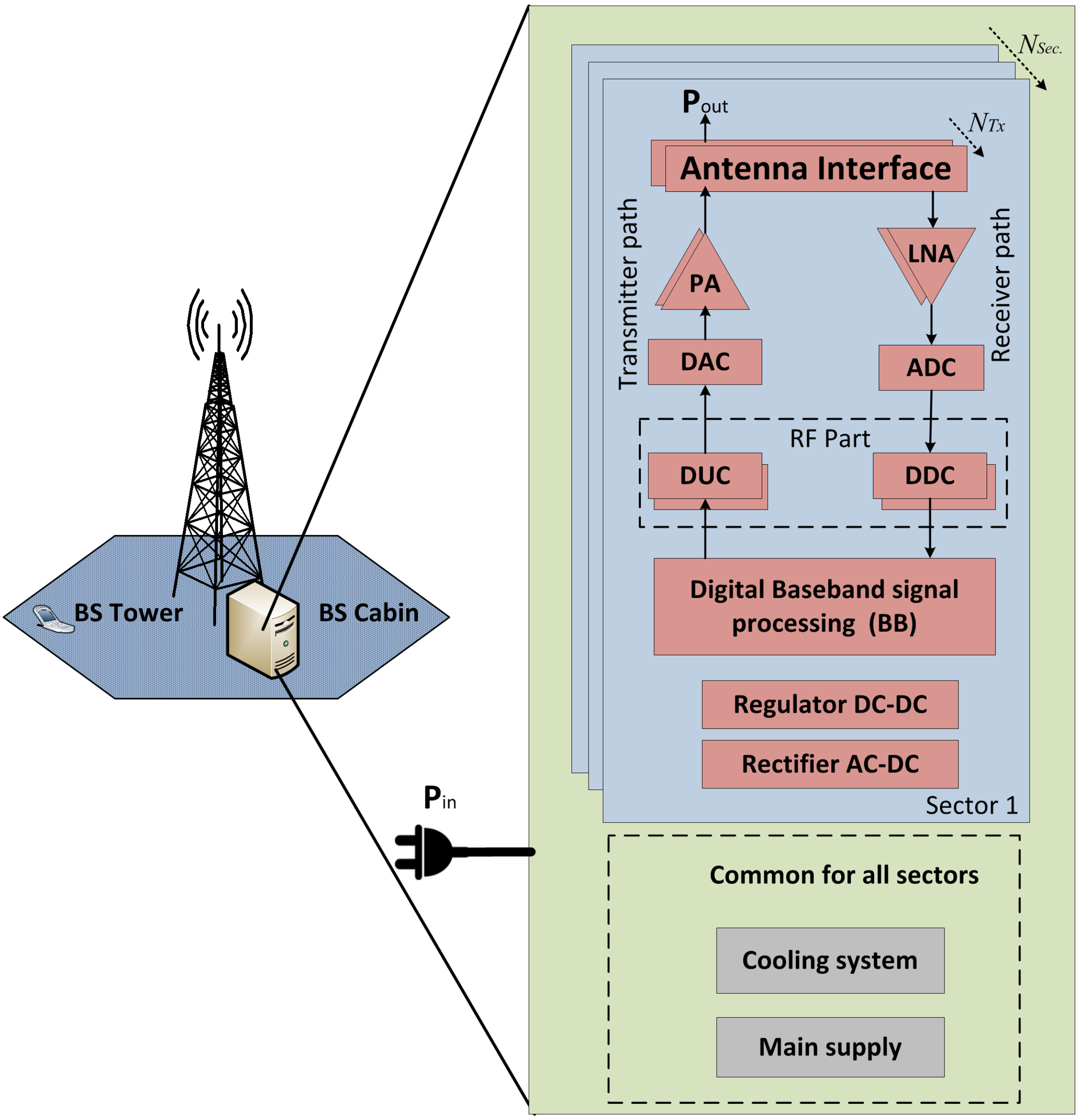


Fig. 3.2 Block diagram of a traditional BS

(i.e. the resources shown in equation 3.3), and the number of antennae N_{Tx}, as well as the PA power consumption depend on the P_{out} per antenna P_{out}/N_{Tx}. Therefore, equation 3.8 can be calculated as follows:

$$P_{in} = \frac{\frac{P_{out}}{N_{Tx}\eta_{AP}(1-\sigma_{feed})} + N_{Tx}W(P_{RF}+P_{BB})}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{3.8}$$

The BS load of the LTE downlink can be defined as P_{out}/P_{in} and this load depends on the power control settings in the context of the transmitted power [81].

$$P_{in} = \begin{cases} N_{sec}(P_o + \triangle_p P_{out} \zeta_n) & \text{if } 0 < P_{out} \leq P_{max} \\ N_{sec} P_{sleep} & \text{if } P_{out} = 0 \end{cases} \tag{3.9}$$

P_{in} and P_{out} is the total power supply, while the output power per antenna is measured at the input of the antenna element. N_{sec} represents the number of sectors in the BS, P_o is the power consumption at the minimum non-zero load, Δ_p is the power gradient variable of a particular BS, ζ_n is the cell load of the nth BS, and P_{sleep} is the energy consumption at the sleep mode. Moreover, the W represent the bandwidth. This model is called The Energy Aware Radio and Network TecHnologies (EARTH) [10]. Therefore, the total power consumption of the traditional LTE system is formulated as:

$$P_{LTE} = \sum_{n=1}^{B} N_{sec}(P_o + \triangle_p P_{out} \zeta_n) \qquad 0 < \zeta_n \leq 1 \tag{3.10}$$

The traffic load of the ζ_n can be normalised (0-1), and B represents the total number of BSs in the network.

3.6 C-RAN Power Model

The EARTH and P_{LTE} models of BSs is widely used in the literature to analyse the energy efficiency and power consumption of cellular networks. These models cannot be used with C-RAN architecture, because the multiple BBUs reside in one BBU pool, so the energy consumption of this pool can be reduced by switching off certain number of BBUs at low traffic load and toggles the tasks of switching off BBUs to the others.

In addition, virtualisation means that the computational resources of the BB can be dynamically allocated, and the BBU can run only when necessary. Hence, a new model for centralisation and virtualisation under C-RAN for a cellular network is required. The proposed power consumption of C-RAN is divided into three separate parts: radio side power consumption, fronthaul power consumption and BBU pool power consumption.

$$P_{C-RAN} = P_{RRH} + P_{FH} + P_{pool} \tag{3.11}$$

3.6.1 RRH Power Consumption Model

An RRH consists of RF and PA that scale linearly with the number of antennae. The power consumption for the radio part can be calculated as [77]:

$$P_{RRH} = \sum_{i=1}^{H} \left(\frac{P_{out}}{\eta_{AP}} R_i^{RRH} + P_{RF}\right) \tag{3.12}$$

R_i^{RHH} represents the computing resource load of RRH_i. The P_{out} represents the output power of RF per transmitted antenna. P_{RF} depends on the number of antennae, whereas H denotes the number of RRHs in the network.

3.6.2 Fronthaul Power Consumption Model

Recently, optical fibre has been proposed as fronthaul link for C-RAN that connects the BBUs with RRHs to provide high traffic demand [5]. Optical power has a significant effect especially when it is used in a large optical network [82]. Many operators and cellular companies are facing difficulties when applying new optical network fronthaul for the next generation. They see economic benefits in using an infrastructure of optical fibres as a fronthaul for the next generation.

In this work, Fibre To The Home (FTTH) network infrastructure is proposed to be used as optical fronthaul for the next generation of cellular networks, as proposed by [63]. A PON can provide a cost-effective scheme to connect RRHs with the BBU pool, which uses components that do not need power. Generally, PON comprises an OLT and a set of associated ONUs through an optical fibre medium. There are three types of optical fibre fronthaul networks: Time-Wavelength Division Multiplexing PON (TWDM-PON), Ethernet PON (EPON) and AON [63].

3.6.2.1 TWDM-PON C-RAN Architecture

TWDM-PON can be defined as a combination of Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM) technology, as shown in Fig. 3.3 [83]. In this architecture, the ONUs are located near to the RRHs and connected to the OLT through optical fibre located in the BBU pool. ONUs can share the same wavelength as the OLT, for which every wavelength is served by a Line Card (LC) (i.e. optical transceiver). Therefore, one LC can serve several ONUs at different sites, which leads to energy saving as demonstrated in [84].

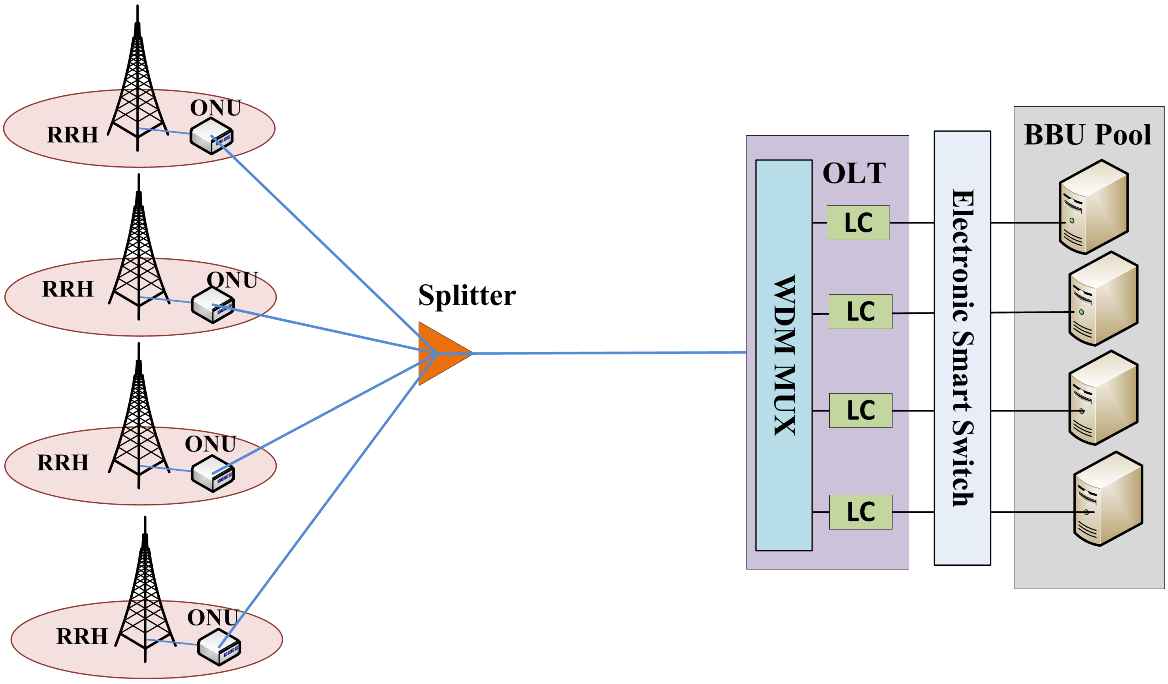


Fig. 3.3 TWDM PON fronthaul architecture

3.6.2.2 EPON C-RAN Fronthaul Architecture

The EPON fronthaul network does not use the WDM, which means the RRH (or number of RRHs) is using a splitter server with single wavelength, as shown in Fig. 3.4. This type is demonstrated in [76] and is explained as Point to Point (PtP) in [63].

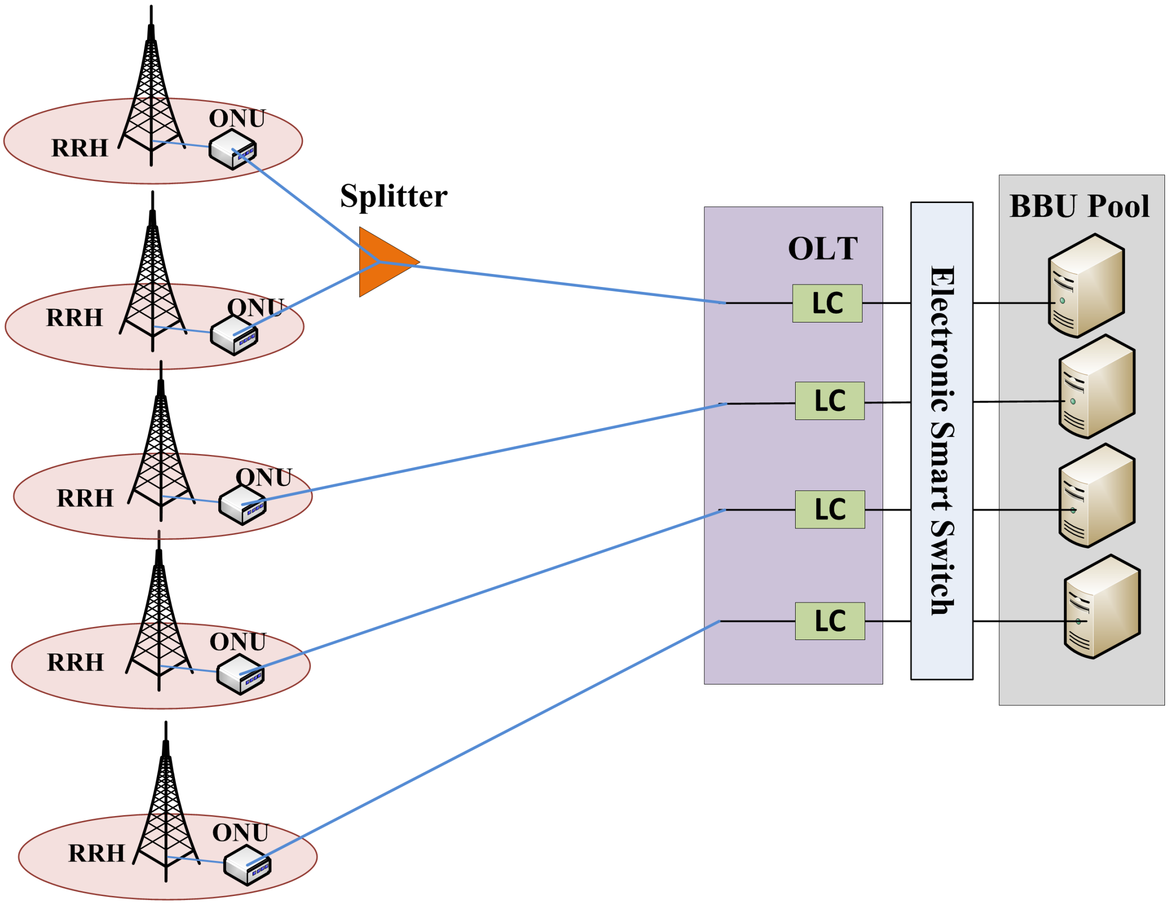


Fig. 3.4 EPON C-RAN fronthaul architecture

3.6.2.3 AON C-RAN Architecture

In an AON, the ONUs are connected to a Remote Node (RN) switch (e.g. in a street cabinet, in a building close to the RRHs or at an RRH site representing a master of a number of slave RRHs), which is in turn connected to a BBU pool switch, as shown in Fig. 3.5. Generally, the proposed RRHs are small, so they can be placed on poles or the rooftops of buildings

[8]. Hence, this architecture is useful for application in FTTH networks. The total power consumption of the optical fibre fronthaul network for C-RAN based on [63] can be given by:

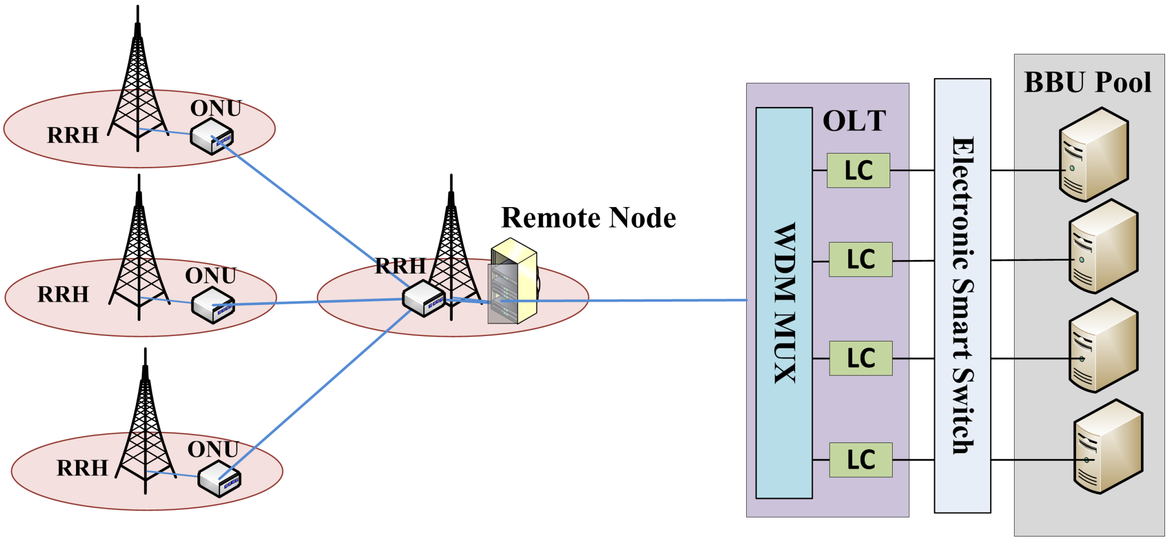


Fig. 3.5 AON C-RAN fronthaul architecture

$$P_{FH} = 2.P_{OLT} + 2.\sum_{g=1}^{G} P_{RN} + \sum_{l=1}^{L} P_{ONU} \tag{3.13}$$

For more elaborate:

$$P_{FH} = 2.\sum_{k=1}^{K} P_{LC} \sum_{i=1}^{H} R_{i,k}^{LC} + 2.\sum_{g=1}^{G} P_{RN} + \sum_{l=1}^{L} P_{ONU} \tag{3.14}$$

where, P_{OLT}, P_{RN} and P_{ONU} are the powers consumed by the OLT, RNs and ONUs, respectively. G is number of RNs in optical fronthaul. At the OLT, every wavelength is served by a single line card LC that is considered as a transceiver, with the OLT consisting of number of LCs and P_{LC} is the power consumed by them. L represents the number of ONUs in the network,whilst $R_{i,k}^{LC}$ denotes a traffic load of RRH_i served by the LCs.

The factor 2 in equations (3.13) and (3.14) of the RN and OLT is power consumption of cooling requirements and external power supply losses. In addition, the power consumed in the OLT depends on the number of active RRHs and the load R_i^{RRH} that is served by them. In the TWDM-PON C-RAN and EPON C-RAN networks there are no RN, which means that $P_{RN} = 0$, while in the AON C-RAN network case there is one.

3.6.3 BBU Pool Power Consumption Model

The power consumption at each BBU is composed of two parts: a static power consumption P_{stat} caused by the procedures (e.g. paging procedures and broadcasting) and a dynamic power consumption P_{dyn} that depends on the amount of processing load at the BBU.

$$P_{BBU} = P_{stat} + \Delta_P P_{dyn} \sum_{u=1}^{U} R_{i,u}^{REQ} \tag{3.15}$$

where, Δ_P represents the linear power model tangent. Generally, the components of dynamic power consumption in a server are the processor P_{CPU}, memory P_{MEM} and hard disk P_{IO} and these have dynamic power P_{dyn} of about 58%, 28% and 14%, respectively [85]. The power is presented as follows:

$$P_{dyn} = P_{CPU} + P_{MEM} + P_{IO} \tag{3.16}$$

where, P_{CPU}, P_{MEM} and P_{IO}, respectively, represent power consumed by the processor, memory and hard disk for each BBU. However, by substituting equation 3.16 into equation 3.15 becomes:

$$P_{BBU} = P_{stat} + \Delta_P (P_{CPU} + P_{MEM} + P_{IO}) \sum_{u=1}^{U} R_{i,u}^{REQ} \tag{3.17}$$

Depending on the EARTH model and the proposed assumption, the power consumption of the BBU pool can be calculated. The total processing power used by the BBU-pool measured in GOPS is:

$$P_{pool} = \sum_{j=1}^{M} (P_{stat} + \Delta_P (P_{CPU} + P_{MEM} + P_{IO}) \sum_{u=1}^{U} R_{i,u}^{REQ}) \tag{3.18}$$

3.7 Problem Formulation

This section introduces the problem formations for the BBU pool and the OLT parts that reduce the power consumption in the proposed system.

3.7.1 Problem Formulation of BBU Pool

In general, virtualisation reduces the total power consumption, as each vBBU can be implemented in the physical BBU server through software. However, it is important to optimise the system by reducing the number of active BBU servers that work with low load. This process is performed by transferring their load to others with respect to the available capacity and thus, shutting them down. The problem of optimising is formulated as shown in equation (3.19) and it can be solved by using Linear Integer Programming (LIP):

$$\min \sum_{\beta_{i,j,u} j=1}^{M} \left(\Gamma_j P_{stat} + \triangle_P (P_{CPU} + P_{MEM} + P_{IO}) \sum_{i=1}^{H} R_{j,i}^{BBU} \right) \tag{3.19}$$

Subject to:

$$\sum_{u=1}^{U} R_{i,u}^{REQ} \beta_{i,j,u} \leq G \quad \forall i \in H, j \in M \tag{3.20}$$

$$\beta_{i,j,u} \in \{0, 1\} \tag{3.21}$$

$$\sum_{j=1}^{M} \sum_{u=1}^{U} \beta_{i,j,u} = U \quad \forall i \in H \tag{3.22}$$

$$\sum_{i=1}^{H} R_{j,i}^{BBU} \leq MG \quad \forall j \in M \tag{3.23}$$

$$\sum_{u=1}^{U} \beta_{i,j,u} = 1 \quad \forall i \in H, j \in M \tag{3.24}$$

$$\Gamma_j = \begin{cases} 0 \sum_{i=1}^{H} \sum_{u=1}^{U} \beta_{i,j,u} = 0 \\ 1\, otherwise \end{cases} \tag{3.25}$$

$R_{i,j}^{BBU}$ in equation 3.19 can be defined as a computing resource at BBU_j that is used by RRH_i in GOPS. $R_{i,u}^{REQ}$ represents a computing resource requirement for user U_u that is served by RRH_i. BBU_j is limited by its processing capacities G, as shown in equation (3.20). The indicator $\beta_{i,j,u} = 1$ when the user U_u of RRH_i is processed by BBU_j and $\beta_{i,j,u} = 0$, otherwise, where, $\beta_{i,j,u}$ is used to minimise the number of BBUs that are illustrated in equation (3.21). Equation (3.22) ensures that the U users for RRH_i can be processed by either a single one or multiple BBUs J. Equation (3.23) indicates that the total processing capacity of the BBU pool is higher than the total computing requirements for all the RRHs. Constraint in equation (3.24) ensures that each user U_u is assigned to one BBU_j. Finally, Γ_j indicates the status of BBU_j, whether it is ON or OFF, as shown in equation (3.25).

3.7.2 Problem Formulation of Fronthaul

The proposed model minimises the total number of used LCs wavelengths.

$$min 2. \sum_{k=1}^{K} P_{LC}.y_{k,j} \sum_{i=1}^{H} R_{i,k}^{LC} + 2. \sum_{g=1}^{G} P_{RN}.s_g + \sum_{l=1}^{L} P_{ONU}.d_l \tag{3.26}$$

Subject to:

$$\sum_{k=1}^{K} y_{k,j} \leq W_k \quad \forall j \in M, \tag{3.27}$$

$$\sum_{k=1}^{K} y_{k,j} = 1 \quad \forall j \in M, \tag{3.28}$$

$$y_{k,j} \in \{0,1\} \quad \forall j \in M, k \in K, \tag{3.29}$$

$$s_g \in \{0,1\} \quad \forall g \in G \tag{3.30}$$

$$d_l \in \{0,1\} \quad \forall l \in L \tag{3.31}$$

where, $R_{i,j}^{LC}$, compute the resource load of BBU j at LC k and $y_{k,j} = 1$, if BBU j is served by the LC k , otherwise 0, as shown in equation (3.29). The LCs are limited by the wavelength capacities W_k shown in equation (3.27). The constraint in equation (3.28) ensures that each BBU j is assigned to one LC. s_g and d_l are Boolean variables indicating weather gth and lth of RN and ONU, respectively, are active or in sleep mode, as shown in equations (3.30) and (3.31), respectively.

3.8 Proposed Algorithm

Obviously, the optimisation problem of the computing resource allocation formulated in equation (3.19) is difficult to solve with an optimal method, because it needs a long time comprehensively searching of all the variables for large scale networks [84]. However, it can be transformed into one of the heuristic methods, such as the Bin Packing Method (BPM) [86]. This is considered as being one of the best heuristic methods for solving the NP-hard problem with a near optimum solution. There are many variables can be adopted in terms of solving these problems, such as packing by cost, linear packing, 2D packing, packing by weight and so on. They have many varied applications, such as creating file backups in media, loading trucks with weight capacity constraints or filling up containers.

The problem can be represented by a finite number of users and bins, which are subject to capacity constraints. The total number of users is weighted in each bin and the capacity considered. The main objective of this method is to find the minimum number of bins to pack the maximum number of users.

There are many algorithms that can be applied by this method, such as First Fit (FF), Next Fit (NF), Best Fit (BF), First Fit Decreasing (FFD), Next Fit Decreasing (NFD), Best Fit Decreasing (BFD), Worst Fit (WF) and so on [8]. MBS considers one of the best algorithm that used in the BPM [87]. Here, an NMBS that is hosted in OS is proposed to solve the problem, where the NMBS algorithm is a modification of the MBS one.

The basic working of this algorithm is same as that of MBS, which considers a nearly optimal algorithm to fill all the BBUs [87]. However, the MBS doesn't achieve load balance among the BBUs. As an example to evaluate the mechanism of the MBS algorithm, six BBUs are given with RRHs working with loads, 80%, 70%, 50%, 30%, 40%, and 20%, as shown in Fig. 3.6 (before load balancing), where the maximum BBU load is 100% and the threshold M_{th} is 90%. By using the MBS, the system will work with four active BBUs with load 80%, (70%+20%), (50%+40%) and 30% and the other units are in sleep mode, as presented in Fig. 3.6 (after applying the MBS algorithm). Whilst this algorithm saves energy by minimising the number of BBUs, it does not deliver the load balancing among them. That is, the fourth BBU works with load 30%, while the others work with nearly maximum load.

Hence, in this work this algorithm is modified to find a set of users that fits the BBU capacity as much as possible with load balancing among them all. The number of active BBUs and the new threshold load for BBU has been determined in advance using equations (3.32) and (3.33):

$$N_M = \frac{\sum_{i=1}^{H} R_{j,i}^{BBU}}{M_{th}} \tag{3.32}$$

$$M_{th}^{N} = \frac{\sum_{i=1}^{H} R_{j,i}^{BBU}}{M_{th} \times N_M} \times 100\% \tag{3.33}$$

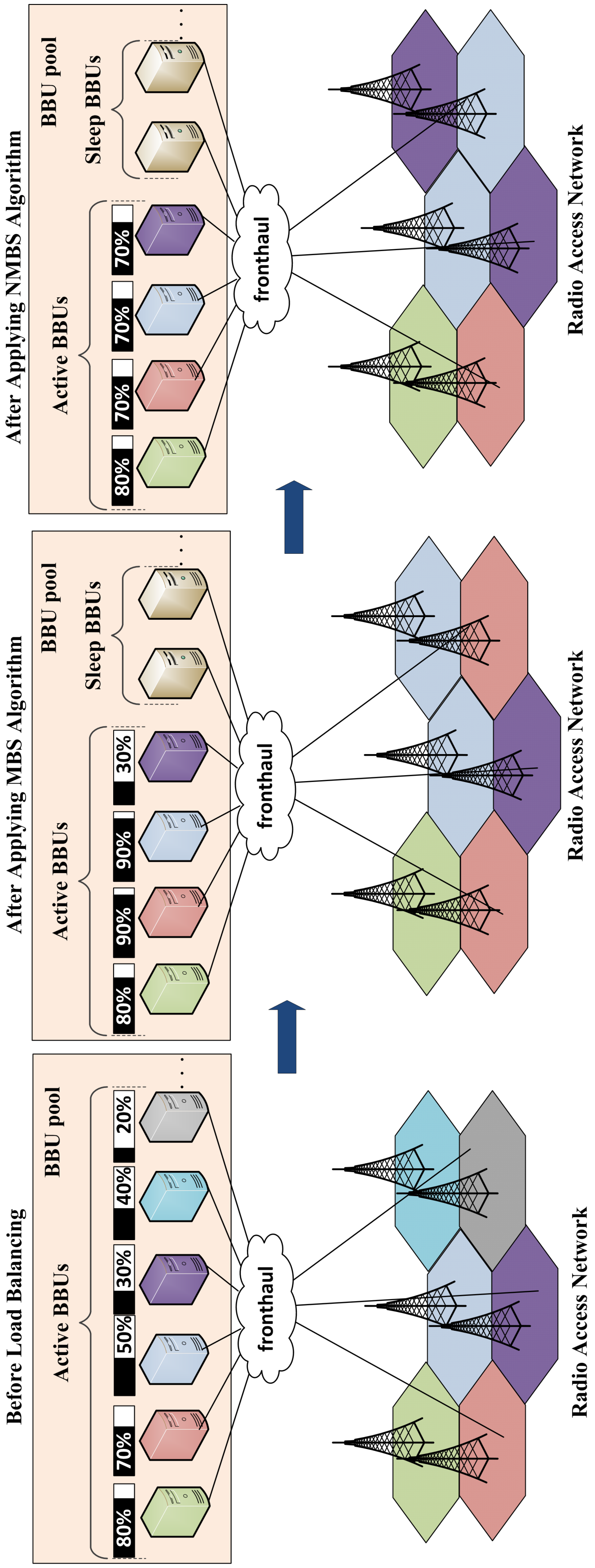


Fig. 3.6 BBU pool before and after applying the load balancing proposed algorithm

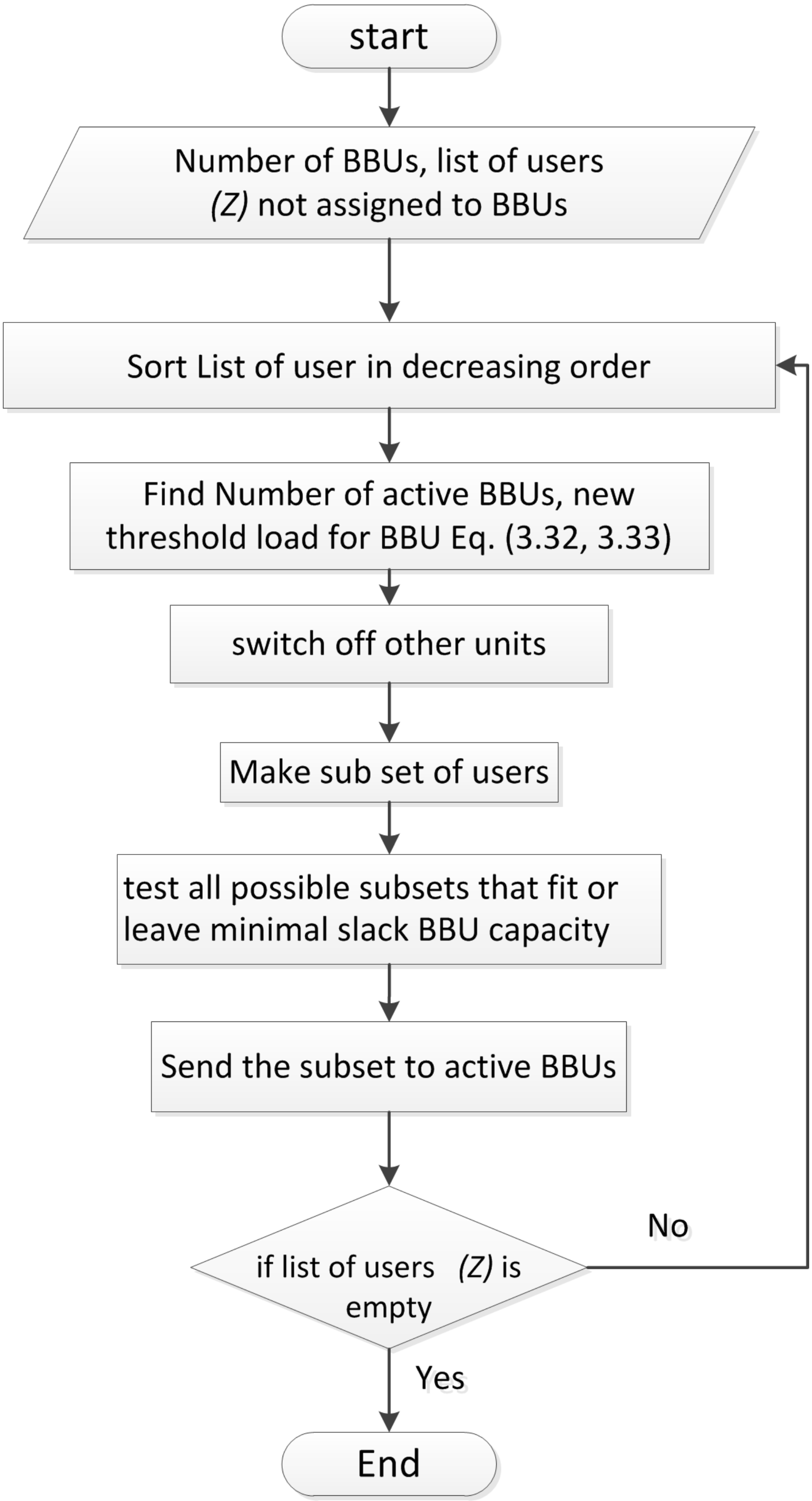


Fig. 3.7 New-Minimum-Bin-Slack (NMBS) flowchart

where, N_M denotes the number of active BBUs. M_{th} and M_{th}^{N} represent the old and the new threshold of the BBU processing capacity, respectively. For the previous example, when applying equations (3.32) and (3.33), four active BBUs will result in 80% M_{th}^{N} compared to 90%. After adding this process to MBS to be NMBS, the result is four active BBUs with loads 80%, 70%, (50%+20%), (40%+30%), as shown in Fig. 3.6 (after applying the NMBS algorithm). We can see, the NMBS achieves load balancing, whilst saving energy at the same time. So, the main difference is finding the number of active BBUs and threshold capacity of the BBUs.

In NMBS, at each step, a list Z of U users not assigned to the BBUs is sorted in decreasing order and determines the N_M and M_{th}^{N}. Each time a packing is determined, the users assigned to a BBU are removed from Z and the sorting order is kept. The procedure ends when Z becomes empty. Each packing is determined in a search process, which tests all possible subsets of users in Z that fit or leave minimal slack in the BBU capacity.

The 3.7 shows the flowchart of NMBS algorithm that starts with each step listing Z of U users not assigned to the M in decreasing order and determines N_M and M_{th}^{N} by equation (3.32) and (3.33), respectively, switching off the others. $n = 1$ and $A = A^* = \emptyset$, where n is the index of the user in list Z from which the processing begins, A is the set of users currently assigned for packing and A^* is the set of users in the best packing, which will be equal to the new M_{th}^{N} . The slack in packing A is represented by $s(A)$, and the number of users in list Z is expressed by U. $s(A)$ can be basically computed by starting from $s(A) = M_{th}^{N}$ and updating every time a user is added to or removed from A. This algorithm also applied with optical fibre fronthaul network to reduce number of active LCs in OLT.

The Best Fit Decreasing (BFD) algorithm is used as a stander to compare with the proposed algorithm shown in Algorthim 1. The basic operation of BFD algorithm is by sorting the incoming load in the descending order. After sorting, load at the top of list is assigned on an already used BBU that has minimum capacity. In case of non-availability of capacity on used BBU, the load is placed on a new BBU that has minimum capacity.

Algorithm 1 Best Fit Decreasing (BFD) Algorithm

```
Input $U\, users\, of\, RRH i, \mathscr{H}, G, R_{i,u}^{REQ}$
Output a packing solution
Sort $U$ in decreasing order of size $R_{i,u}^{REQ}$ of $RRH\ i$
for each $R_{i,u}^{REQ}$ that arrives to BBU pool do
    if $R_{i,u}^{REQ}$fits in $M_j$ then
        Calculate remaining capacity $M_j$
        Place the $R_{i,u+1}^{REQ}$ into $M_j$ which will minimum remaining capacity
    else
        Open new BBU;
    end if
end for
```

3.9 Simulation

This work considers the BBU pool consists of 10 BBUs serving a variable number of RRHs. Each BBU has 1 GOPS capacity. The detailed simulation parameters are shown in Table 3.1 [81]. Moreover, this work is use MATLAB program to get the results.

Table 3.1 Simulation parameters

Model component	Symbol	Value
Static power at BBU	P_{dyn}	175 W
Dynamic power at BBU	P_{dyn}	250 W
Linear model slope	Δ_P	0.44
Power consumption of ONU	P_{ONU}	10.5 W
Power consumption of LC	P_{LC}	5 W
Power consumption of Remote Node	P_{RN}	50 W
PA efficiency	η_{AP}	0.31

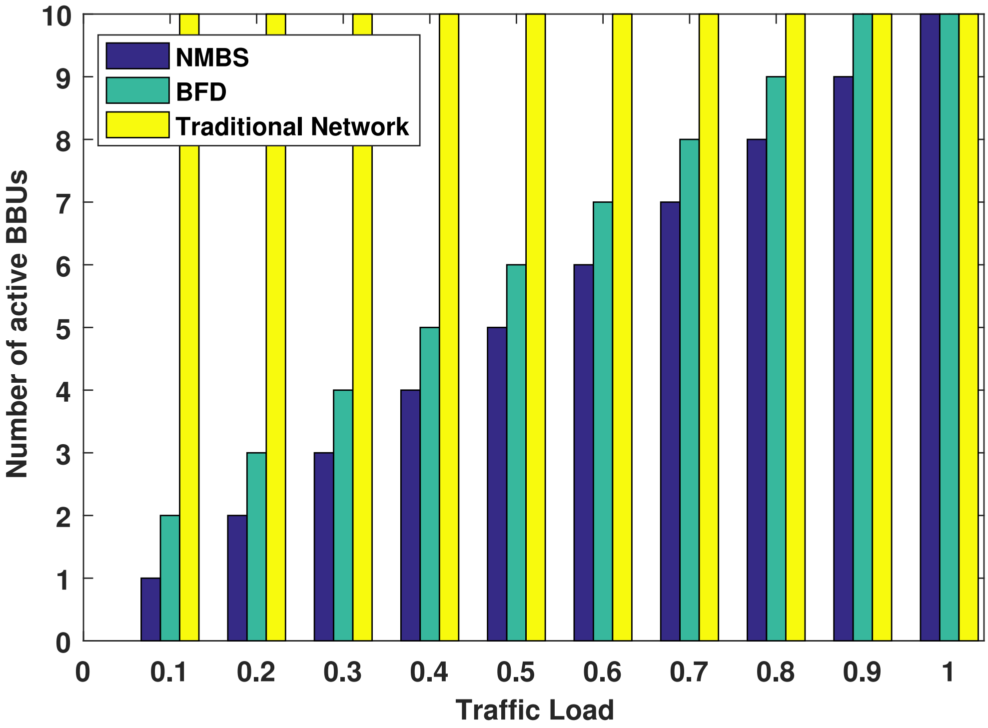


Fig. 3.8 Number of active BBUs in BBU pool

Fig. 3.8 shows the number of active BBUs in the BBU pool for normalised loads (0-1). The results show that the number of active BBUs increases with increasing of traffic load. When the traffic load reaches its peak, all BBUs are active to process all of it. The graph shows the NMBS algorithm outperforms the BFD algorithm and traditional network in minimising the number of active BBUs. This is because of the modification of the algorithm with the proposal that a user can be processed either by its BBU or other BBUs to achieve load balancing and save energy in BBU pool.

The traditional network is expected to use more active number of BBUs, equal to the number of RRHs, in this case 10 BBUs. Fig. 3.9 illustrates the power consumption versus a normalised traffic load. The power consumption by the algorithms and traditional network are increased when the traffic load is increasing. At peak traffic load, maximum energy is consumed for both the algorithms and the traditional network, because all the BBUs are active. The NMBS algorithm consumes less power than the BFD algorithm and traditional network owing to the utilisation of fewer BBUs.

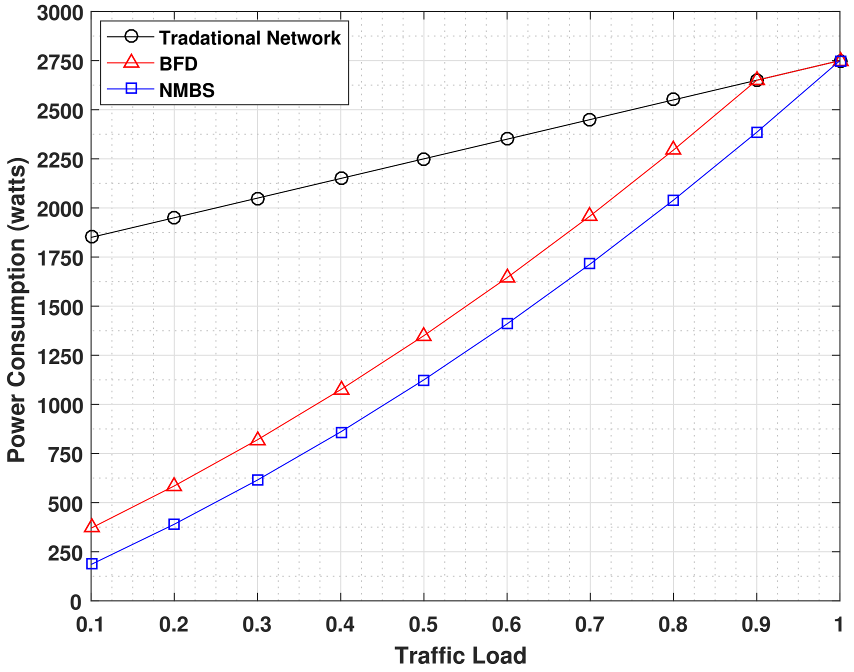


Fig. 3.9 Power consumption in BBU pool

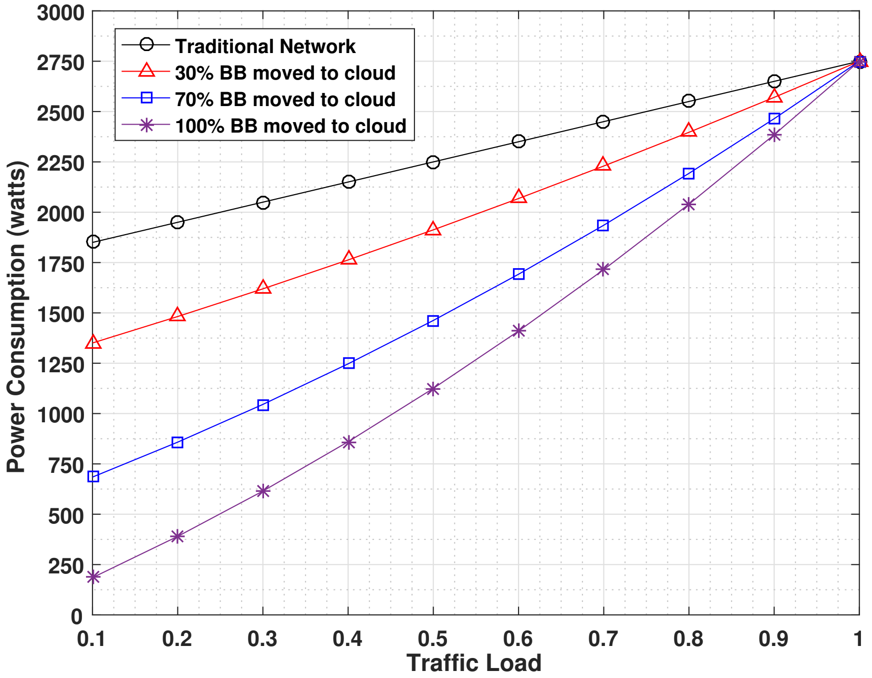


Fig. 3.10 Power consumption for different BB shift options to the cloud

Fig. 3.10 shows how the power consumption versus normalised traffic load for all or part of the baseband function can be processed in the cloud for C-RAN. When all baseband functions are moved to the cloud, it is called full centralisation. When part of the baseband function moves to the cloud and some baseband function is processed in the RRH, it is called partial centralisation [5]. The benefit of leaving some baseband functions in the BS is to reduce the high bandwidth BB signals transported between the cloud and the BS that lead to a high cost in fibre.

In C-RAN architecture, a certain percentage of baseband processing function is moved to the cloud to evaluate the effect on the power consumption of the system. As shown in Fig. 3.10, as more BB processing function moves to the cloud, more power savings are gained, because of more sharing of resources between the BBUs. The power consumption increases with the increase in traffic load. At the peak traffic load, maximum power is consumed for all assumptions because more BBUs are used and they consume more energy. The traditional network consumes more power as expected, because all the BBUs are active at all times. For more realistic values, Fig. 3.11 shows the actual readings of cellular network traffic load taken from China Mobile Company [5], which shows two types of traffic load: business and residential areas, for 24 hours and computing resource expressed in GOPS.

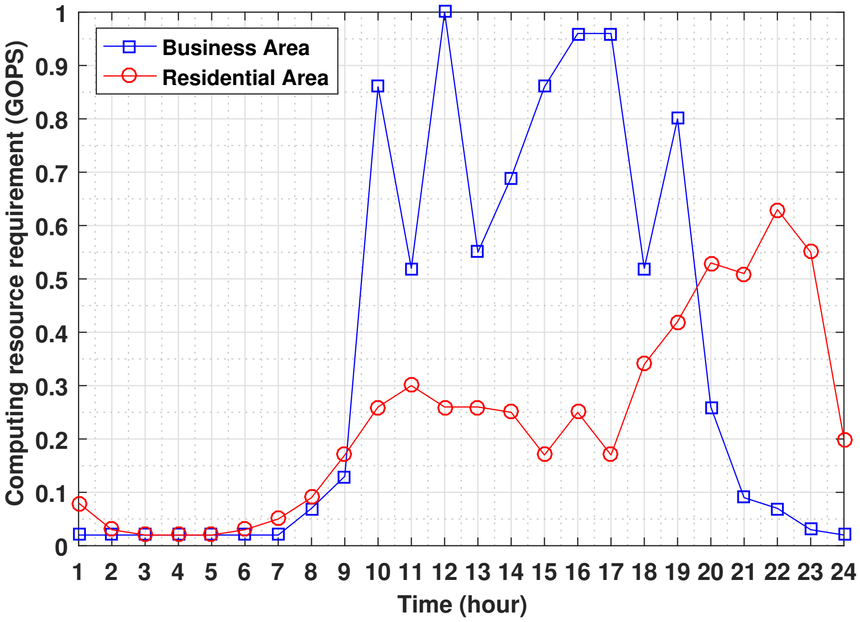


Fig. 3.11 Mobile network traffic load in workday

Fig. 3.12 shows the number of active BBUs in BBU pool that used in the network for the business area of the traditional network, BFD, and NMBS, as well as it illustrates how the NMBS outperforms the traditional network and BFD. Furthermore, the peak hours of the business area are (10:00-19:00) that has a significant effect on the system. Fig. 3.13 illustrates the number of BBUs allocated to a number of RRHs duration of 24 hours in a residential area.

However, 10 BBUs are dynamically assigned to RRHs with respect to the RRHs traffic load required by an algorithm in OS that feed BBUs. In this Fig., the number of BBUs assigned by NMBS and BFD are adaptive and change according to the traffic load; it shows the traditional network is always fully using BBUs during of 24 hours. For both adaptive algorithms, more

BBUs are utilized during high traffic than low traffic load periods. Generally, the NMBS is better than the traditional network and BFD by reducing a number of active BBUs in BBU pool during of 24 hours.

Fig. 3.14 shows the power consumption of 10 BBUs in the BBU pool of the business area for three schemes; traditional network, BFD and NMBS duration of 24 hours. In addition, the figure illustrates NMBS better than traditional network and BFD in saving energy. At the peak hours of (10:00-19:00) that consider a significant time for consuming power, the traditional network and BFD are nearly the same of consuming power, while the MBFD less than them in consuming power. However, Fig. 3.15 illustrates the power consumption of residential area for three schemes; traditional network, BFD and NMBS duration of 24 hours. In this figure, the power consumed by NMBS is less than BFD and traditional network in BBU pool during 24 hour.

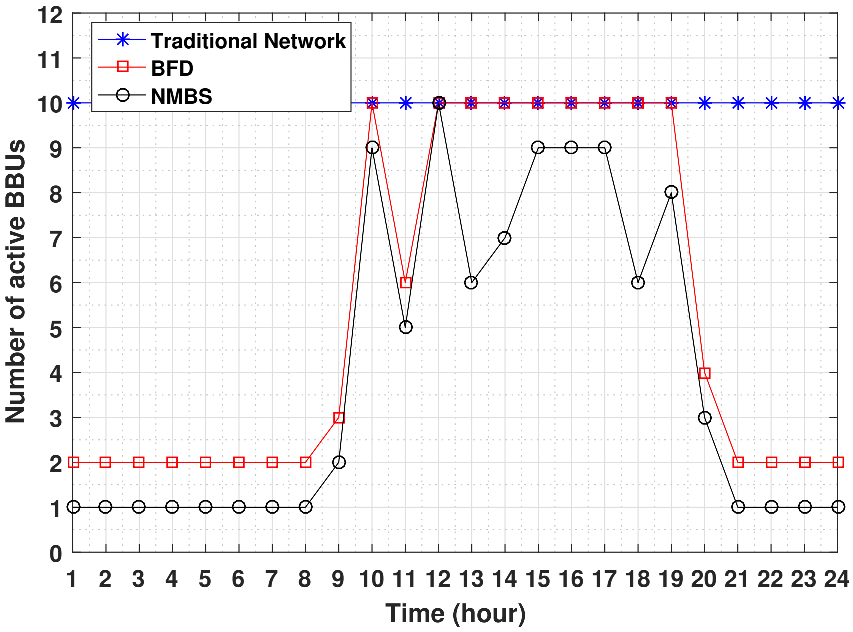


Fig. 3.12 Nmber of active BBUs for a business area

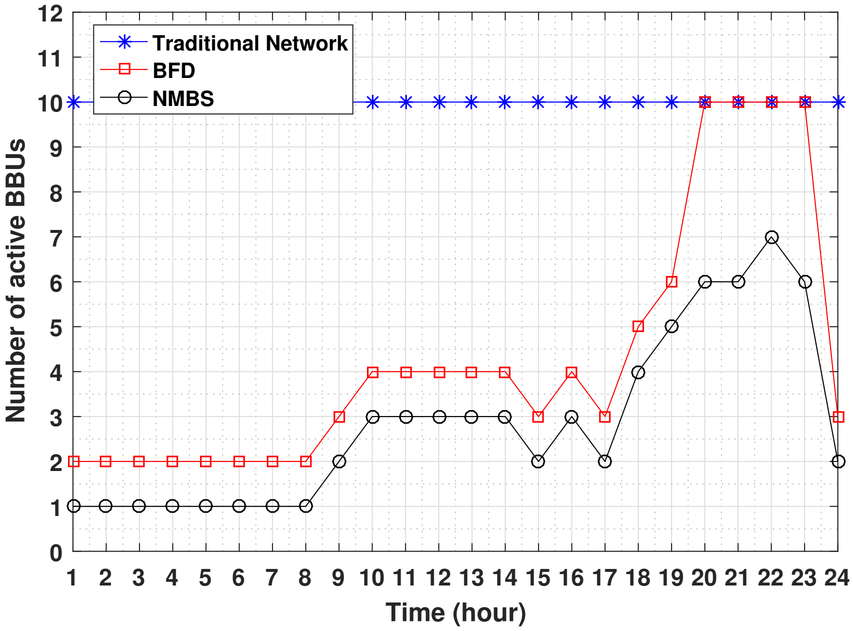


Fig. 3.13 Number of active BBUs for a residential area

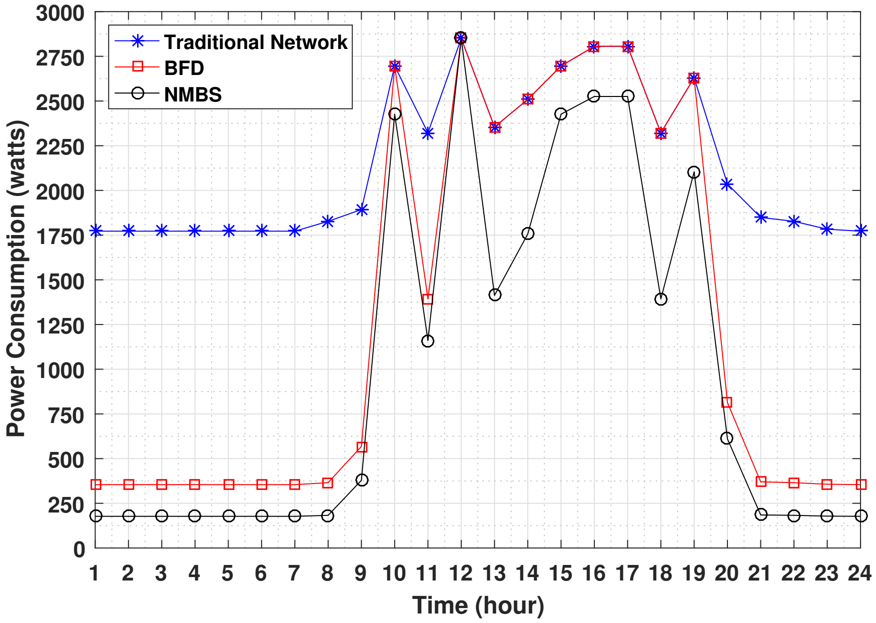


Fig. 3.14 Power consumption in BBU pool for a business area

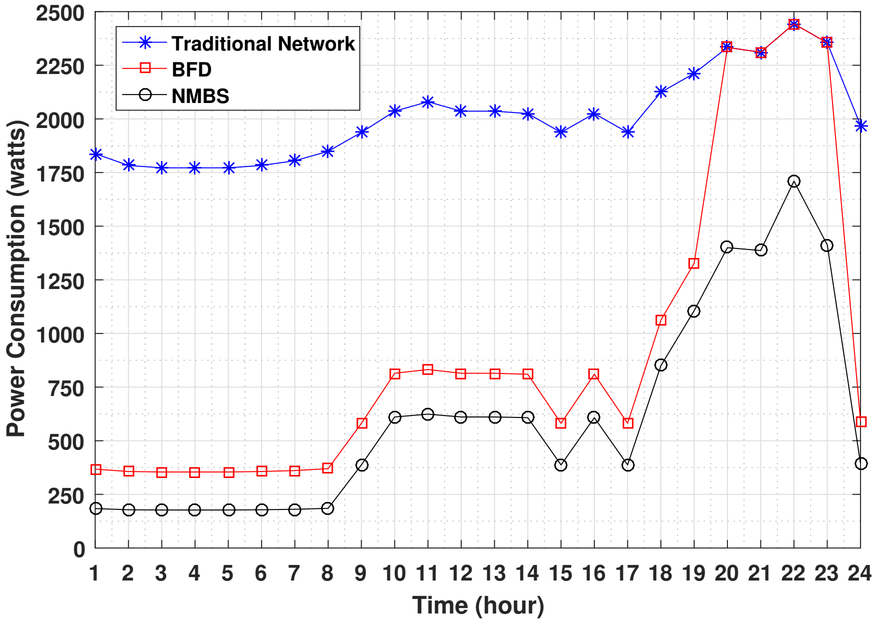


Fig. 3.15 Power consumption in BBU pool for a residential area

Fig. 3.16 shows the number of active BBUs on a daily basis, during low, average and peak traffic of a business area, where, during peak times (10:00-19:00 hours) under 30% traffic load is considered as low traffic, while average traffic is considered to be average load during 24 hours. The proposed algorithm saves up to 90%, 60% and 20% of BBUs utilised during low, average and peak traffic load, respectively, when compared to the traditional network.

Moreover, it saves up to 50%, 20% and 10% of active BBUs of low, average and peak traffic load respectively, when compared to the BFD algorithm. In addition, for residential area; as shown in Fig. 3.17; the NMBS algorithm saves up to 90%, 70% and 50% of active BBUs of low, average and peak traffic load, respectively, when compared to the traditional network. Moreover, it saves up to 50%, 25% and 30% of the BBUs used during low, average and peak traffic load respectively, compared to the BFD algorithm.

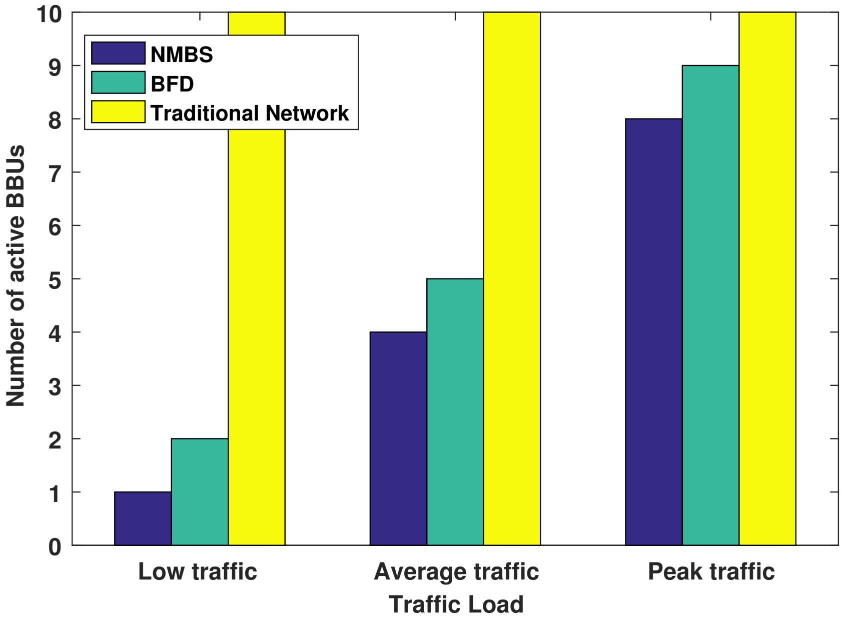


Fig. 3.16 Daily low, average and peak traffic load of active BBUs of a business area

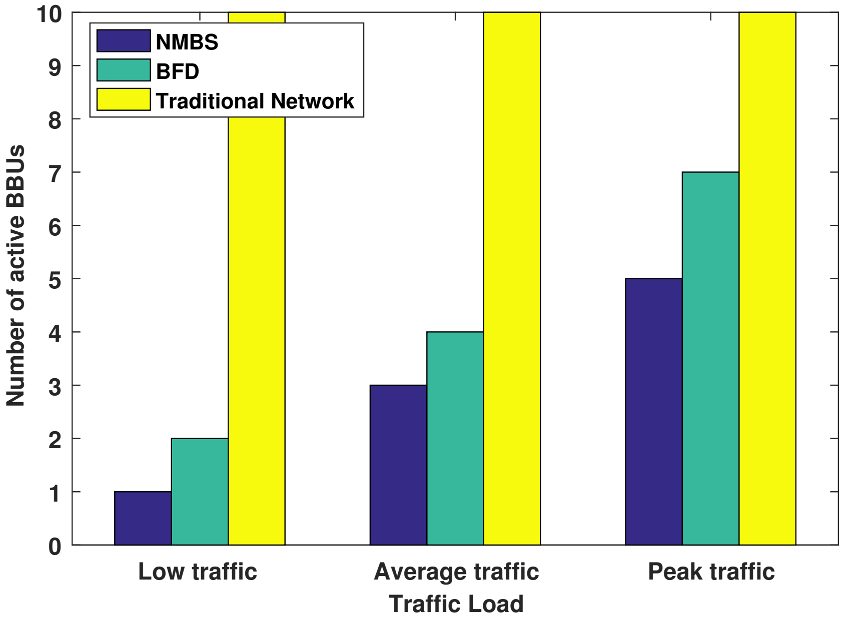


Fig. 3.17 Daily low, average and peak traffic load of active BBUs of a residential area

The power consumption in the business area is shown in Fig. 3.18. The NMBS scheme has consumed 177 W during low traffic since only 1 BBU is used. In contrast, the BFD scheme consumes 355 W with 2 active BBUs, while traditional architecture consumes 1772 W with all BBUs utilised. Hence, NMBS reduces power consumption in the network by 90%, while BFD reduces it by 80% compared to the traditional scheme.

Moreover, during average daily power, NMBS consumes 988 W (4 BBUs), while the BFD scheme consumes 1280 W (5 BBUs) while traditional architecture consumes 2140 W with all BBUs utilised, thus standing at 62% and 53%, respectively, when compared to the traditional scheme. The peak traffic load consumption for NMBS of 2058 W represents a 27% power reduction over the traditional network, while BFD and the traditional network consume 2506 W and 2600 W, respectively.

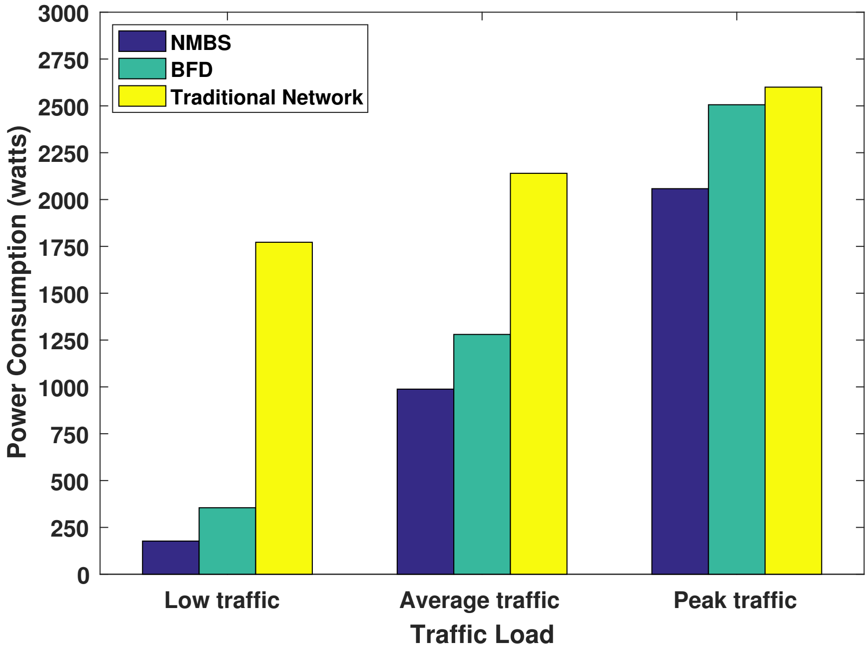


Fig. 3.18 Daily low, average and peak traffic load of power consumption of a business area

Fig. 3.19 shows the power consumption of the residential area. For both the business and residential areas, the power consumption is nearly the same at the low traffic load. During an average traffic load, NMBS uses 3 BBUs leading to 605 W consumption with 74% power reduction, while the BFD algorithm uses 4 BBUs with 913W consumption at 66% power reduction when compared to the traditional scheme, which consumes 2007 W. The peak daily power consumptions for NMBS and the BFD algorithm are 1310 W and 1970 W at 63% and 29% power reduction, respectively, when compared to the traditional scheme, which consumes 2296 W.

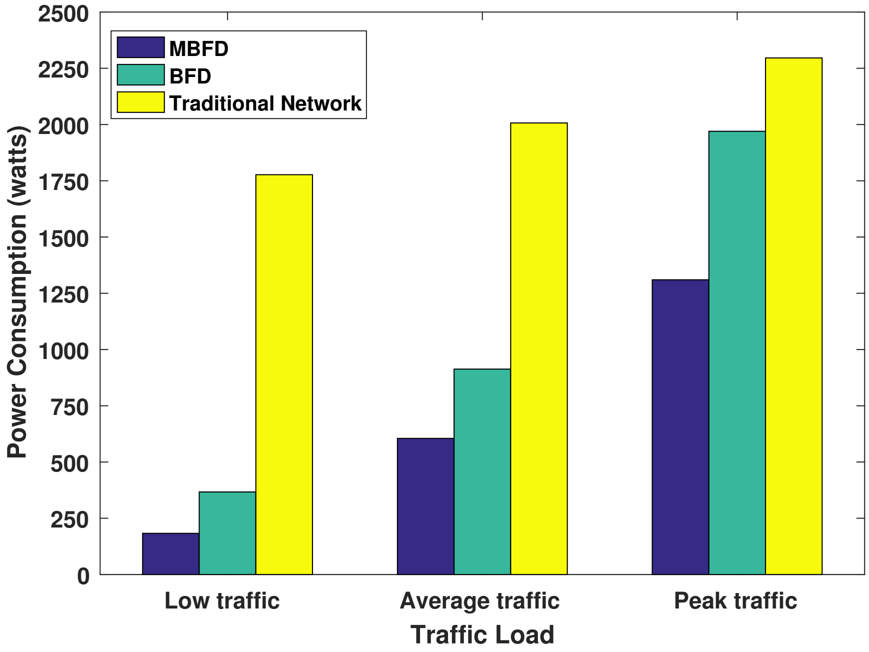


Fig. 3.19 Daily low, average and peak traffic load of power consumption of a residential area

Fig. 3.20 shows a three-dimensional shape of power consumption according to varying number of users and RRHs. It illustrates the power consumption increase with increasing number of users that are served by RRHs as well as increasing the number of RRH in the network. Moreover, Fig. 3.21 shows power consumption against varying numbers of PRBs that are dedicated to RRHs and varying numbers of RRHs. It illustrates how the power consumption increases with an increasing number of PRBs and RRHs in the network.

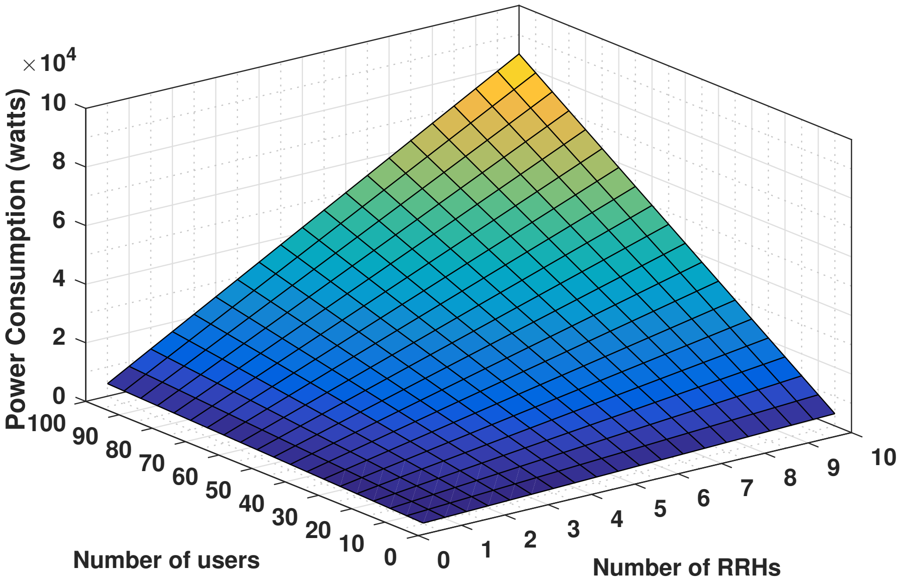


Fig. 3.20 power consumption versus the varying number of users and number of RRHs

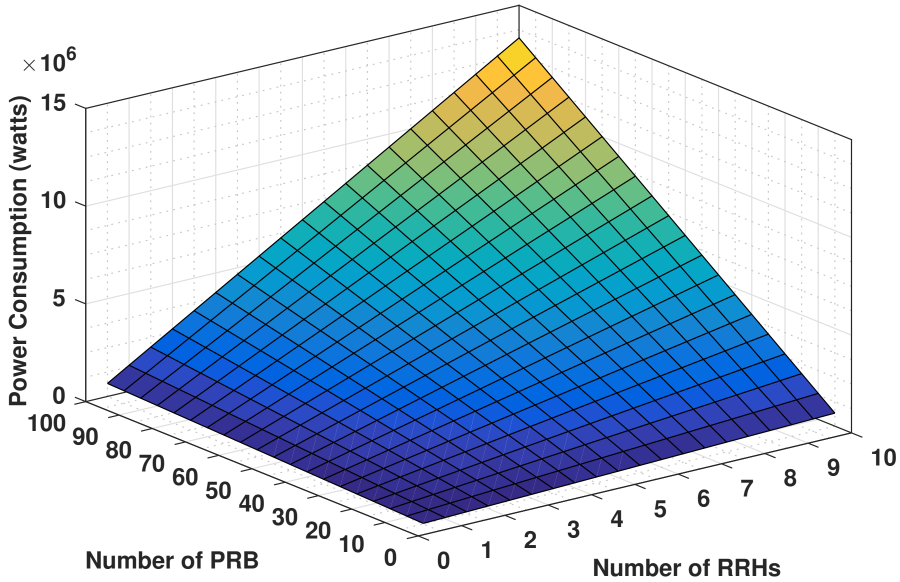


Fig. 3.21 Power consumption versus a varying number of PRBs and RRHs

Fig. 3.22 shows the power consumption of the RRH power model for one, two and four antenna configurations. It shows a dramatic increase in their power consumption with an increasing number of antennae. Fig. 3.23 shows the power consumption of optical fibre fronthaul for three configurations AON, EPON and TWDM-PON C-RAN against the traffic load. It shows that the power consumption of optical fibre fronthaul increases with increasing the traffic load.

TWDM-PON C-RAN consumes power less than the AON C-RAN and EPON C-RAN, because the TWDM-PON C-RAN architecture can use the optimise formulation and proposed algorithm, while the EPON cannot do so. Whilst the AON C-RAN architecture can apply the proposed algorithm, it experiences much more power consumption, because it uses a remote node. In this case, AON C-RAN architecture uses one remote node that consumes 50 W. The average power consumption for TWDM-PON C-RAN and EPON C-RAN is 143 W and 160 W representing 41% and 34% power reduction, respectively, when compared with the AON C-RAN scheme, which consumes an average power of 243 W.

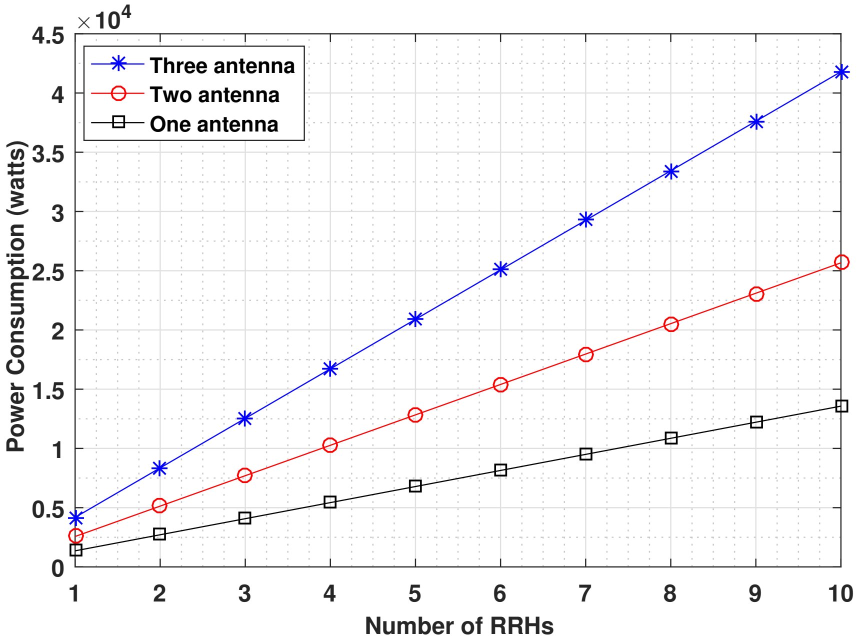


Fig. 3.22 Comparison of RRH power consumption for one, two and three antennae

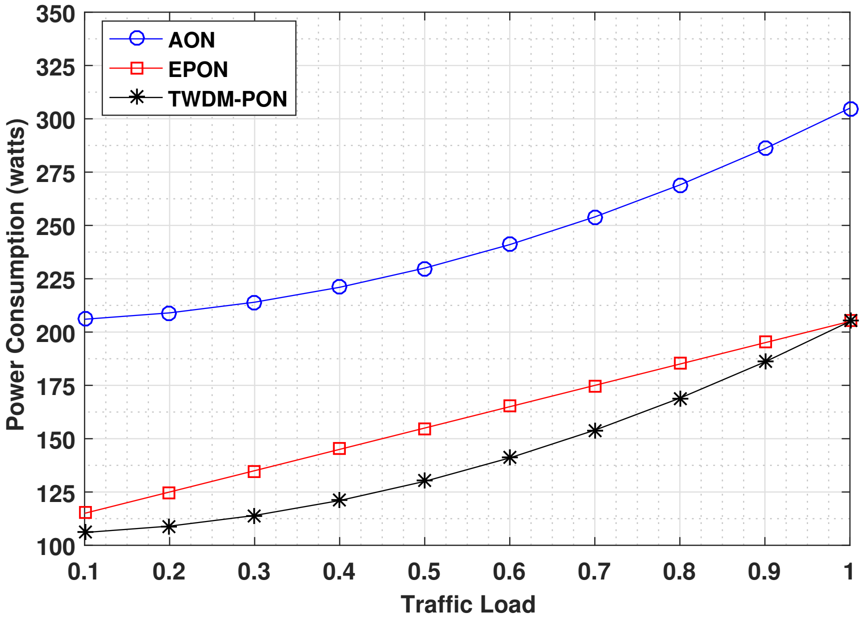


Fig. 3.23 Power consumption of optical fibre fronthaul for three configurations AON, EPON and TWDM-PON C-RAN

3.10 Summary

To conclude this chapter, the dynamic BBU allocations in C-RAN architecture with respect to the data traffic demand of RRHs have been examined, with the aim of reducing power consumption in the BBU pool. A power consumption model for C-RAN based on virtualisation technology is proposed. The dynamic remapping concept of C-RAN has been exploited to optimise the reconfiguration of the RRHs to achieve proper BBU in a time-varying traffic load to save energy.

An OS is proposed in the BBU pool to support the system in terms of self-organization. an intelligent algorithm is utilised by OS to find the proper network configuration. The OS produces a decision to the switching system to make reconfiguration of BBUs-RRHs, as well as sending commands to the BBUs in order to switch them on/off with respect to the traffic demands of the RRHs. Furthermore, in this chapter, an optimisation power consumption model for the C-RAN based on a bin packing algorithm, namely, NMBS is introduced and compared to BFD and the traditional network to evaluate the system. NMBS is a modified version of MBS, which tries to find a set of users that fits into the bin capacity with load balancing among them as much as possible.

The simulation result show that the NMBS algorithm performs better than BFD and the traditional network by reducing the number of active BBUs in residential and business areas during the day time. Moreover, the average daily power consumption of the business area is reduced by 62% by using NMBS algorithm, while the BFD reduced by 53%, when compared with the traditional network. The peak daily power consumption for NMBS and the BFD algorithm of the residential area is reduced by 63% and 29%, respectively, when compared to the traditional scheme.

Regarding the optical part, TWDM-PON C-RAN is considered than the other types tested due to its flexibility, whereby it can provide dynamic reconfiguration if needed. Finally, the average power consumption for TWDM-PON C-RAN and EPON C-RAN are reduced by 41% and 34%, respectively, when compared to the AON C-RAN scheme.

Chapter 4

Planning and Optimizing C-RAN Architecture for the 5G Communication Network

This chapter is introducing the approach to determine the placement of Base Band Units (BBUs) pool and dimension pools area for the Cloud Radio Access Network (C-RAN) architecture to introduce a simpler system in terms of management and evaluated system performance. The model takes as input of Remote Radio Heads (RRHs) positions in the network result as output optimal positions of BBU pool in the network based on latency constraints. The Quasi-Newton Method (QNM) algorithm is proposed in this work to estimate the best locations of BBU pools as well as the Particle Swarm Optimization (PSO) algorithm used to solve the pooling problem.

The position of BBU pool is chosen as a closest location of all RRHs to optimize the latency of the network. Furthermore, this chapter finds the minimum required number of the BBU pools in the proposed network with respect to the fronthaul delay constrains. A real heterogeneous network is used to evaluate these algorithms. This work shows the RRH coverage area is very considerable value in determining the fronthual link.

Moreover, this chapter investigates the Dynamic (DC-RAN) which adaptively adjusts the master RRH coverage according to traffic load required in a cellular network. The DC-RAN based on pooling concept. The purpose of DC-RAN is to balance the traffic load and reduce the energy consumption.

4.1 Introduction

Cellular networks are critical infrastructures by their nature. The continuous increasing in mobile access devices (e.g. smartphones and tablets) has caused demand that outstrip the current cellular network capabilities (or cannot faced by the current network) [88]. Moreover, a large number of applications and services depend on mobile device connectivity to allow them to work professionally. Several Internet of Things (IoT) applications (such as telemedicine systems, traffic control systems and others) will use cellular networks in the next generation of the mobile communication system [89]. These applications and increasing under of mobile devices will share the resources in the network, which will cause an explosion traffic with sinefigant effects on the cellular network performance. Therefore, the existing mobile network requires some changes in technologies and architecture to face these issues.

Fifth Generation (5G) can be regarded as a solution to evolve the current cellular networks. The 5G will require Quality of Service (QoS) guaranteed with continuous access to the internet, low latency, green communication and high capacity [39]. Development of the 5G is currently underway to allow full deployed by year 2020 [90, 91]. In term of evolution for current cellular networks (Second Generation (2G), Third Generation (3G) and Fourth Generation (4G)), the centralized of radio signals processing is proposed to be 5G with the C-RAN architecture [21]. The C-RAN architecture is explained in detail in chapter two.

The main advantage of C-RAN is one BBU can run multiples RRHs that have different data traffic load throughout the day. This can occur when one site covers residential and a second one covers offices area. Generally, users moving from one area to the other throughout the day within different data traffic load on the sites. Naturally, office areas are loaded in working hours while sites in residential areas are mainly lightly loaded, and vice versa. Therefore it is useful to share the resources and processing between the BBUs to accommodate more loaded sites.

Regarding the C-RAN architecture and 5G requirements mentioned in chapter two, the field of network planning is essential for cellular networks deployment to meet the increasing demand of high data traffic and enhanced QoS. However, for the current and future cellular network deployment the BBU pool placement is required. The planning task is a result to determine where BBU pool should be located, and dimension pool area. However, there are challenges relevant to the network planning such as latency constraints of fronthaul links, which shall be carefully considered in the design process.

Therefore, a trade-off between fronthaul latency and where to place BBU pools is considerable. The problem requires the knowledge of several parameters as inputs related to the network planning such as a geographical cell distribution, average cells coverage area, and time delay of Hybrid Automatic Repeat reQuest (HARQ). However, optical fibre front haul latency considers a main constraint to determine the BBU pool placement and its area. Optical fibre fronthaul distance between the RRHs and BBU pool is about (20-40 km) [8], this limitation is coming from the base band processing and propagation delay in optical fibre. This figure is widely adopted in the literature to analyse constraints latency fronthaul of cellular systems [8, 31, 35, 38, 92–97].

The stage network planning takes as input the locations of the RRHs for BBU pool hosting to compute the optimal positions and required number of the BBU pools, considering only the fronthaul delay constraint into account HARQ, in terms of maximum distances between RRH and BBU pool. Not all the positions can be considered as optimal places, the position should be able to meet delay constraints and infrastructures required to host BBU pool.

However, network operators cannot place BBU pool in arbitrary sites, such as difficult geographical area, protected buildings, and so on. Therefore, a careful network planning of BBU pool location must be performed. Planning network is considerable to determine the required number and optimal BBU pools position in the C-RAN architecture to provide performance guaranteed service in a large cellular network area. As a result, planning task for current and future cellular networks in a cost-efficient way is important, required and crucial for such a C-RAN.

4.2 Related Work

Pools planning issue for the C-RAN architecture is not studied widely as far as the researchers have known. The optical fronthaul network should be carefully designed, in particular one of the significant elements that contribute to capacity, end-to-end latency, network deployment and the cost of the C-RAN.

In [98] the authors introduce the BBU pool placement optimization problem for C-RAN architecture and classified different deployment solutions. The problem is addressed based on Integer Linear Programming (ILP) and evolving the proposed model with optimization of the BBU pool and electronic switches placement. The authors in [99] provided a model, which considered the cell site positions in an urban area as input to the proposed algorithm and computed the possible location of the BBU pool for different constraints, as well as, estimating the number of required BBUs in the pool.

The scholars in [100] introduce a proposal for the BBU placement, where they are moved to the edges of the network. Moreover, they propose using of reconfigurable wireless mmWave links fronthaul instead of optical fibre in order to provide the RRHs with connectivity. In [101], the authors propose a model by an ILP formulation to determine the BBU pool placement on a converged Multi-Stage Wavelength Division Multiplexing-Passive Optical Network (WDM-PON). The purpose is to choose in which cell to place BBU pool, as well as to take in account the routing and wavelength assignment of traffic demands in order to minimize the number of BBU pools. Moreover, they study the maximum latency of Digital Radio-over-Fibre (D-RoF) between each BBU and RRH, which becomes a constraint on the maximum propagation delay of corresponding nodes.

In [102], the researchers investigate the BBU pool placement issue in C-RAN architecture, they are trying to minimize the distribution cost of the BBUs with respect to their processing capacities. They propose an algorithm to solve the problem formulation of the BBU pool planning and placement. In [103], the authors introduce and formalised a BBU placement problem for C-RAN deployment, which considers the fronthaul transport links. Their work is based on realistic data describing suburban, urban and rural scenarios, with different multiplexing/routing choices for the fronthaul and placement of the BBU pools.

In [104], the scholars introduce an algorithm for BBU pools placement with their allocated RRHs as subsets of radio access nodes. In [105], the authors define a cluster set of RRHs and considere the geographical constraints to determine the placement of the BBU pools. In addition, they minimize the installation cost of the C-RAN architecture by minimizing the total optical fibre length. The authors in [8] stressed the importance of optimized clustering of RRHs in single network to prevent the BBU pool from overloading, due to resource limitation, but they do not propose any solution for this issue.

The authors in [11] introduce Round Trip Time (RTT) calculation C-RAN architecture, and they do not show latency in the fronthaul due to the effect of cell coverage area (i.e. RTT delay values between the RRH and user). Authors in the previous literature review, whose are investigate in the BBU pool planning in C-RAN architecture, they ignore the wireless effect between the user and RRH (i.e. cell coverage area) in length of fronthaul and in determining the optimal position and required number of BBU pool in C-RAN architecture.

However, cell coverage area has an important effect on BBU pool position and optical fibre fronthaul. The literal review don't considered and ignored this factor in network planning design. Therefor, this study presents the influences of this factor on planning network and fronthaul size. In order to solve the BBU pool position problem, a heuristic algorithm is adopted, based on the concepts of distance pool position.

4.3 Fronthaul Link and Delay Budget

The fronthaul access is one of the considerable parts in C-RAN ecosystem; it potentially supports the adoption of C-RAN architecture. Fronthaul is the transmission link that provides connectivity between the centralised BBU pool and multiple distributed RRHs. There are two common types of fronthaul which are wireless and wire links; this chapter focuses on the wire link using optical fibre links as a candidate to be used in the Next Generation Network (NGN) [91, 21]. It can meet the increasing demands for high data rate.

The innovation of C-RAN architecture is introduced to fulfil the high user expectations, along with solving the problem in the current 4G network related to the system management, besides efficient usage of network resources, which is the main driver for energy saving. There are many challenges accompanied with the proposed C-RAN architecture. The rigid specifications are the low latency and high throughput in the fronthaul link.

In general, there are three different types of C-RAN architectures according to the split function options of baseband processing unite between RRHs and BBU pool as mentioned before in chapter two.

The proposed configuration in this chapter of the C-RAN architecture is based on the emerging one (full centralization), therefore the HARQ needs to provide the channel reliability not only to the wireless link between UE and eNB as a single hop but also for the new modules and protocols that have been introduced between the UEs' Transport Shared CHannel (SCH) and the Transport SCH in the BBUs' entity. To guarantee effective latency engineering and a strict latency control for any delay variability in the RTT of Transport Channels (TrCH) Link Delay Budget (LDB).

Therefore, LDB has to be accurately measured and monitored [107]. Therefore, new delay factors added to the LDB, such as the propagation delay of the transmitted signal in the optical fibre used in the fronthaul link. Subsequently, this delay value is going to define the maximum length of the optical fibre between each RRH and its BBU unit. It is a postulate that each RRH unit has a different LDB, matching its deployment distance from BBU location. Furthermore, the fronthaul link dimension requirements should take into account any related functions or elements inserted to perform the required C-RAN framework. The Common Public Radio Interface (CPRI) and Open Base Station Architecture Initiative (OBSAI) standards are proposed to be used as a transport interfaces in the fronthaul link [57], such as optical fibre link which is considered here, they are transporting a D-RoF and sharing a number of similarities [38].

4.4 Hybrid Automatic Repeat Request

HARQ is performing retransmissions and FEC (reliability requirement of shared transport channels) of the erroneous frames or transport blocks, to reduce FER or BLock Error Rate (BLER) and enhance shared logical link throughput between the eNB and the UE, in UL and DL directions. Rather than waiting for upper layer retransmissions; such as Automatic Repeat reQuest (ARQ) functionality in TCP for non-real time applications. This of course results in latency reduction, if the use of HARQ is just for one hop between eNB and UE; as the wireless propagation delay can be neglected and just deal with TTI and processing delays in eNB and UE [106].

Today, the situation is completely different, in the C-RAN architecture, the eNB is sliced into BBU and RRH. Furthermore, the optical fibre link used to connect BBU and RRH using CPRI protocol all these combination is using RoF. HARQ is imposing constraints on maximum distance between BBU and RRH in terms of TTI and processing delays. Fibre propagation delay and multi-hop routing, within the front-haul fibre network add extra delays on HARQ time [64].

4.5 Interaction of HARQ within C-RAN

The HARQ is a protocol candidate for NGN to use in C-RAN [64, 108]. The mechanism of the HARQ protocol in the C-RAN, taking UL process as an example is as follows, the UE MAC layer receives ACK/NACK over the DL TrCH after sending TB over the UL TrCH. Therefore, C-RAN modules' processing, which are UL CPRI interface processing, UL TB decoding process, ACK/NACK creation process, DL TB creation process and DL CPRI interface processing, they should complete within 3 msecs after receive the UL data from the UE as shown in Fig. 4.1.

The BBU designed to complete the processing and send ACK/NACK within 2.7 msecs, instead of 3 msecs [11], to compensate any additional delay created from the variation of the propagation velocity of optical signal by the optical fibre media in the fronthaul link. Furthermore, active equipment such as active WDM, PON, Ethernet, etc, add extra delay to the LDB.

Table 4.1 lists the RTT delay values of all components of the link between the BBU and RRH, which are used to evaluate the total delay produced in the link between RRH and BBU as well as to calculate the maximum permissible optical fibre link distance. Where the maximum fibre link distance depends on residual tolerated time delay and the transmission latency δ_s of optical signal propagated into optical fibre, which is 10 usec/Km [11].

Generally, optical signal propagation into optical depend on fibre type, fibre's refractive and wavelength. Therefore, the light travels more slowly in optical fiber than in vacuum due to the fibre's refractive. In standard single mode fibre defined by ITU-T G.652, the optical signal propagation of 1310 nm wavelength is 4.895 μsec/km and optical signal propagation of 13550 nm wavelength is 4.897 μ/km [107]. Subsequently, about 250 μsec as a maximum

Table 4.1 Round trip time delay values of C-RAN

no.	Delay Components	Unit delay	Typical values	
			min	max
1	RTT of RF processing	RRH (δ_R)	25 μsec	40 μsec
2	RTT of CPRI processing	RRH, BBU ($\delta_{R,B}$)	10 μsec	10 μsec
3	RTT of BBU processing	BBU (δ_B)	2.7 $m$sec	2.7 $m$sec
4	RTT of Active equipments	Fronthaul (δ_A)	4 μsec	40 μsec

delay can be permitted in the front haul link [109]. Additionally, any further delay added due to the optical fibre media propagation characteristics would limiting the maximum allocation distance between BBU and RRH. The HARQ's LDB components could be used and carefully defined to form the RTT of the TrCH either in UL and DL.

In this chapter, the effect of RTT delay values between the BBU pool and RRH in addition to the wireless coverage area of RRHs is interested. The coverage area of RRHs are very considerable values in determining the optical fibre fronthaul, where, Fig. 4.1 show delay link budget of MAC-Layer RTT in C-RAN architecture.

4.6 Impact of Radio Interface Delay

There are many studies oriented about the LDB dimension and design of RTT in UL/DL's TrCH [6, 99, 61, 88]. These studies rely on the original LDB dimension for LTE TrCH RTT design, which neglected any consideration of the wireless wave propagation delay at physical layer radio link. In LTE system, HARQ RTT dimension provides a tolerated LDB design that is appropriate for the requirement of UEs' high speed mobility and to enable wide coverage area in eNB deployment. The supportive procedures are the delay spread, timing advance and transmit/receive switching functions [110].

With the existence of C-RAN the LDB model and analysis should consider the consequence

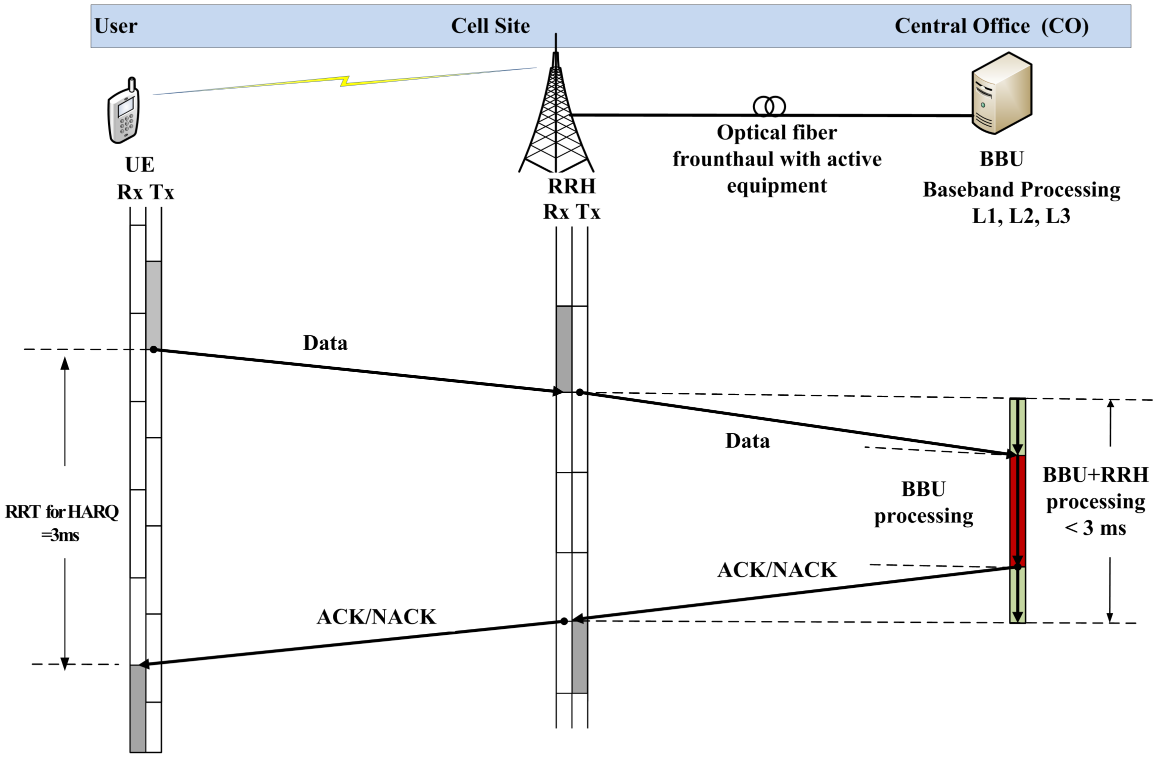


Fig. 4.1 Delay link budget of MAC-Layer RTT in C-RAN architecture

of new delay components introduced by the fronthaul transmission link between BBU and RRH. This delay will be added to the wireless media delay components. As a logical result, the dimension of HARQ protocol RTT is governed by aforementioned LDB, which is biased among fronthaul link delay components and the wave propagation delay between the UE and the BBU. Wireless wave propagation delay depends mainly on the distance between UE and the associated RRH, as a single connected radio access node for the UL and DL directions, excluding the Coordinated MultiPoint connectivity when the UE is served by two different radio access nodes, which produces an asymmetric LDB of UL and DL, as presented by CoMP case as Eq. (4.1).

The maximum wave propagation delay achieved in radio access link when the UE is close to the cell edge (worst scenario case). Fig. 4.2 shows the effect delay of users distance from

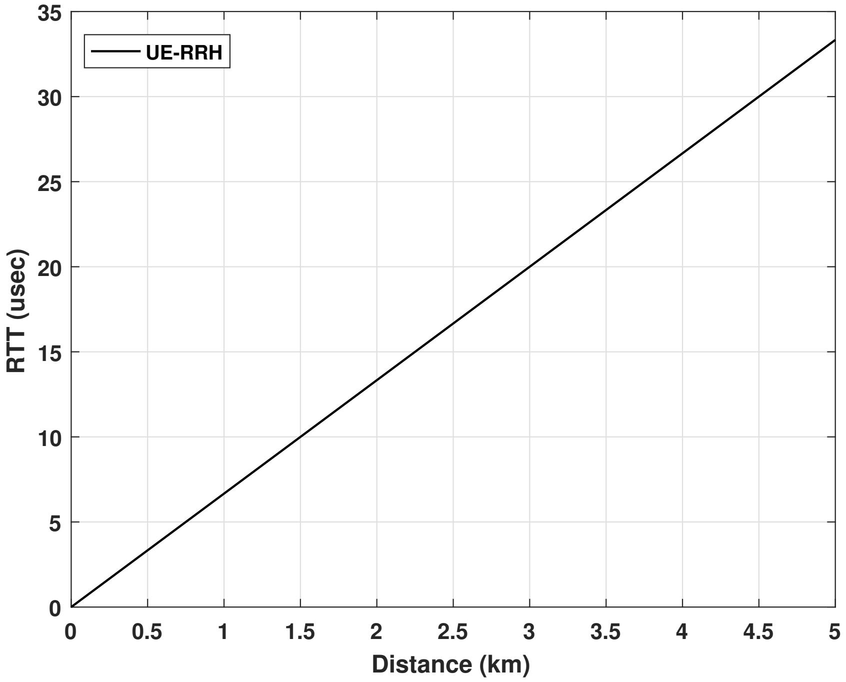


Fig. 4.2 RTT between RRH and user for different cell coverage

cell centre to cell edge of site with respect to the cell coverage, it shows the delay increase with increasing the cell coverage by increasing distance of user from cell centre.

This delay production of UE interface (i.e. the RRT between the user and RRH) can be calculated as:

- CoMP case

$$\delta_{U,R} = (ULDelay + DLDelay) \times \frac{d}{c} \times 10^3 \quad ms \tag{4.1}$$

- Normal case

$$\delta_{U,R} = 2 \times \frac{d}{c} \times 10^3 \quad ms \tag{4.2}$$

Where, the c and d represent the speed of light in vacuum, and the distance between the UE and RRH, respectively. $ULDelay$ and $DLDelay$ represent up-link and down-link delay, respectively . The 2 factor refers to UL and DL RRT between the RRH and user. The maximum value of $\delta_{(U,R)}$ is related to the cell coverage range as shown in Fig. 4.3. 5 km is the typical range of cell coverage in LTE system, whereas it can reach 100 km with a stable operation in order to enable wide area deployments such as in rural areas. However, the RRT for the C-RAN can be calculating as follow:

$$\delta_{C-RAN} = 3msec - (\delta_R + \delta_{R,B} + \delta_B + \delta_A + \delta_{U,R}) \tag{4.3}$$

where, the δ_R denote the RTT of Radio Frequency (RF) processing in RRH for DL and UL. The $\delta_{R,B}$ represents RRT of CPRI processing for DL and UL. The δ_B is RRT of the BBU processing and δ_A is RRT processing delay of front haul equipment such as active WDM, PON, etc. $\delta_{U,R}$ RTT between the UE and RRH (i.e. RF effect on the system). Therefore, the optical fibre fronthaul link distances in Km can be calculated as follows:

$$F_d = \frac{\delta_{C-RAN}}{\delta_s} \tag{4.4}$$

The effect of cell coverage range on the fibre link distance is shown in the Fig. 4.4, it gives clear illustration of the impact of the cell radius on the fronthaul fibre link distance. Therefore, it is crucial to consider the cell coverage range as part of the HARQ RTT dimension design.

4.7 BBU Pool Location and C-RAN Deployment Types

The proposed BBU pool placement process has to consider the latency constraint with respect to the all served RRH within the planned pool area to find out the optimized latency BBU pool position. This position is bounded by the delay constraint of the proposed BBU-RRH slice model delay consequences and maximum cell coverage range propagation delay, which are considered as main contributors to the HARQ RTT LDB.

In the proposed C-RAN model the BBU pool location allocation investigates two main

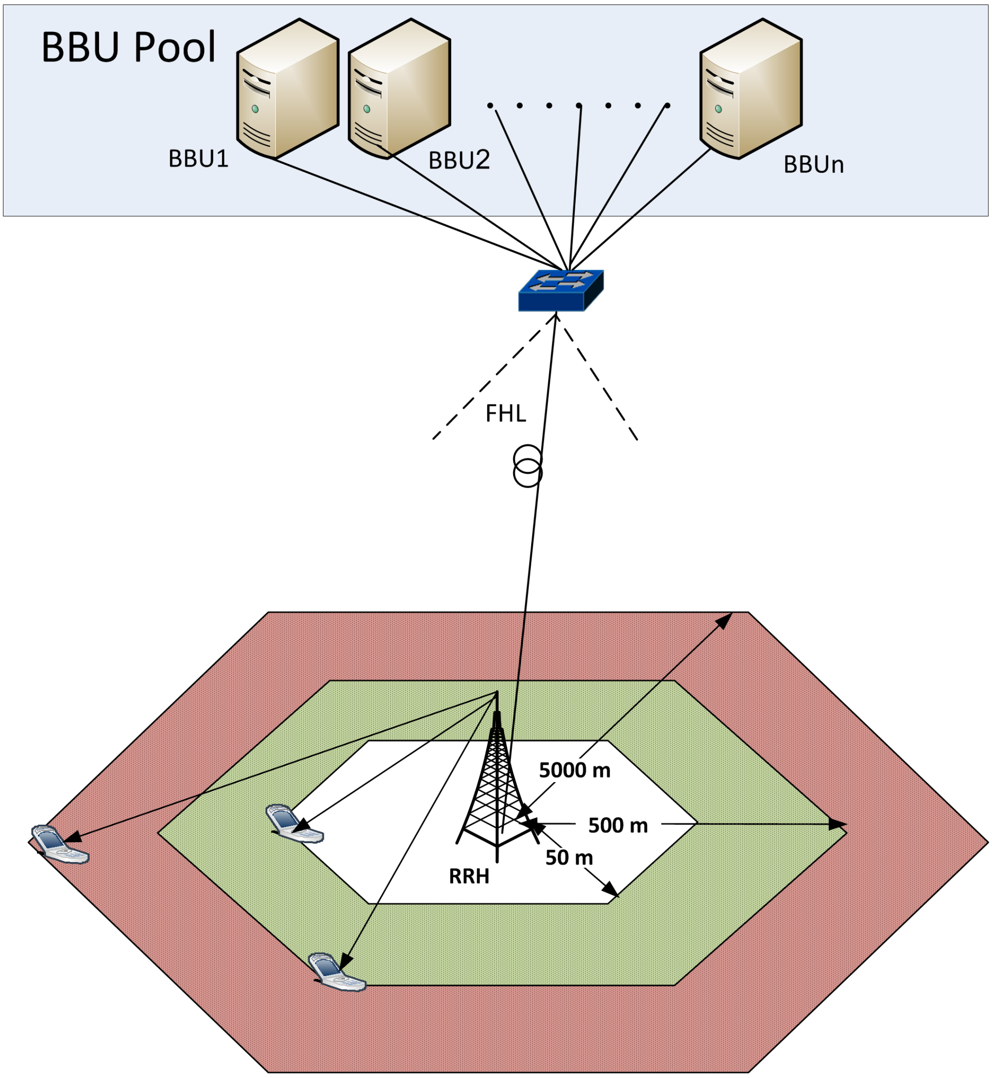


Fig. 4.3 Cell coverage area effect on FHL

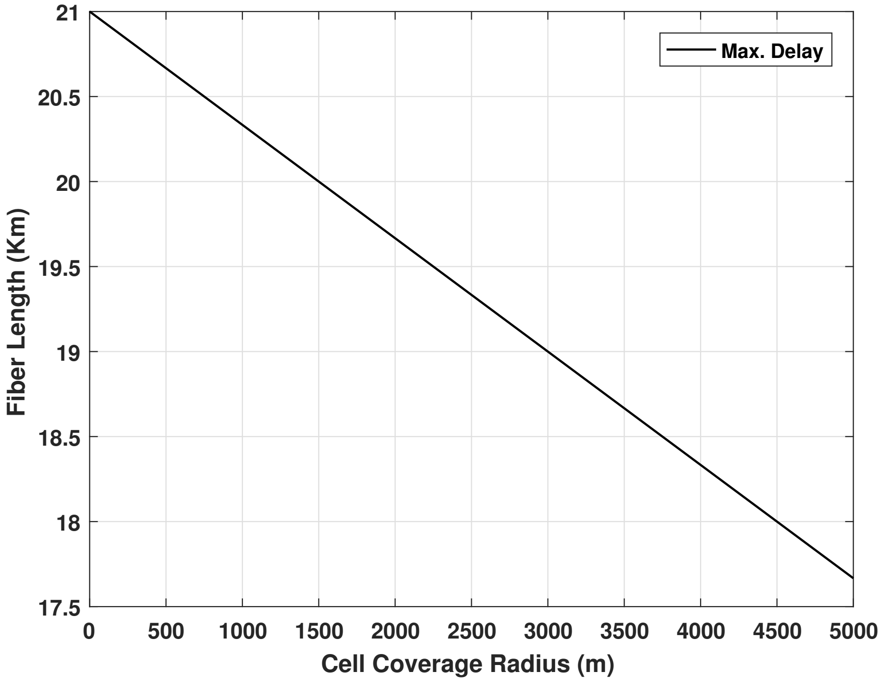


Fig. 4.4 Effect of cell coverage range on the fibre link distance

network deployment scenarios, which depend on the type of RRH in the cell site, these can be classified into homogenous and heterogonous C-RAN deployment scenarios.

- **Homogeneous C-RAN Deployment**: for the C-RAN system the planned network layout is a network of radio access nodes and a collection of UEs' terminals. Only one type of RRHs is deployed in the pool area, such that the transmitted power of the RRHs has a same output level, identical antenna patterns, receiver noise floors and a similar fronthaul connectivity to the their BBUs. What's more, all radio access nodes provide unrestricted access to the UE's within the pool area, and offer approximately the same capacity from the attached UEs number per RRH point of view, where all UEs are provided with a similar Network QoS (NQoS) supplies or shares for their Application QoS (AQoS) demands or requests.

  Furthermore, the maximum cell coverage range could be different from one cell to another among each radio access node, where it depends on the real terrestrial area constraint and shadowing factors if considered in the network deployment phase [111]. The locations of the RRHs must be carefully chosen through network planning, and the RRH-BBU setting should properly configure to maximize the coverage and control the interference among radio access nodes.

However, homogenous C-RAN deployment procedure is iterative and complex, specifically, if it relies on macro cell RRH type as an example, where site acquisition in dense urban zones for macro cells RRH type deployment with required height towers is very hard.

- **Heterogeneous C-RAN Deployment**: A more flexible C-RAN deployment model is needed in order to afford network operator prerequisites and provide a better Quality of Experience (QoE) to the end users in a ubiquitous and cost-effective way.

  The heterogeneous C-RAN system looks appealing, as it provides more flexibility in the RF environment to afford the AQoS requirement and to attain the needed NQoS. The heterogeneous C-RAN system consists of different or mixed types of radio access nodes, which are presented by different types of cell RRH such as macro cell RRH, micro cell RRH and small cell RRH [111]. Thereby, the main differences between them are in the mapping of propagation path losses model of wireless radio in the DL or UL direction, which converts the maximum allowed propagation loss to the maximum cell range. It depends on:

  - Environment: urban, rural, dense urban, suburban, open, forest, sea ...
  - Distance.
  - Frequency.
  - Atmospheric conditions.
  - Indoor/outdoor.

It could be considering the homogenous network a special type of heterogeneous network and build or introduce a general model.

4.8 Dynamic C-RAN

For effective network deployment the cells dimension and maximum capacity have to be related to the expected peak traffic load of the associated radio access nodes coverage area size. Any traffic load fluctuates depending on the geographical area type such as rural, suburban and urban as well as time i.e. morning, rush hour, evening, night and off peak. For instance, in the daytime, the traffic load is heavy in office areas and light in residential ones, while the opposite happens in the evening time. Hence, static network deployment is not optimal owing to the varying traffic load.

Therefore, the DC-RAN is proposed in this work to deliver optimal network deployment as well as to enhance end users' QoE as future traffic demands grows and provides energy saving. DC-RAN adjusts the cell size according to the traffic demand. It can be defined as being when neighbouring cells can interact with others such that one cell can decrease its coverage area or switch itself off.

Generally, the neighbouring cell able to increase its coverage area to prevent the creation of a gap in the radio coverage within the network area as shown in Fig. 4.5. The interaction between cells requires techniques that can adapt cell coverage area. Increasing or decreasing the radio access node coverage area provides a potential capacity gain and enable the cells to modify their coverage area at any time for optimum configuration.

4.9 Coverage Range Extension Mechanism

The main driver of the proposed DC-RAN is the Coverage Range Extension (CRE) mechanism that is introduced by the 3GPP [20, 112], which is either cell coverage range expansion

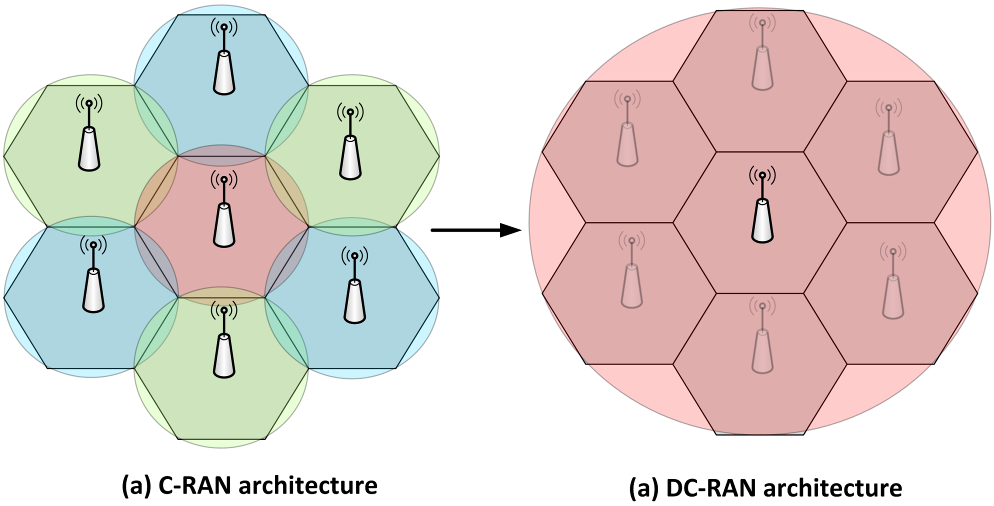


Fig. 4.5 DC-RAN concept

or contraction. It can be applied by the main RRH cell site within the BBU pool area to adjust the main RRH coverage range span. The CRE is used to change the coverage range of small and medium cell RRHs, such as femtocell, picocell, or microcell RRHs. Furthermore, CRE is used to enhance Inter-Cell Interference Coordination (eICIC) in a heterogeneous network. CRE can now be applied in macro cell RRH, which is located at the main RRH site. In the Self Organising Network (SON) procedure proposed to be used in the 4G network, there are three identified techniques to adopt CRE in the conventional radio access node [113].

The ***first*** one is mechanical and can be achieved by changing the antenna tilt angle and height. The ***second*** one is cell selection criteria, which can be done by instructing the UEs at the cell edge to select the second suitable cell. This reduces the coverage range of the intended cell by ceasing its cell edge users, and increase the coverage range of the neighbours' cells by associating the abovementioned ceased users' to the neighbor cells.

The ***third*** technique is achieved by increasing or decreasing the main RRH Transmitted (Tx) power. This concept relies on changing of the Signal to Noise Ratio (SNR) level at the receiver in the UL/DL directions, where SNR is one of the important Key Performance Indicators (KPIs) of the offered NQoS at the receiver PHY layer level.

4.10 Interaction between RHHs

The real network deployment is a multiple radio access nodes that are represented by RRHs and its geographical coordinate's positions. These positions are depending on many factors including but not limited to capacity node, coverage area requirement and etc. Most of the network deployments are configured as heterogonous one with respect to the sites' or access points' positions point of view, when the inter-site distances not steady over the network. This can be demonstrated in Fig. 4.6 Voronoi Diagram (VD) local effect as shown below, which represents part of the presented network in this chapter. In this model all RRHs antennas radiation pattern are considered to be omni sector antenna type. It is obvious that the tessellation is governed by its sites coordination and each tile area size and shape are tied with its site's coordinate. Therefore the actual achieved maximum coverage range is Rmax, which is coming from the interaction of this node's site coordinate with its neighbour nodes and is called local effect in VD construction.

Therefore, it is possible to calculate the maximum coverage range accomplished by each radio access node represented here as RRH associated with its site coordinate. This calculation can be done thought an algorithm 2 (Cells Max Range Calculator) that has been programed using Matlab with the usage of Voronoi function.

Algorithm 2 Cells Max Range Calculator

```
Input Voronoi
Check the tile bounded or not
Polygon Vertices coordination of each site
Euclidean distances between site coordinate and all its vertices
Find max coverage distance
End
```

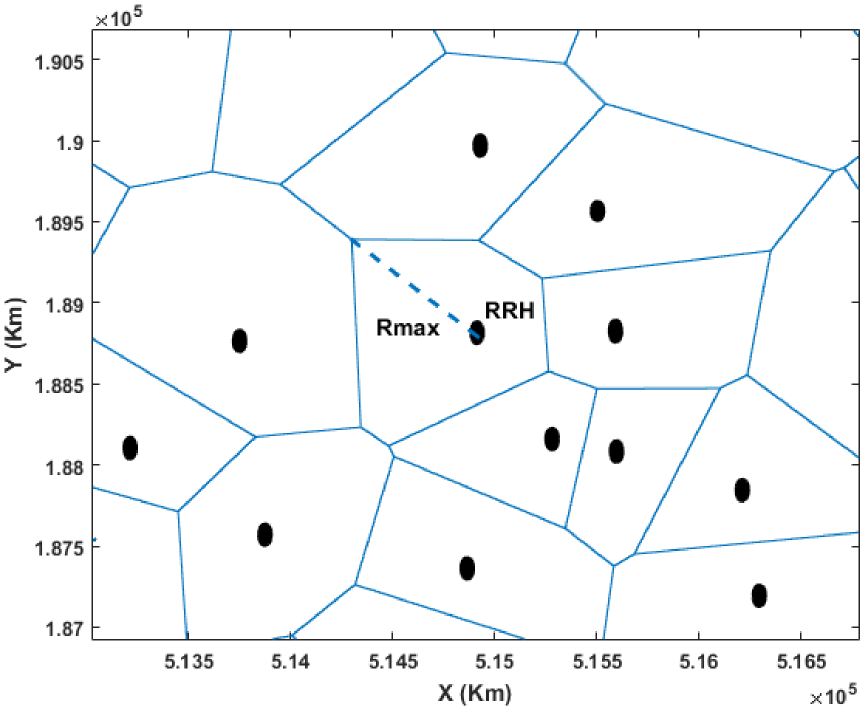


Fig. 4.6 VD local effect

4.11 Proposed System Model

4.11.1 Generic Model

The proposed system is a generic model of C-RAN based cellular network so that each cell practices its radio access node related coverage area, which is represented by RRHs' antenna radiation pattern. The chosen antenna radiation pattern for the cell site is proposed to be omnidirectional type radiation pattern in order to match the publicity of the proposed system model. In addition, this eases the coordination process of inter cell interference during the network deployment phase. Each RRH is served by its allocated BBU that is located at the BBU pool. It is assumed that there are N RRHs in the associated geographical area of the BBU pool.

The plan is to allocate the BBU pool geographical position at a certain point (x_o, y_o) within Central Office (CO) area. The location allocation process considers all served RRHs latency

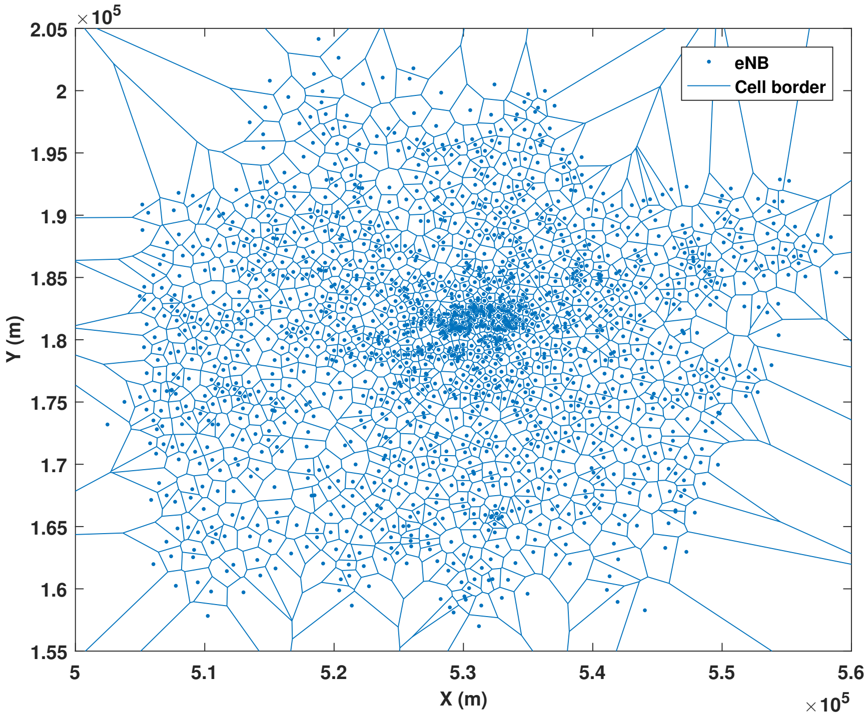


Fig. 4.7 LTE eNBs deployment

requirements considering the consequence of RRH coverage range R_i with its propagation delay effect on the FrontHaul (FH) optical link distance r_i. These served set of N RRHs are placed at a known positions starting from (x_1, y_1) to (x_N, y_N) depending on network deployment strategy.

4.11.2 System Mechanism

The proposed BBU pool placement mechanism has to consider all served RRH positions inside the planned pool area to find out the optimal CO position, which is bounded by the delay constraint for the proposed eNB slice model such as HARQ RTT LDB, in the contexts of FH optical fibre link distance between RRH and BBU pool including cell coverage range consequences. The UE to RRH association policy depends on the cell coverage range according to the network policy and cellular network deployment configuration. This coverage becomes Voronoi cell shape, where any UE in Voronoi cell has a shorter distance to the associated RRH than other RRH. Each RRH has its Euclidean distance with respect to the BBU pool position.

The BBU pool dimension reflects the impact of LDB for HARQ RTT with its main contributors such as the FH link distance as fibre optic transmission media, cell coverage range and others LDB components. Hence, the maximum pool serving geographical area dimensions are governed by the maximum allowable LDB.

The Number of radio access nodes served by a single BBU pool depends on two factors where the first one is the pool serving area and the second is the cells' coverage ranges. Additionally, it depends on the type cells and its deployment distribution i.e. network planning and configuration in the pool area such as homogenous or heterogeneous radio access deployment.

4.11.3 System Model and Problem Formulation

A geographical area $\mathscr{S}$, has $\mathscr{N}$ number of eNBs (i.e. RRHs), as shown in Fig. 4.7 , that represents actual network deployment. The main objectives of this work are finding the optimal location and minimum required number of BBU pool in the proposed network model.

1. **Single Pool Problem Formulation**

   Each RRH has its Euclidean distance with respect to the BBU pool position and can be expressed as follow:

$$Ed_{(B_o,R_v)} = \sqrt{(x_o - x_v)^2 + (y_o - y_v)^2} \tag{4.5}$$

   where (x_o, y_o) is coordinate of the BBU pool position B_o and (x_v, y_v) is the coordinate of the vth RRH position R_v, where $[v = 1, ..., w]$ and w is the maximum number of RRHs in the pool. The sum of all the distances of the B_o pool site location to all RRHs positions is represented by:

$$d_{B_o} = \sum_{v=1}^{w} Ed_{(B_o,R_v)} \tag{4.6}$$

BBU pool position of minimum delay is resultant of the centre of minimum distance in the pool serving area. This centre is a unique statistic, which defines the BBU pool geographical position (x_o, y_o) where the sum of the radial distances to all RRHs' positions is the smallest based on latency constraint. This can be representing by the following formula:

$$min \sum_{v=1}^{w} Ed_{(B_o,R_v)} \ , \quad when \quad (x_o = x_v, y_o = y_v) \tag{4.7}$$

Subject to:

$$x_v \mid_{min} \leq x_o \leq x_v \mid_{max} \tag{4.8}$$

$$y_v \mid_{min} \leq y_o \leq y_v \mid_{max} \tag{4.9}$$

where, the equations (4.8) and (4.9) are constrains which show the position of BBU pool should be within $x_v \mid_{min}$ and $x_v \mid_{max}$ dimensions of the x-axes, and within $y_v \mid_{min}$ and $y_v \mid_{max}$ dimensions of the y-axes.

2. **Proposed Algorithm for Single Pool**

There is not a specific method that can calculate such optimum BBU pool location. Therefore, an iterative algorithm is used to find it. There are many optimization methods to solve this problem. Quasi-Newton Method (QNM) considers one of the best methods to solve this optimization problem.

QNM is used to determine the optimal solution either by finding zeroes of the function $f(x)$ (i.e. eq. 4.7) that is twice-differentiated or by finding local maxima and minima of the function. It is considered as an alternative to Newton's method [26]. In this chapter

QNM is used to find the optimal location for BBU pool placement. QNM requires the Jacobian or the Hessian function in order to search for zeros, for finding extrem value. In higher dimensions, QNM uses the gradient $\bigtriangledown f(x)$ and the Hessian matrix H_k of second derivatives of the function to be minimized. QNM is used to determine the root of the first derivative for multidimensional problems.

QNM is involving a series of line searches from x_k that are employed during the iteration for the computations of $f(x)$ and $\bigtriangledown f(x)$. QNM is characterized over other methods by its approach to choose the search direction. Specifically, at the kth run of the algorithm iterations the procedure considers H_k matrix, which is an approximation to $H^{-1}(x_k)$ as the inverse of the Hessian of $f(x)$. Then, compute the gradient of function $\bigtriangledown f(x_k)$ and takes the search direction as $h_k = H^{-1}(x_k) \bigtriangledown f(x_k)$. Then, Do a line search from x_k in the direction h_k and calculate the change in x_k by equation bellow:

$$x_{k+1} = x_k - H^{-1}(x_k) \bigtriangledown f(x_k) \tag{4.10}$$

By this process of approximation there is no need to solve the set of linear system equations, but instead doing a simple multiplication process to determine the search direction toward the solution point. The form of the process is shown in Algorithm 3.

Algorithm 3 Quasi-Newton Method (QNM)

```
Set $k$=0;
Chose a starting point $x_0$;
Compute $\bigtriangledown f(x_k), H^{-1}(x_k)$;
Calculate search direction $h_k$;
Calculate change in $x_k$ by eq. 4.10;
Determine new $x_k$ value;
if QNM converged toward solution point then
    Find minim point;
else
    Repeat from step 2;
end if
```

3. **Multi Pool Problem Formulation**

   This section is based on the multi pool problem formulation analysis that is explained in detail in chapter five because chapter five is more specified to solve the problem of multi pooling. Furthermore, chapter five's goal is to find the optimal number of the pools and the optimal network configuration. However, this chapter aims to find the minimum required number of the BBU pools in the proposed network.

4. **Proposed Algorithm for Multi Pool**

   Two algorithms are adopted to solve the multi pooling issue where the first one is the PSO algorithm that is explained in chapter five. This algorithm is used to configure the network to clusters (pools) with fair configuration. The second algorithm is QNM algorithm which is used to chose the optimal BBU pool location to the each cluster, the QNM algorithm is explained in the previous.

4.12 Numerical Results

This section divides into two parts; first part explains the results of fronthaul delay effect on the system by determining the position, and number of BBU pool and limitations of fronthaul link for homogeneous network deployment. Second part illustrates numerical results of an real heterogeneous network deployment to determine position and minimum required number of BBU pool in the proposed network. Moreover, this work is use MATLAB program to get the results.

4.12.1 Homogeneous Network Deployment Analysis

The numerical results in this section are based on table 4.1 and on homogeneous network deployment.

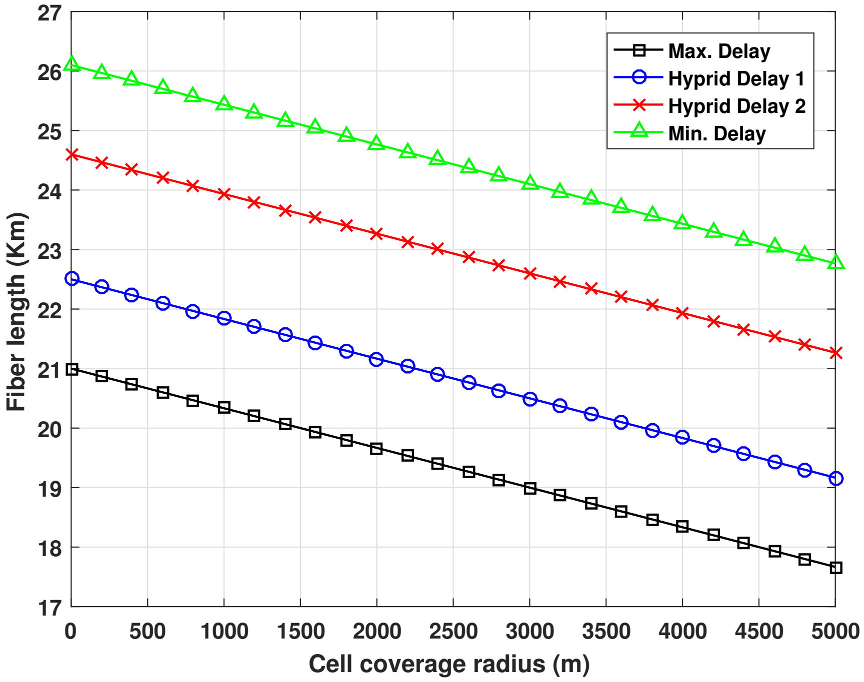


Fig. 4.8 FH length consider different delay factors with RF delay effect

Fig. 4.8 illustrates the optical fibre fronthaul link, which decreases with increasing the cell coverage radius based on four delay components as shownn i table 4.1 and with the worst case scenario (i.e. user is at cell edge), the Min. and Max. Delay in the figure are the minimum and maximum delay values, respectively in table 4.1. Moreover, the Hybrid Delay 1, which depends on both max and min delay values in table 4.1 (i.e. RTT of RF, CPRI, BBU, and active equipments are 40, 10, 2700 and 4 μsec, respectively) and the Hybrid Delay 2, which also depends on max and min delay values (i.e. RTT of RF, CPRI, BBU, and active equipments 25, 10, 2700 and 40 μsec, respectively).

Fig. 4.9 illustrates the number of RRHs in BBU pool area of different cell coverage radius for single sector cell sites. The dashed lines represent the radius of the BBU pool coverage area for R1, R2 of max, min delay component, respectively, without RF effect, while R3, R4 of max, min delay component, respectively, for the worst scenario case with RF effect. The

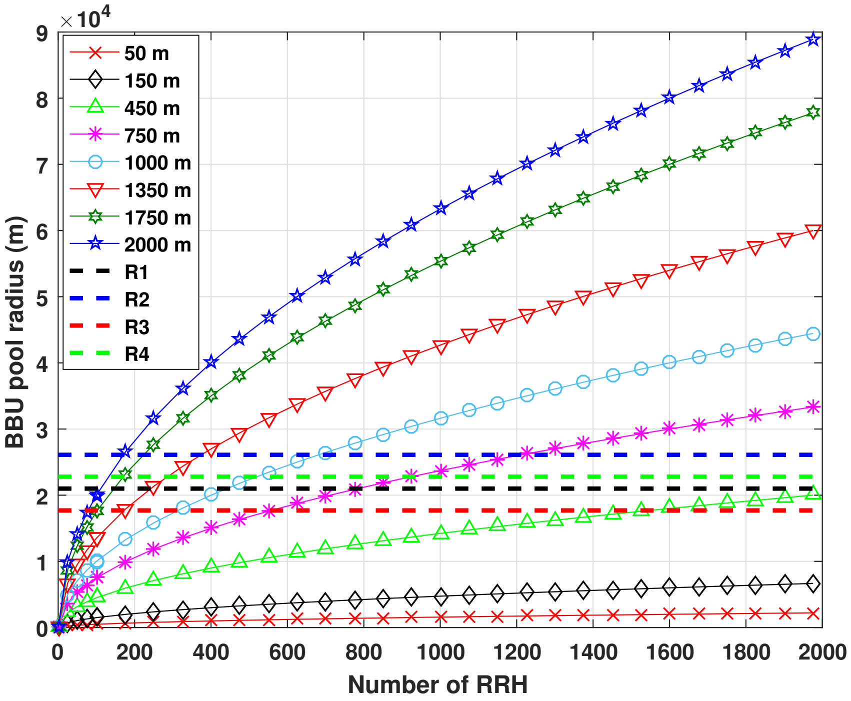


Fig. 4.9 Number of RRH in pool area of different fibber lengths for single sector cell sites

RRHs above these dashed lines use two or more BBU pools and under these lines used one BBU pool.

Fig. 4.10 illustrates number of RRHs for different coverages in pool area for two different coverage BBU pool radius for minimum and maximum delay component effect (as shown in table 4.1) for single, three and six sectors cell sites. It is noted that the number of cells decrease by increasing their radius area.

Fig. 4.11 shows number of RRHs for two different coverage BBU pool area; minimum and maximum delay component for single sector of two architecture deployment; C-RAN and DC-RAN. It is noted that the number of cells decrease by increasing of their radius area. However, the number of RRHs in BBU pool area for the DC-RAN is less than the number of RRHs in BBU pool area for the C-RAN, this can do at the low traffic demand. This leads decreasing the power consumption in cellular network.

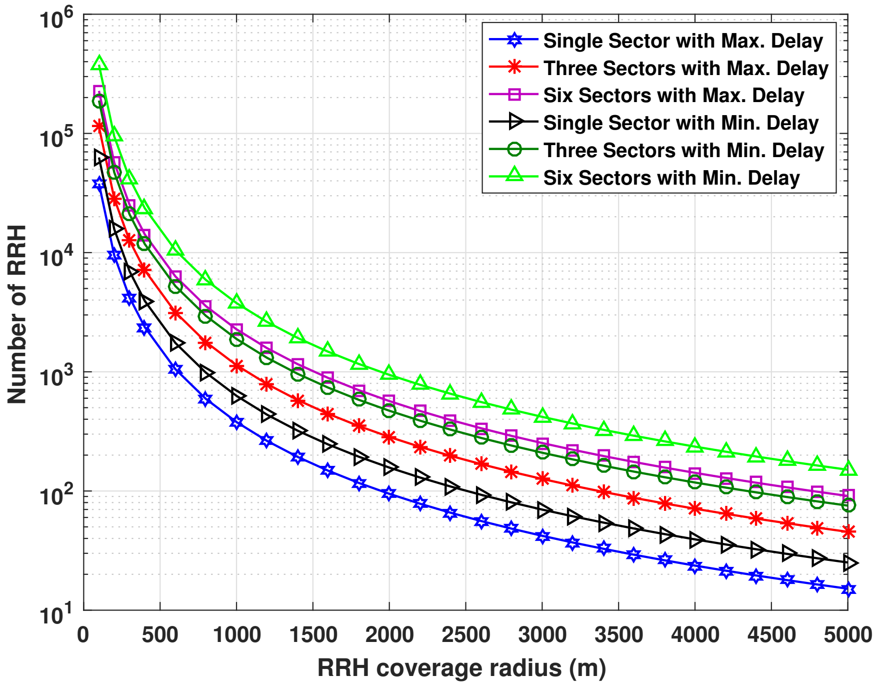


Fig. 4.10 Number of RRH in pool area for single, three and six sectors

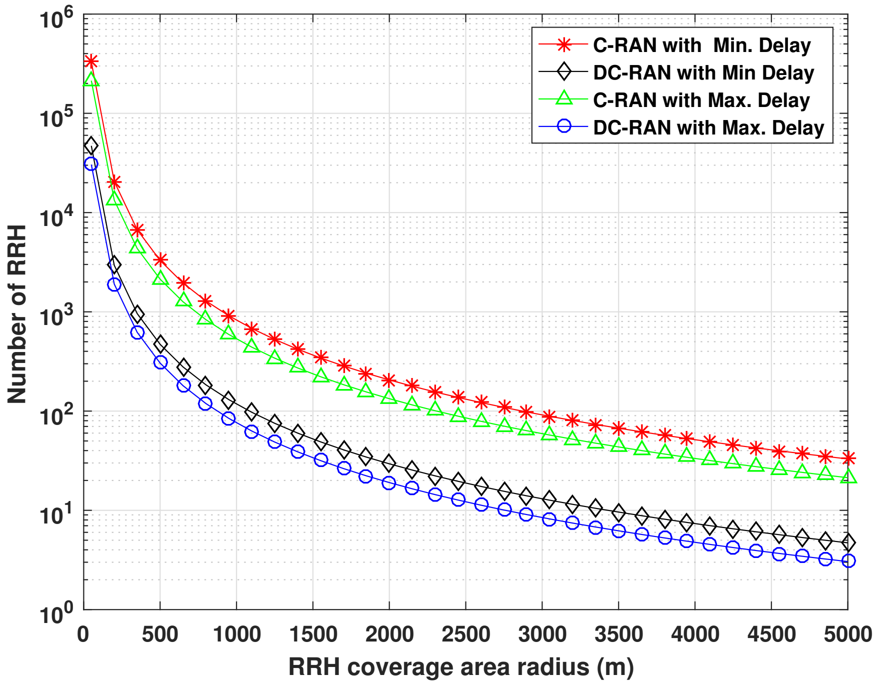


Fig. 4.11 Number of RRH in pool area for C-RAN and DC-RAN for single sector

4.12.2 Heterogeneous Network Deployment

The section introduces a real network deployment as a case study to locate the optimum position and minimum required number of BBU pool for this network. Moreover, this section is divided into two parts; first part is single pool analysis and second part is multi pool analysis. Fig. 4.7 demonstrates the real heterogeneous network deployment scenario of area 2657.04395 km^2 (56x47 km) for 1517 RRHs (eNBs). For the purpose of generic analysis model, each site demonstrates a single sector eNB as 4G heterogeneous network deployment scenario. This 4G realistic system is to migrate toward C-RAN deployment network architecture. Where all radio access nodes comprise an RRH at the same location of eNB.

Additionally, all these RRHs have to be served by its BBUs, which are collected in BBU pool site, via FH links. The placement of BBU pool as (x_o, y_o) is identified by using the proposed Algorithm 4. This BBU pool location allocation is optimised among all RRH sites geographical locations from the latency point of view. It consideres all the served RHHs in the specified network region. In this chapter this scenario with (x_o, y_o) BBU pool coordinate is considered as a base line model, since this BBU pool location is optimized for minimum euclidean distances among all network sites locations. Moreover, each cell in Fig. 4.7 has cell ID that represent (x_v, y_v) to show the actual cell in the deployment scenario. The number of cells in this deployment is 1517.

4.12.2.1 Single Pool Analysis

The Fig. 4.12 is a three dimension figure that shows the effect QNM algorithm to find optimum position of the BBU pool for eNBs (RRHs) of Fig. 4.7. Fig. 4.13 shows the optimum position of BBU pool after applying the QNM as well as the coverage radius of the BBU pool for max and min delay components of with and without RF effect. As it can be seen, there are a number of RRHs out of the pool coverage, which presents a significant

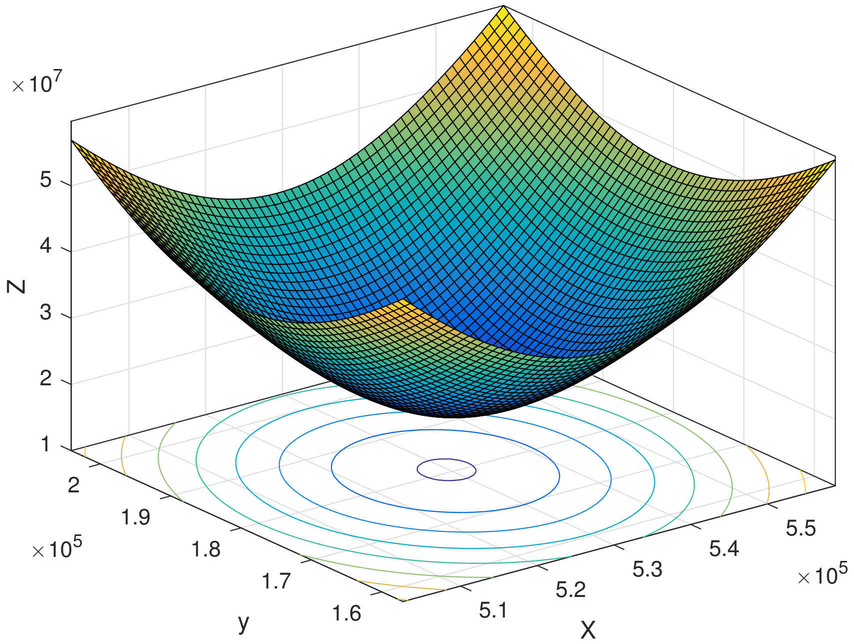


Fig. 4.12 Optimal position by using QNM

issues to investigate. The green circle is minimum delay without RF effect, the black circle is maximum delay without RF effect, the red circle is minimum delay with RF effect and the blue circle is maximum delay with RF effect.

Fig. 4.14 shows the percentage of RRHs site for in and out of four different coverage pool area, where 1st constraints, 2nd constraints, 3rd constraints and 4th constraints, represent the min delay components without RF effect, max delay components without RF effect, the min delay components with RF effect and max delay components with RF effect. Obviously, max delay components with RF effect has a largest number of RRH out of BBU pool area, therefore multi pool in the same cellular network considers a best solution.

Fig. 4.15 show number of cell site that will be in side the BBU pool coverage area versus number of simulation run to find optimum position for BBU pool that covers the most possible number of sites. Fig. 4.15 (a) shows the effect of maximum delay components without RF effect which reach to optimum pool area that coves 1306 cell site while, Fig. 4.15

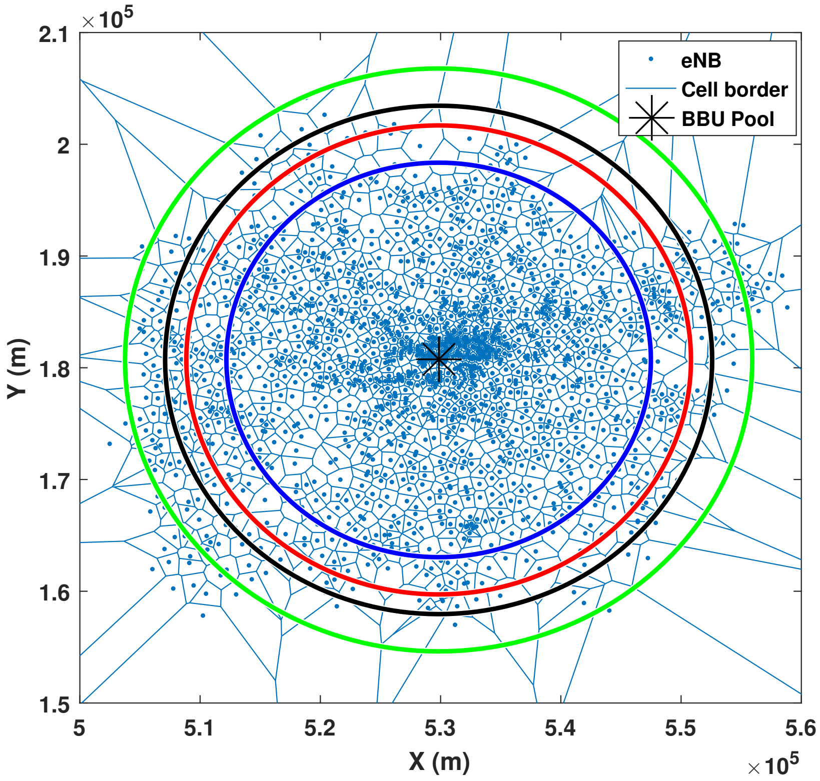


Fig. 4.13 Optimal BBU pool position by using QNM

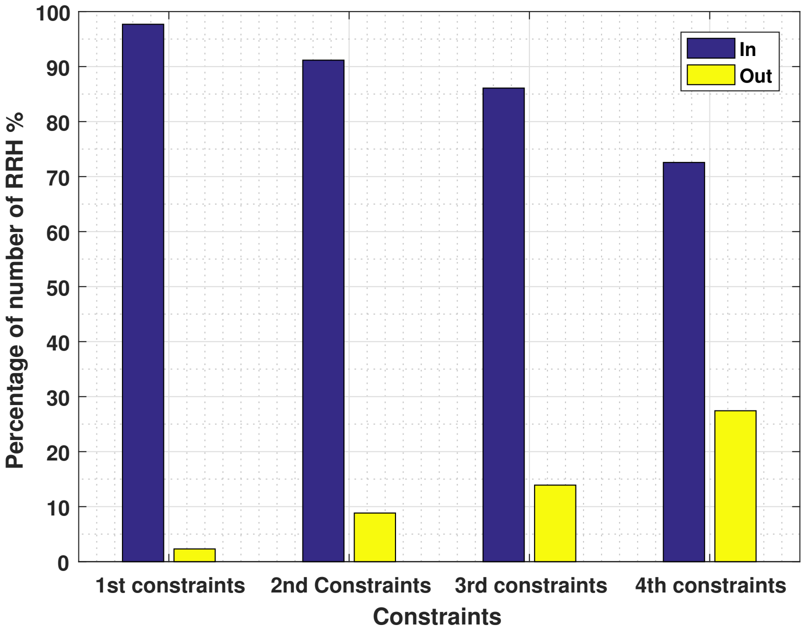


Fig. 4.14 Percentgae of RRHs in and out pool coverage area

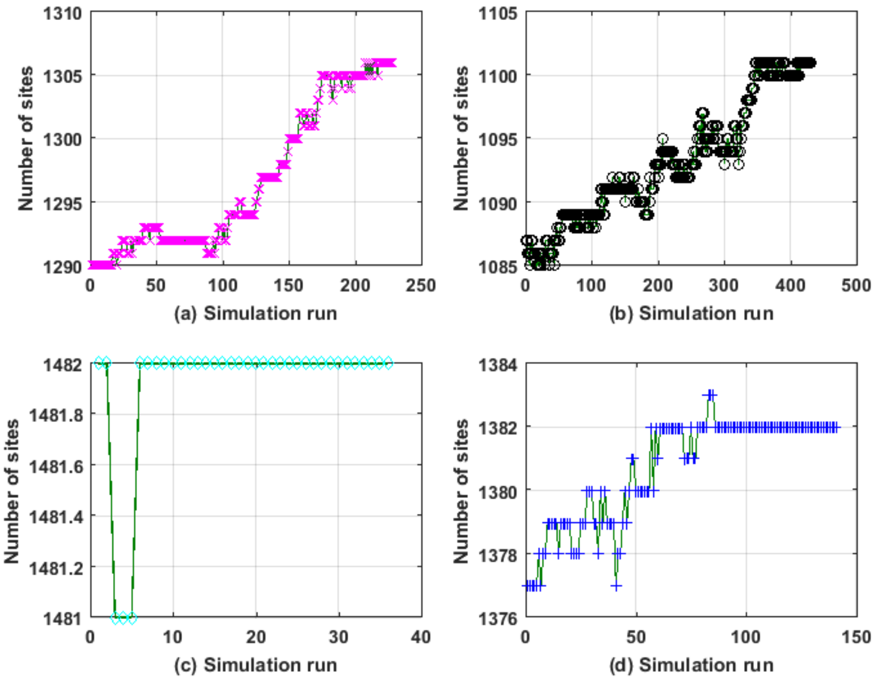


Fig. 4.15 BBU pool position for the second optimization running

(c) shows the maximum coverage BBU pool area, it is cover 1482 cell sites for minimum delay components effect without RF effect. However, 4.15 (b) shows the effect of maximum delay components with RF effect which reach to optimum pool area that covers (1101) cell site while, Fig. 4.15 (d) shows the maximum coverage BBU pool area, it is cover (1383) cell sites for minimum delay components effect with RF effect.

4.12.2.2 Multi Pool Analysis

From the previous analysis, the single pool is not enough to run cellular network special for a vast area and huge number of RRHs such as a network case study that adopted in this work due to fronthaul constraints. Therefore, this section introduces a multi pooling concept to apply for the proposed network to solve fronthaul constraints problem and cover all RRHs in network.

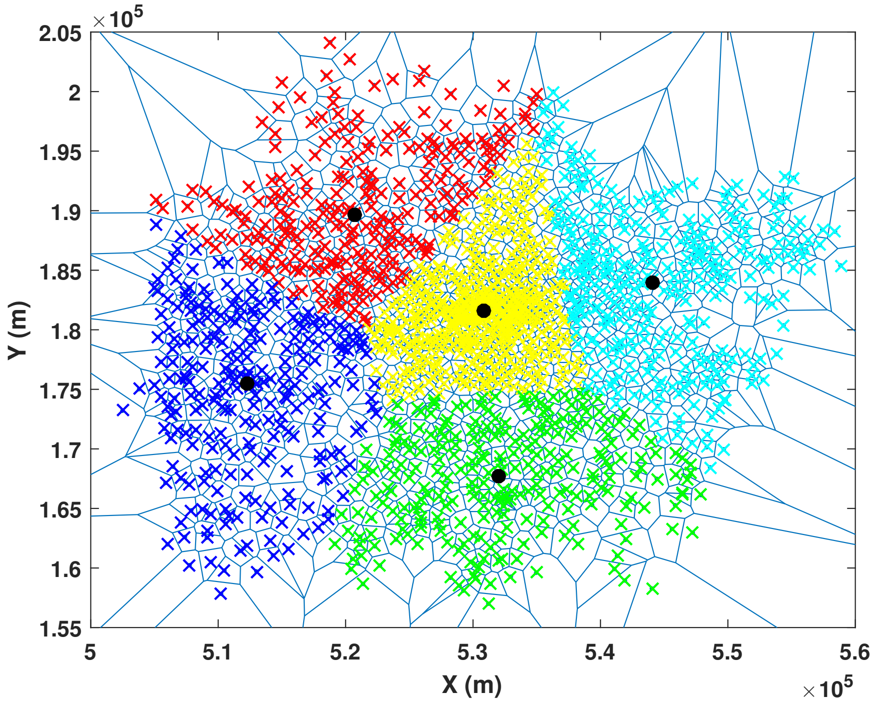


Fig. 4.16 Multi pool partition for the proposed network

The Fig. 4.16 shows multi pool partition for the proposed network by using clustering concept. The clustering is based on PSO algorithm to create multi pool for the heterogeneous network deployment for 1517 RRHs. However, QNM algorithm uses to compute the sites positions of the BBU pools for each cluster in network with respect to the constraints of fronthaul. This network needs 5 pools to cover all RRHs of the network with services. Fig. 4.18 shows the proposed network served by 4 pools with max. latency constrains and with RF effect, It is noted some of RRHs are out of the pools services, while with 5 pools configuration all the RRHs are served under the same constrains as shown in Fig. 4.17. for more details, Fig. 4.19 illustrates coverage area limitations of each pool, where this coverage limitation represents the max delay requirements, it can see all RRHs under the service of BBU pools.

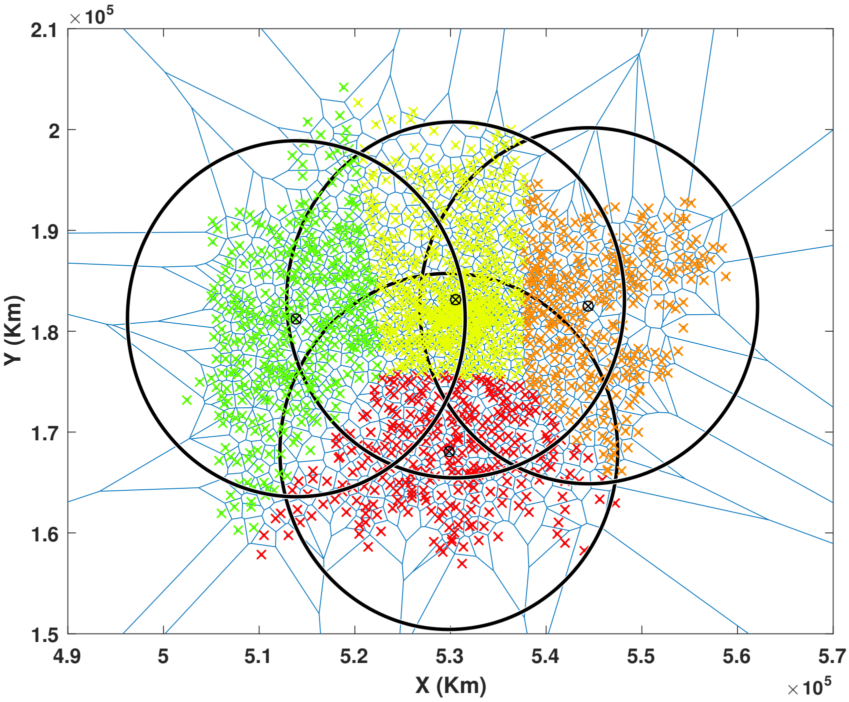


Fig. 4.17 Four pools configuration with coverage area of each pool

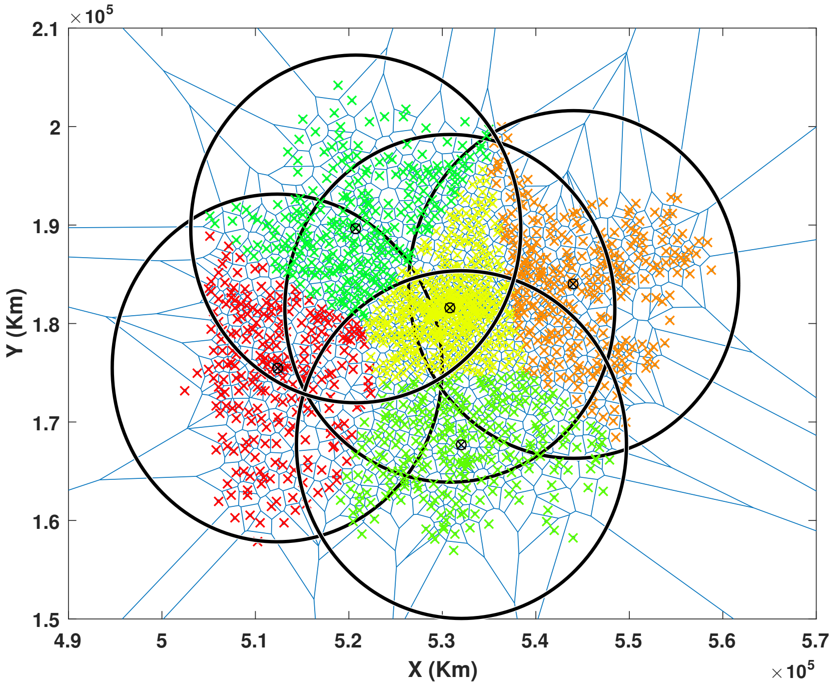


Fig. 4.18 Five pools configuration with coverage area of each pool

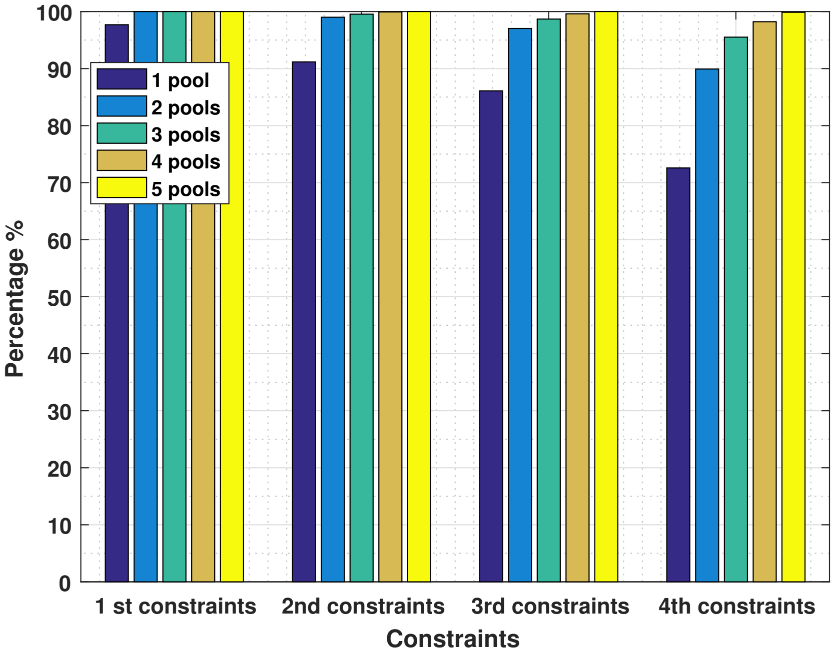


Fig. 4.19 Multi pool for the proposed network with coverage area limitations of each pool

Fig. 4.19 shows comparison of five BBU pools for four different delay constraints for the percentage of RRHs number that are in and out the BBU pool coverage for the proposed network where the 1st constraints, 2nd constraints, 3rd constraints and 4th constraints, represent the min delay components without RF effect, max delay components without RF effect, the min delay components with RF effect and max delay components with RF effect. It shows that see five pools for this scenario cover all RRHs with four different delay components while other pools may e cover their area but for the specific constraints that means not for all constraints situation as shown in Fig. 4.19.

4.13 Summary

The main challenge of C-RAN architecture is BBU pool position in network. This chapter proposes an approach for allocating BBU pool position of the C-RAN architecture to improve the offered NQoS. real heterogeneous network is used to evaluate this approach. Optimizing optical fibre fronthaul delay is applied to determine the optimal location of the BBU pool by using the QNM algorithm. The PSO algorithm is used to solve the clustering problem in the proposed actual network.

Moreover, this work illustrated the effect of the RRH coverage area on the optical fibre fronthaul on the network planning. The simulation results are based onto two network scenarios, homogenous and real heterogeneous network. The results illustrate that five pools are the minimum required number to cover the actual heterogeneous network regarding the maximum fronthual latency.

Chapter 5

Heterogeneous Dynamic C-RAN Deployment Based on a Multiple BBU Pools Approach for 5G Network

For the current and future cellular network deployment, the BBU pool placement and optimal required number of the BBU pools in network is needed. In this chapter, an approach for solving the multiple BBU pools planning problem over Dynamic Cloud Radio Access Network (DC-RAN) architecture using optimization processes is proposed. This aim for C-RAN architecture to achieve high Network Quality of Services (NQoS) by optimizing the placement and the number of Base Band Unit (BBU) pools as well as the number of Remote Radio Heads (RRHs) in each BBU pool across the whole network. The clustering concept is adopted to determine the best pre-configuration of pools in the architecture.

Real heterogeneous Long Term Evolution (LTE) network deployment is used to represent the model problem. The clustering is applied using the Particle Swarm Optimization (PSO) algorithm to group the RRHs (i.e. pooling the RRHs) of the network as well as to determine the BBU pool position for each pool. The Bayesian Information Criterion (BIC) is successfully applied to the problem of determining the optimized number of BBU pools in the network by ascertaining its minimum value [114]. The measure of spread of the radio access nodes presented by Range, Variance and standard deviation (Stdv) have been used to verify and support the BIC criterion in the optimized pooling concept. This can determine the differences between the maximum and minimum number of RRHs among all BBU pools in the network area. This work also is adopted a load balancing in network deployment by fair number of connected RRHs with each BBU pool.

Furthermore, Voronoi tessellation of the main RRHs as the requisite of the DC-RAN concept for the proposed deployment is utilised to simplify the network management and can be used to improve energy saving. That is, it switches off a number of RRHs at low traffic load demand and serves the User Equipments (UEs) by the main RRH.

5.1 Introduction

Radio Access Network (RAN) planning prior to the network deployment phase is an important concept in terms of designing optimized Key Performance Indicators (KPIs) for cellular networks in order to meet customers' Quality of Experience (QoE) satisfaction levels and Application Quality of Service (AQoS) requirements by providing high NQoS [115, 116]. Such planning includes the deployment of radio access nodes by optimizing their KPI configurations and their site locations allocation with respect to the users' traffic demands [117].

The Fifth Generation (5G) of cellular network requires new architectures and concepts in order to increase its deployment flexibility, to improve the offered performance, and to reduce its cost [118]. The innovation of C-RAN architecture is one of the candidates for Next Generation Network (NGN) deployment for 5G, which provides simplified network management architecture for mobile RAN [119]. Issues associated with this innovation include BBU pool position allocation, with respect to its RRHs and the maximum number of BBU pools in a specified network area with the number of RRHs connected to their driver

BBU pool.

C-RAN can be defined as the traditional eNB separated into three main elements, which are BBU, RRH and fronthaul link, with the required interfaces among them [120, 121].

The RRH has interface with a fronthaul link to provide connectivity with its associated BBU [8]. This connectivity can be provided by one of the following interfaces [122]: i) Open Radio Interface (ORI); ii) Open Base Station Architecture Initiative (OBSAI); or iii) the Common Public Radio Interface (CPRI).

The C-RAN architecture requires precise BBU pool placement and number in each particular C-RAN to ensure a high NQoS. BBU pool positions in the network need to be set in the optimal locations with respect to its related RRHs. Hence, the fronthaul link propagation delay and BBU processing have to be considered carefully. This means, the network operator cannot allocate BBU pools in an arbitrary fashion. Currently, the adopted approach is by considering any random group of radio access nodes' locations and choosing one as a feasible position to allocate their BBU pool, as proposed by Zainab et al.[123], based on radio access nodes' traffic capacity limits. In summary, multiple pool configuration allocation is essential for achieving effective network resource management and cover all the RRHs in the network as mentioned in chapter four.

5.2 Related Work

To date, there has been much research about optimal BBU pool placement for C-RAN. Chapter four in section (4.2) introduced a wide literature review about the BBU pool placement. The BBU pools planning deployment issue is not investigated extensively as far as the authors have known. However, currently there has been a very little research on clustering the BBU pools in large networks.

The authors in [8] stressed the importance of optimized clustering of RRHs in a single network to prevent the BBU pool from overloading, due to resource limitation, but they did not proposed any solution for this issue. To date, studies have not considered the required number of BBU pools in any specific network. The work in this chapter provides a detailed study and propose a solution about converting a single network to multiple sub networks (i.e. multiple BBU pools) to simplify network management and enhance NQoS and achieve a load balancing among the BBU pools.

5.3 RRHs Multi-Pooling

C-RAN is presented as a one of the proposed architectures for 5G, so traditional cellular networks should transit to a new concept of BBU-RRH configuration. For this deployment, the BBU pool placement and dimension pool area is now needed. However, how many BBU pool required running the network and how many RRHs can be run by one BBU pool. There are many constraints that restrict this configuration such as optical fibre fronthaul latency, handover, load distribution and load balancing. Proper BBU pool place and determining number of the BBU pool in network can provide enhanced flexibility in network management. Increasing pooling in network can mitigate load on the BBUs as well as reduce the latency requirements in network but increase inter BBU pool handover. Therefore, these challenges should be carefully considered in network deployment.

This work is based on the clustering concept to determine the number of BBU pools in the network. Clustering can be defined as a concept for finding groups or clusters in a dataset. However, clustering technique is widely used in different field such as, economics, psychology, Engineering and biology. Many algorithms are used to solve clustering problem such as k-means, Genetic Algorithm (GA), Particle Swarm Optimisation (PSO). There are several techniques to estimate the desirable number of clusters such as statistical indices, variance based method, Information Theoretic, goodness of fit method etc. This work has been adopted a Bayesian Information Criterion (BIC) to determine the right number of pools in a cellular network.

5.4 System Model and Problem Formulation

A geographical area $\mathscr{S}$, has N number of radio access nodes, as shown in Fig. 4.7, that represents actual sites of radio access node locations. The main objective of the proposed approach is finding the optimal C-RAN multiple BBU pools configuration that achieves high NQoS through:

- Optimal number of pools.
- Optimal pools sites configuration.
- Optimal location of BBU pool.
- Optimal number of connected RRHs with each BBU pool.

For the introduced real network deployment model that proposed for deploying the C-RAN.

The multi pooling deployment in d-dimensional Euclidean space is the process of partitioning N given nodes into a group of M pools as shown in Fig. 5.1. This figure shows M pools partitioning process, applied on the network model shown in Fig. 4.7; this figure is presented for describing the related formulas be used to run the proposed optimisation algorithms.

Let's take a two dimensional space of x and y, where, (x_r,y_r) are coordinates of the r^{th} BBU pool position B_r, [$r = 1$, ..., M], M is the maximum number of pools in the network, and ($x_{(v)r}$, $y_{(v)r}$) are the coordinates of the $vth\ RRH$ position $R_{(v)r}$ within the r^{th} pool, where, $[(v)r = 1, ..., (w)r]$ and $(w)r$ is the maximum number of RRHs in the r^{th} pool. Each RRH's site $R_{(v)r}$ has its Euclidean distance with respect to its B_r pool position as in Eq. 5.1.

$$Ed_{(B_r,R_{(v)r})} = \sqrt{(x_r - x_{(v)r})^2 + (y_r - y_{(v)r})^2} \tag{5.1}$$

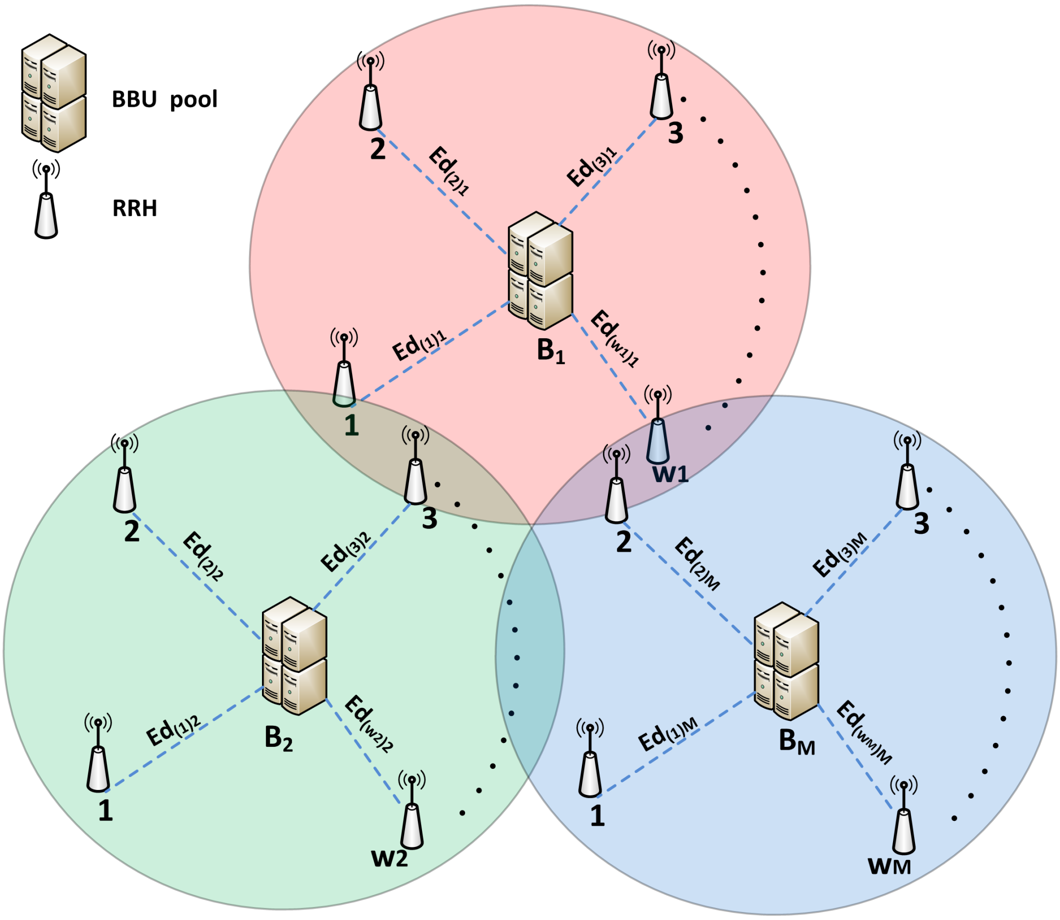


Fig. 5.1 Multiple BBU pooling and RRH clustering

The sum of all the distances of the pool r from the B_r pool site location to all its RRHs positions is d_{Br} , which is represented by Eq. 5.2 is:

$$d_{B_r} = \sum_{(v)r=1}^{(w)r} \sqrt{Ed_{(B_r, R_{(v)r})}} \tag{5.2}$$

In the single BBU pool network configuration, this function can be used as a fitness/cost subject to a minimum, which helps the search process on the optimal solution as Br with respect to its associated $R_{(v)r}$. In this case $r = 1$, $(v)r = [1, \ldots, \mathrm{N}]$ and $(w)r = \mathrm{N}$.

In terms of the multiple pooling situation, when the proposed network number of BBU pools to be formed is M. The Global Sum (GS) of d_{B_r} as shown in Eq. 5.3.

$$GS = \sum_{r=1}^{M} d_{B_r} \tag{5.3}$$

Hence, to achieve a candidate M pool network configuration that is subjected to conform for the minimization of the global optimization function among all other pools' solutions, which achieves a minimum possible front-haul distance, then the cost function can be expressed as a minimization of GS as in Eq. 5.4,

$$cost function = min\ (GS) \tag{5.4}$$

which is considered as a global fitness/cost function in the search for the optimized solution.

5.5 Multi Pools Partitioning Based PSO

Methods and approaches for solving Non Polynomial (NP) hard problem have become a very important topic in recent years. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are considered very popular and they are similar evolutionary algorithms for solving the NP-hard problem.

The GA is used for discrete optimization, while the PSO is more suitable for continuous optimization [124]. The GA has an expensive computational cost in comparison to the PSO. The authors in [125] attempted to prove that the PSO algorithm has the same effectiveness in finding the optimal solution as the GA but with less function evaluations. Thus, the work in this chapter is based on PSO algorithm to find optimal solution of network configuration.

PSO algorithm is built based on the location of the centres (BBUs' pool position) that achieves minimum distances with all cluster members (RRHs' positions), this is called centre of minimum. The network partitioning process based on the proposed PSO algorithm is used to search the solution space to find the solutions which are:

1. Optimal partitioning allocation configuration for M pools in the whole network.
2. Optimal RRH number $(w)r$ in each BBUr pool area.
3. Optimal position allocation (x_r, y_r), which is B_r of each BBU pool within the r^{th} pool area.

With the PSO algorithm, as particles have random speeds through the solution space [126], where each particle i is assessed at instance t by the minimized cost function, with adjusted position toward

- Particle's best solution (position) found as $pbest_i(t)$.
- Best overall solution as $gbest_i(t)$.

Then, based on the particle parameters at instance t, which are $B_i(t)$ at (x_i, y_i) as a current solution, its speed $s_i(t)$ as well as its best position $pbest_i(t)$ and its best global position with respect to other particles $gbest_i(t)$, then the speed update formula, in the pool r, of the particle i at instance $(t+1)$ will be represented as in Eq. 5.5.

$$\begin{aligned}(s_r)_i(t+1) = a*(s_r)_i(t) + C_1*b_1*[(pbest_r)_i(t) - (B_r)_i(t)] \\ + C_2*b_2*[(gbest_r)_i(t) - (B_r)_i(t)]\end{aligned} \tag{5.5}$$

where, $(s_r)_i(t)$ is the current velocity, $(s_r)_i(t+1)$ shows the updated future velocity, $(B_r)_i(t)$ represents the current position of the BBU pool, C_1 and C_2 are the acceleration coefficients, b_1 and b_2 are vectors of uniformly distributed random numbers in the range [0 1], and a represents the initial value. Each new iteration produces a new $(B_r)_i(t+1)$ as the updated position of the r^{th} pool, as in the following Eq. 5.6.

$$(B_r)_i(t+1) = (B_r)_i(t) + (s_r)_i(t+1) \tag{5.6}$$

until the iteration process reaches the projected cost function. Each individual particle represents a possible optimal solution; they are updated interactively with other particles for all pools simultaneously.

The proposed PSO algorithm undergoes the process that is described in Fig. 5.2, where for each single B_r the Euclidean distance of its possible related RRH as $R_{(v)r}$ is calculated amongst each possible particle position (x_r, y_r) as a possible solution for the B_r as pool position, as in Eq. 5.1, which settles inside the r^{th} possible BBU pool area. Thus, each particle i needs to achieve minimum distance from its (current or future) position to all its anticipated RRH sites that can provide minimum cost, according to d_{B_r}, as in Eq. 5.2. Additionally, regarding the interaction with the others pools' particles with their sets of possible associated RRHs, the anticipated B_r's RHH sites' Euclidean distances maximum limits constraint is according to Eq. 5.7.

$$d_{B_r} \leq d_{B_l} \quad (where,\ l \neq r) \tag{5.7}$$

specifically, for the r^{th} pool as well as for all the other BBU_l $\{l = [1, ..., \text{M}],\ where,\ l \neq r\}$ pools during the search procedure simultaneously. This constraint limit represents the interactive relationship among all the other particles in all M pools simultaneously.

This constraint criterion effects the proposed cost function Eq. 5.4, which produces an updated $gbest_r(t)$ $\{r = [1, ..., \text{M}]\}$. These processes are performed in each iteration, for as many as the number of the populations until the iteration reaches the required solution for all M pools in the network area $\mathscr{S}$.

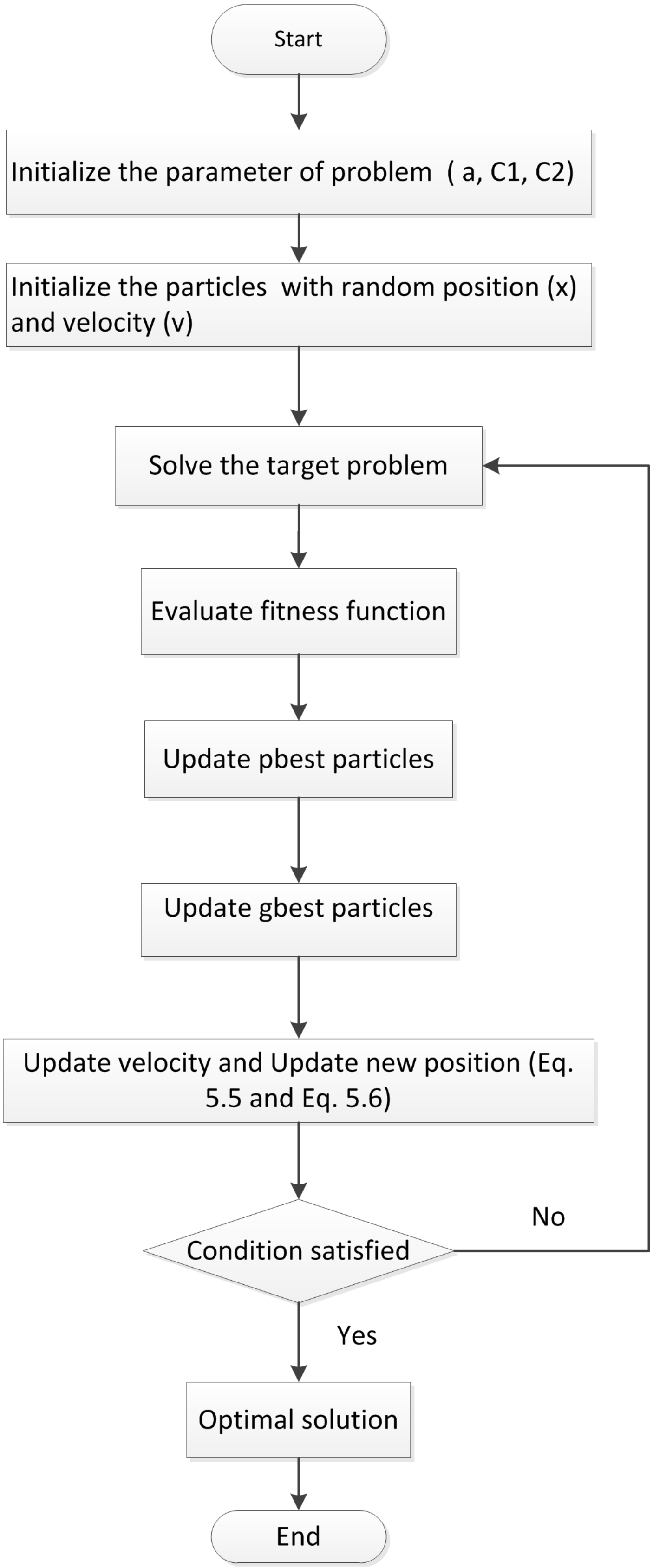


Fig. 5.2 Multiple-Pools Partitioning (PSO)

5.6 Bayesian Information Criterion

For a predetermined number of BBU pools M, the PSO multiple pools algorithm gives optimal pools locations and optimal number of connected RRHs, which are subject to the introduced cost function and constraint limits.

The required number of pools for a particular network can be determined in order to fit a specific requirements of the network operators or services and applications needs. For example, it can serve to establish the:

- Fronthaul latency requirements [11].
- Limitation of the BBU pool processing capacity [98].
- Backhaul capacity limits [127].

Therefore, this optimal number of BBU pools in the specified network is needed. Additionally, the optimization process aims in this work for the equilibrium in the RRH densities (RRH number/pool Area) with minimum delay and minimum latency fronthaul considerations among all COs. Accordingly, the PSO algorithm based center of minimum has to be complemented with another technique to find the optimal number of BBU pools that conforms to the required network planning goals.

The most popular technique is the BIC, which aims at selecting the number of BBU pools that maximizes the posterior probability among the RRH sites' geographical coordinates information. BIC focuses on an information approach that takes into account the specific statistical analysis, by estimating the likelihood function of all set of models of interest for each candidate model; the model here referring to the multiple pools network configuration as an output of the PSO algorithm [128]. In general, BIC can be defined as a means of selection among a finite set of models, where the system with the lowest BIC value is chosen as the optimal solution [114]. The BIC formula is shown in Eq. 5.8 [129].

$$BIC = [N * ln(\frac{GS}{N})] + [M * (d+1) * ln(N)] \tag{5.8}$$

where, d is number of the dimensions of coordinate system, which is two as counts of x and y. The BIC is successfully applied to integrate the PSO multiple BBU pool algorithm by determining the candidate set of the multiple BBU pools network configurations as shown in Algorithm 5, which runs the BIC evaluation K times as the number of the achieved network partition configuration.

Algorithm 5 Bayesian Information Criterion (BIC)

```
Input PSO results [1 C]
Output BIC=[];
for K=1 to C do
    Clear old GS value;
    Calculate GS as in Eq. 5.3;
    Calculate BIC as in Eq. 5.8;
    Next K
end for
END
```

5.7 Measure of RRH Spread Technique

BIC algorithm is adopted in order to choose the optimal number of partitioned pool configurations of the proposed network. However, it gives a group of optimized solutions for the multiple BBU pool configurations, which are approaching to the required optimal solution. Hence, it is still necessary to find the optimum number within this filtered group of partitioned network configurations. Another criterion can be used to narrow the search toward the optimized number of partitions, which is based on the fair distribution of the number of connected RRHs among all the BBU pools.

The measure of spread technique [130] relies on analysis of the statistical characteristics of each multiple pool network configuration for the number of connected RRHs with each BBU pool, which are the outcome of BIC. These statistics are Range, Standard deviation (Stdv) and Variance, which serve to measure the spread of RRH connections for each multiple BBU pools network configuration. When the evaluated model achieves minimum values of these statistics among others models that indicates that this model can provide the essential equality among all other models in the sharing of network loads and fair distribution of the network resources of the observed network.

5.8 Effect BBU Pool Area and Interaction of the Main RRH Coordinates

After the optimal network configuration has been identified for each pool area. The main RRH location is chosen as the nearest RRH to the position of the CO. This choice is made because the fronthaul link of the nearest RRH to the BBU pool has the highest NQoS, such as achieving lower latency, since it has lower propagation delay.

Hence, the main RRH can provide high NQoS requirements when set as a central radio access point among the other RRHs within the pool area. The abovementioned process is undertaken in all the BBU pool areas within the network. Then, it is necessary to consider the interaction among all these homotypic main RRHs. This interaction serves to determine the borders and areas of each BBU pool as well as helps to specify the connected number of RRHs belong each CO, such that the main RRH can cover them and thus, work under the umbrella of DC-RAN.

This can be verified by the Voronoi Diagram (VD) local effect, as shown in Fig. 5.3, which represents part of the presented LTE network, after pooling. The borders and coverage area of each pool can be calculated after activation of the main RRHs, when the other RRHs are setting into sleep mode so that coverage through the interaction of the main RRHs can be determined. It is taken that all the main RRHs are homotypic and their antenna radiation

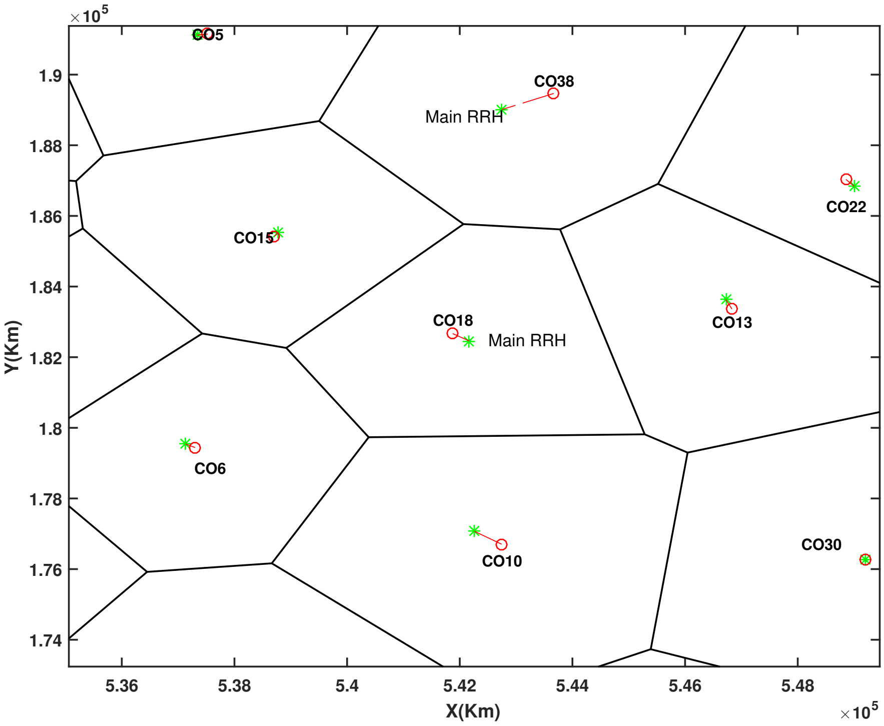


Fig. 5.3 Voronoi Diagram (VD) local effect

patterns are the omni sector antenna type. It is clear that the Voronoi tessellation is governed by the main RRH sites' coordination, such that each tile area's size and shape is tied with its site coordinate [131].

Actually, the attained maximum coverage range is Rmax, as shown in Fig. 5.4, which comes from the interaction of the main RRH site's coordinates with its neighbouring pools' main RRHs, this is called the local effect in VD construction. Thus, it is possible to calculate the maximum coverage range accomplished by each radio access node position, which is represented here as main RRH coordinates.

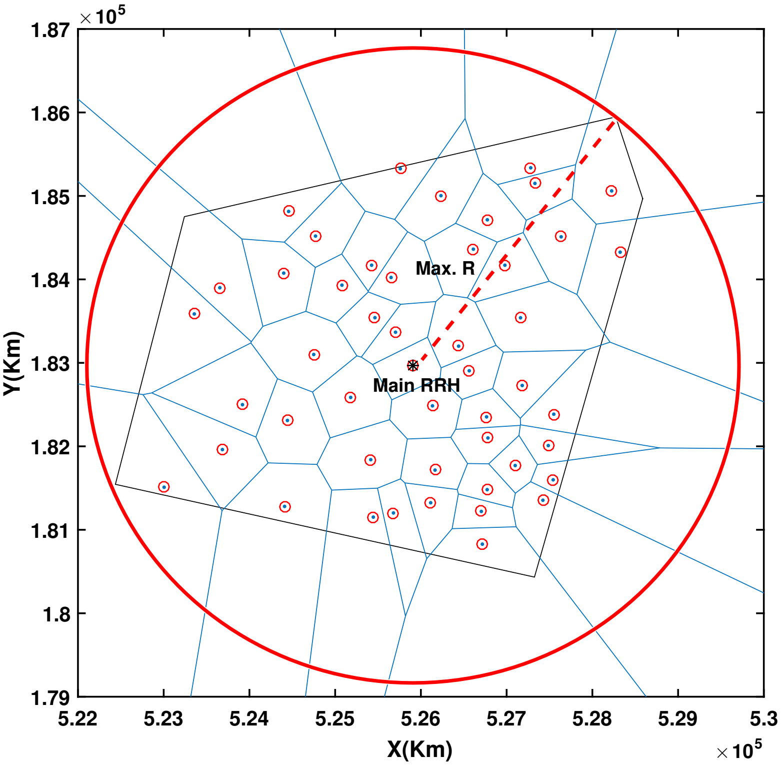


Fig. 5.4 Main RRH maximum coverage range span

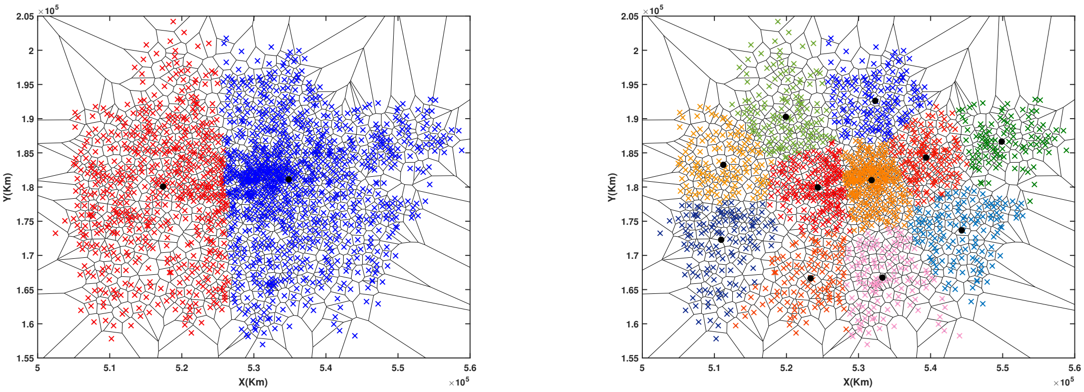
5.9 Numerical Results

The numerical results of this chapter are divided into two parts; first part is the results of multi pooling concept and second part illustrates numerical results of a DC-RAN concept. Moreover, this work is use MATLAB program to get the results.

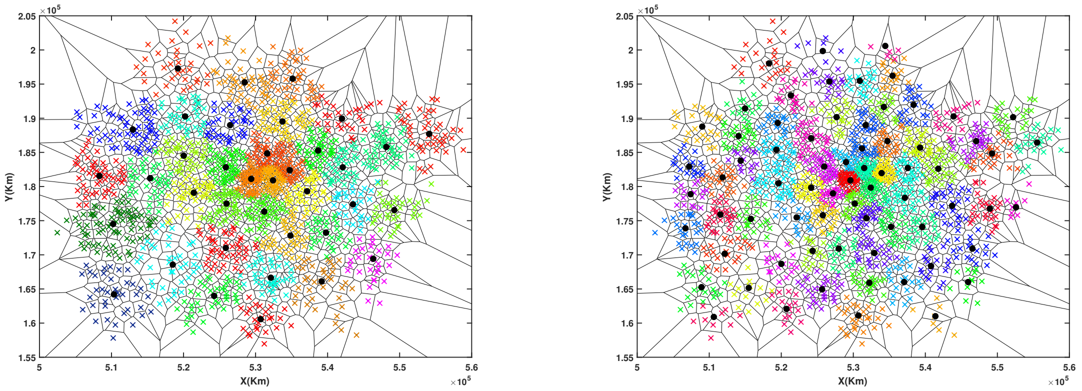
5.9.1 Multi-Pooling Concept Results

In this section, the following results are determined:

1. Optimal multiple pools configuration of the predetermined number of BBU pools in the whole network;
2. Position of each BBU pool inside its pool area;
3. The number of connected RRHs for each BBU;



(a) 2 BBU pools network (b) 11 BBU pools network



(c) 37 BBU pools network (d) 70 BBU pool network

Fig. 5.5 PSO results for different number BBU pools deployment partition configuration

4. The related coverage area of the main RRH for each BBU.

The proposed PSO algorithm is successfully applied for the proposed network model as shown in Fig. 4.7. The algorithm is simulated to divide the whole network radio access nodes into clustered groups of M BBU pools, starting with M=1 pool network configuration, then ending with M=70 pools network configuration as shown in Fig. 5.5. It represents examples of PSO results of 4 selected solutions, as Fig. 5.5a represents 2 pools network configuration, Fig. 5.5b represents 11 pools configuration, Fig. 5.5c represents 37 pools configuration and Fig. 5.5d shows 70 pools network configuration. What's more, Fig. 5.5 shows the COs' locations for each pool.

The decision to stop the network partition process with respect to the number of pools, which is 70, is based on the observation of the value of the BIC function, since it is showing an increased pattern. This procedure is done through the calculation of the BIC function, which is the resultant for each network partition process.

The BIC function versus the number of BBU pools is shown in Fig. 5.6, with an increase after M=44 clustered groups of RRHs, the partitioning process is taken up to 70 to widen the observation and to increase the accuracy of the proposed approach. The abovementioned two manipulations gave a group of candidate solutions of partitioned network configurations; they can be determined from Fig. 5.6, they are laid between 27 to 44 pools because they have achieved minimum BIC values. That is, within this range, the optimal solution of BBU pool network configuration shall lie.

Consequently, the optimal network configuration is within these candidates' solutions. It could be chosen subject to the measure of spread characteristics of the statistical analysis to the all aforementioned candidate solutions with respect to the number of the connected RHHs among all the BBU pools in each configuration. This is achieved in terms of the values of the Stdv, Range and Variance. Fig. 5.7 shows Stdv and Range values of the data represented by the number of connected RRHs with their pools in all the multi-pool network configurations with respect to the number of pools. In this figure and within the elected pool configurations, the selected number of BBU pools is 41, as this attains the minimum Stdv. Furthermore, Fig. 5.8 shows that the 41 BBU pool network configuration achieves minimum variance.

According to these measures, this network partition configuration can provide fairness in the loading of each BBU pool from the perspective of the number of connected RHHs point of view. Hence, the optimal number of the BBU pools, based on PSO clustering, with respect to the minimum BIC algorithm as well as the statistical analysis based on the number of connected RRHs to each BBU pool is 41.

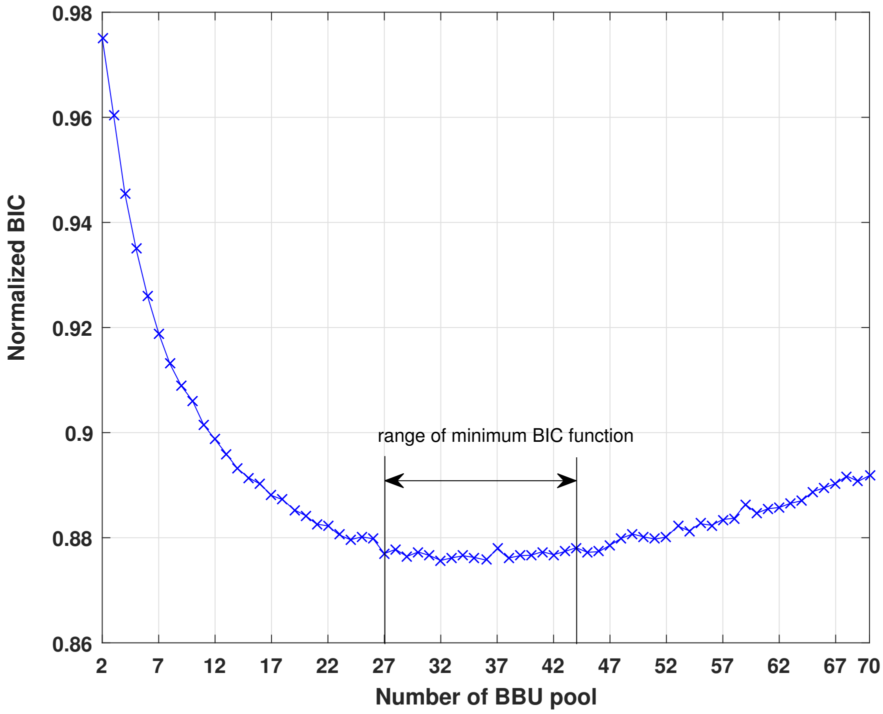


Fig. 5.6 BIC function versus the number of BBU pools

Fig. 5.9 shows the optimal 41 BBU pools network partition result by using the PSO algorithm for a heterogeneous network deployment of area 2,657.04395 km^2 (56×47 km) that contains 1517 radio access nodes. The algorithm uses the positions of the RRHs and the required number of BBU pools, which is 41, as an input to find optimal COs' positions as well as the optimal number of connected RRHs in each single BBU pool in the network. The PSO algorithm considers in the optimization process the latency constraints in terms of the minimum distance between the pools CO site location and its selected RRHs' positions. The positions of the COs are chosen as a closest location of all its related RRHs, as in the proposed algorithm that is defined in the PSO cost function as in Eq 5.4.

Fig. 5.10 shows best cost versus the number of iterations for the run of the PSO algorithm for 41 pools network configuration. It can be seen that the best cost decreases as the number of iterations increases and the optimum 41 partitioning pooling run is achieved after the 350^{th}

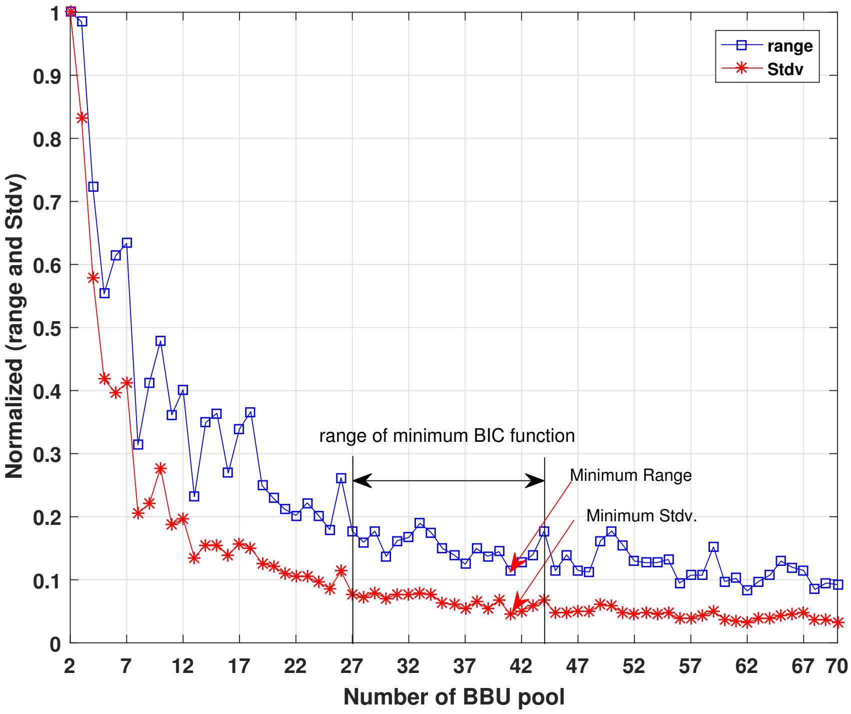


Fig. 5.7 Stdv and Range values versus number of BBU pool

iteration.

The RRH density (no. of RRHs/network area) of the original network configuration is 0.781 (RRHs/unit area,) which is calculated prior the proposed algorithm being used. This could be considered as a reference measure for checking the RRH density of the final optimal solution represented by the average RRH density of all the pools in order to verify the accomplished pooling configuration. The average density of the RRHs in the partitioned network (41 BBU pools) is 0.78098 (RRHs/unit area), as shown in Fig. 5.11. In comparative terms, the difference between the original density and achieved average density of the RRHs is just 0.002% , as shown in Fig. 5.11 as doted red line, which is very low.

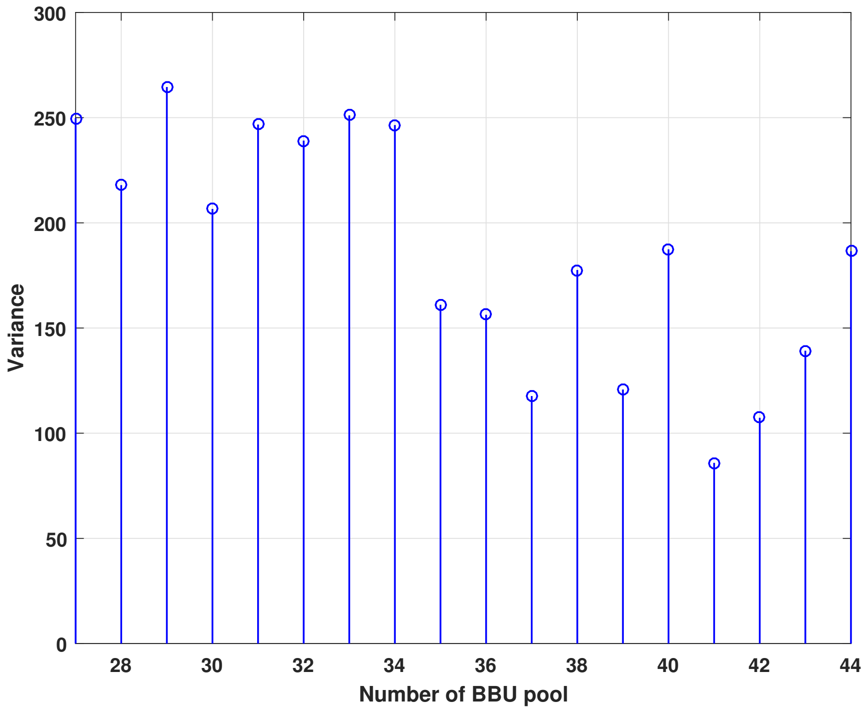


Fig. 5.8 Variance versus number of BBU pools

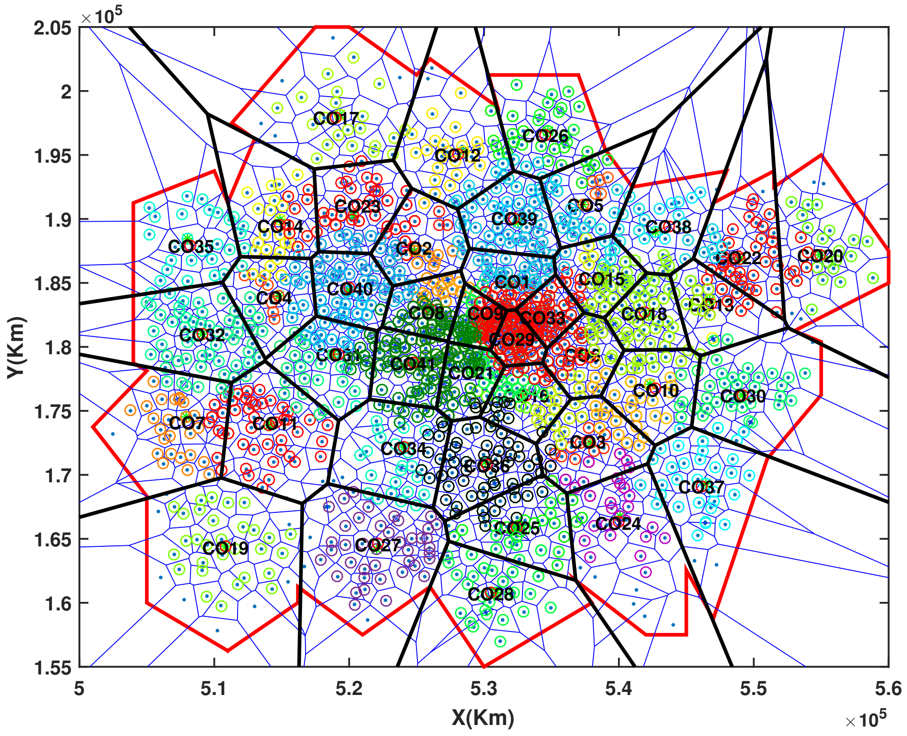


Fig. 5.9 Multi pool partitioning for the network planning

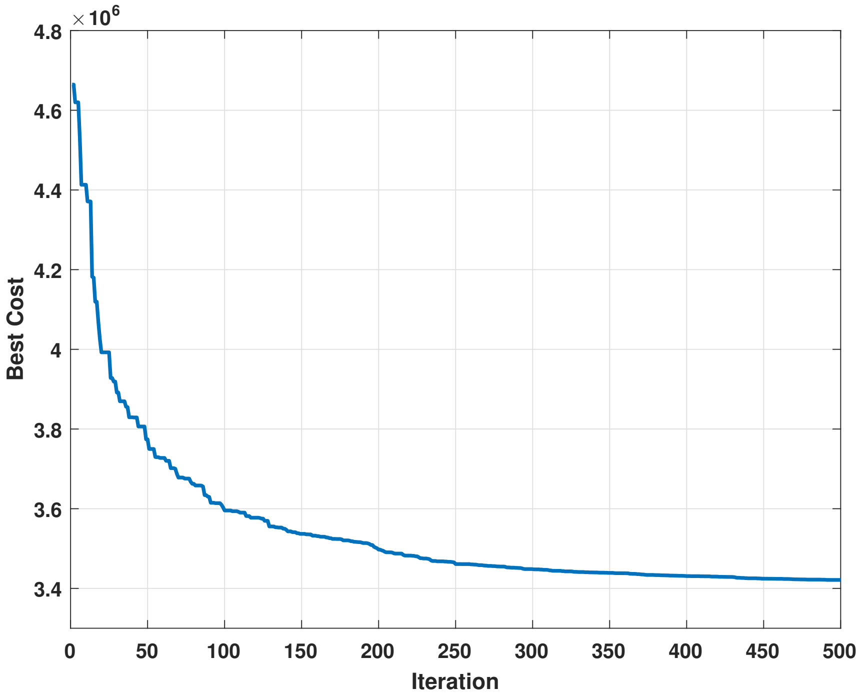


Fig. 5.10 Iterations number of the performance system

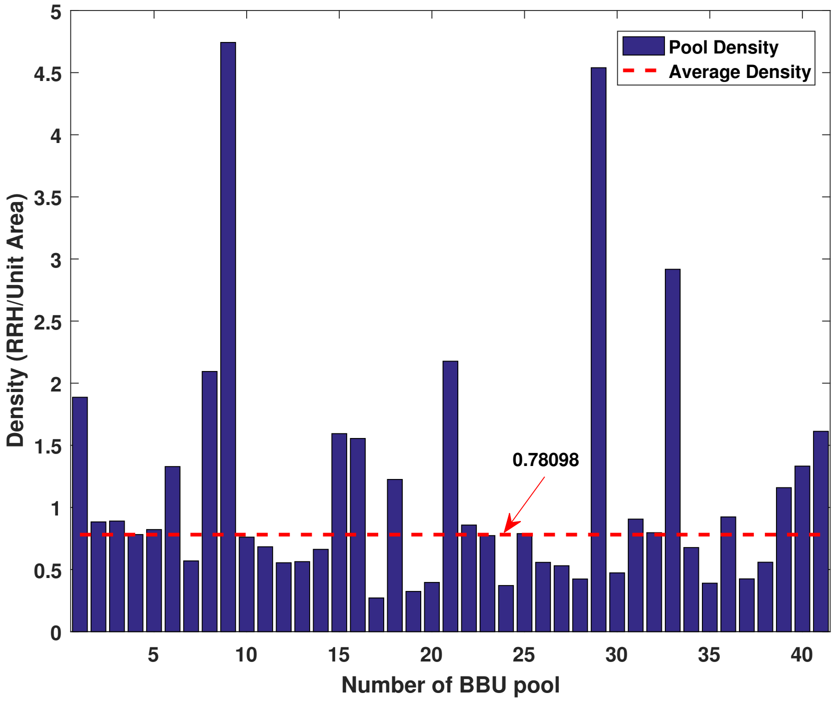


Fig. 5.11 RRH density

5.9.2 DC-RAN Concept Results

Fig. 5.12 shows the DC-RAN model example for a single pool, it is pool number 08, which is one of the 41 pools in multiple pools C-RAN network deployment. The main idea of DC-RAN is that of organising the transmission and reception processes by the CO among all the related RRHs with UEs within the pool area. The introduced example is based on switching off a number of RRHs that have a low traffic load demand and to serve their UEs by the main RRH. The main RRH can use CRE in order to change its coverage range with respect to the traffic load demand, as shown in Fig. 5.12.
Another use for DC-RAN is setting the main RRHs to provide the DL connection to the UEs, whilst the UL connection can be provided by other RRHs that are related to the same CO. Furthermore, the main RRH for each pool can be used to transmit a Multimedia Broadcast Single Frequency Network (MBSFN) to deploy mobile TV network (Broadcasting/Multicasting) services through the existing network structure.

The number of active RRHs as $active.rrh_v$ in the single pool v by using DC-RAN can be calculated as in Eq. 5.9:

$$active.rrh_v = [(w)v - (D_v * C_{mainRRH_v})] + 1 \tag{5.9}$$

Whereas, the total number of active RRHs as $ACTIVE.RRH_{net}$ in multi pool network by using DC-RAN can be calculated as in Eq. 5.10:

$$ACTIVE.RRH_{net} = (N+M) - \sum_{u=1}^{M} D_u * C_{mainRRH_u} \tag{5.10}$$

where, $C_{mainRRH_u}$ denotes the achieved coverage area of the main RRH of the pool u, and D_u is density of pool u. Fig. 5.13 shows the consequence of the introduced example of DC-RAN in pools no. 13, 29 and 15 when the main RRHs use CRE. As can be seen, when the main RRH in specific pool work with 50% of the coverage area, then it possible to switch off up to 20% of the active RRHs in pool no. 13, while it is possible to switch off about 45% and about 60% of active RRHs pools no. 29 and no. 15, respectively. These differences in percentage of active RRHs are due to the differences in the RRH densities, D_u, among the BBU pools. The DC-RAN could have a significant effect in the control process of the energy saving and network throughput.

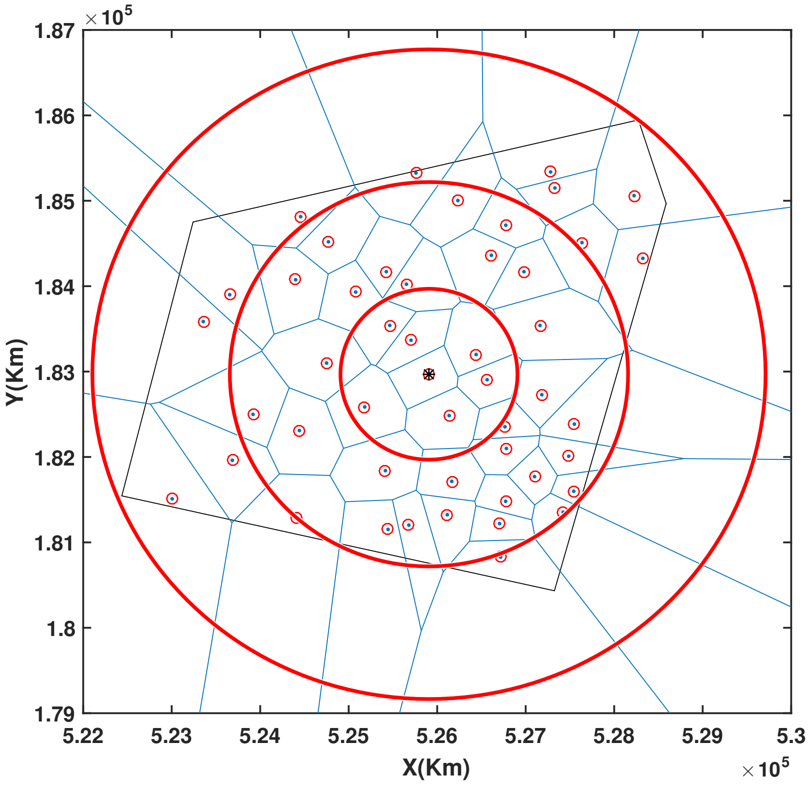


Fig. 5.12 DC-RAN concept for a single BBU pool

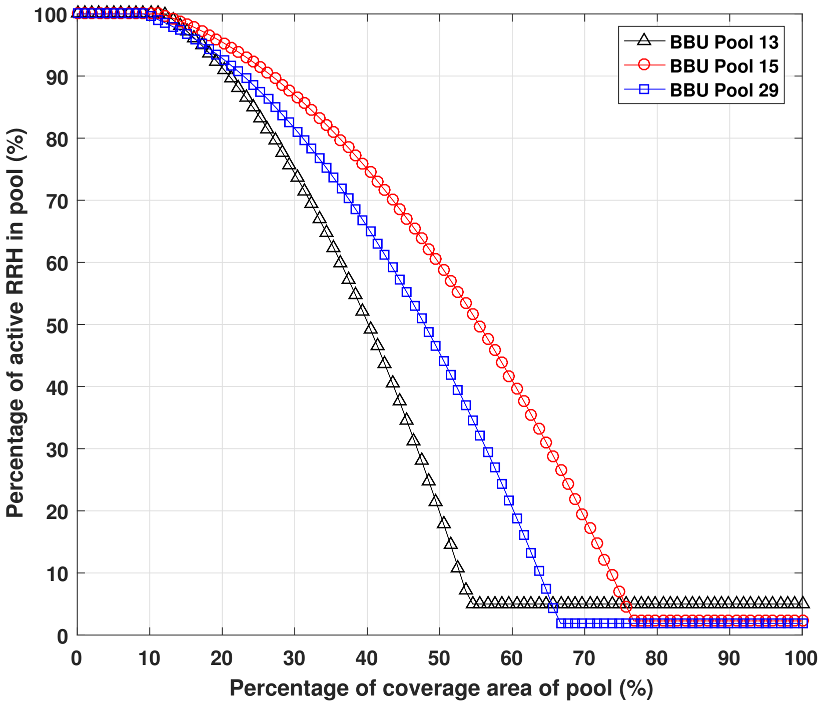


Fig. 5.13 Number of active RRH in single pool using DC-RAN for different pools

5.10 Summary

With the innovation of C-RAN, the allocation of BBUs pools such as best locations, optimized number of pools and connected RRHs in the network become a crucial and important problem. By determining these issues make the system simpler in terms of management and evaluated system performance.

This chapter proposes an approach for allocating the already deployed network radio access nodes to multiple BBU pools to improve the offered NQoS. The proposed approach performs four sequential algorithms starting by radio access nodes clustering based PSO algorithm passing through model selection BIC with measure of spread technique, then ends by Voronoi tessellation to consider DC-RAN operation, which adaptively adjusts the main RRH coverage range according to traffic load required as well as considering energy saving.

The numerical results of the approach show that the optimized partition of the proposed network model is 41 BBU pools with an average density of the RRHs per pool area that has matched the primary average density of the radio access nodes per network area. Actual heterogeneous network is used to evaluate this approach.

Chapter 6

Conclusions and Future Work

This chapter finalises this thesis and overview conclusions, moreover some ideas are presented to be developed in future work. The main aim of this thesis is to analyse the performance of the of a Cloud Radio Access Network (C-RAN) architecture deployment for the current and future network, calculate and optimize power consumption for this architecture.
C-RAN deployment was introducing as separation of eNodeB of Long Term Evolution (LTE) into Remote Radio Heads (RRHs) and Base Band Unit (BBU) Pools, and how to deploy the BBU pools in network. A study focused on critical parameters that have significant effects on the implementation of this new architecture. Such as fronthaul link, namely the delay, the capacity and load balancing that represented by number of RRHs that connect to the BBU pools.

6.1 Conclusions

This thesis is made up of four main chapters:

Chapter Two introduced a general cellular network background and presented a comprehensive overview of C-RAN architecture. Facts of C-RAN are provided, along with its

technical challenges and benefits. C-RAN adapts well to traffic fluctuations among RRHs, due to sharing of baseband resources. In C-RAN architecture BS functionalities are split between cell site RRH and the BBU pool. It is a challenge to find an optimal splitting and efficient interconnectivity between the parts.
However, requirements of low delay are put on the fronthaul network, and virtualization techniques is discussed in this chapter. C-RAN deployment scenarios requirements are presented. Heterogeneous Network (HetNet) are explained and how can to exploit in C-RAN depoloment. Clustering concept in C-RAN can be defined as a controlling number of RRHs in one group, this concept has been discussed in this chapter.

In **Chapter Three**, the C-RAN architecture has been introduced as a case study of the Data Center (DC) to discuss the challenges of energy management and find the optimum solution for the proposed system. However, the dynamic BBUs allocation to RRHs in C-RAN architecture is examined, with an aim to reduce the power consumption in the BBU pool. A power consumption model for C-RAN based on virtualization technology is proposed.
Orchestra Server (OS) is proposed in the BBU pool to support the system in term of energy management and self-organization. Intelligent algorithm is holed by OS to find the proper network configuration setting. Furthermore, the OS produces a decision to the switching system to make reconfiguration of BBUs-RRHs. Moreover, it sends commands to BBUs in order to switch on/off them with respect to the traffic demands of RRHs to decrease the number of BBUs that leads to decreased the amount of total energy consumption within the system. Additionally, this chapter introduces an optimization power consumption model for the C-RAN based on bin packing algorithm. It's namely New Minim Bin Slack (NMBS) and it is compared with Best Fit Decreasing (BFD) and traditional network to evaluate the system performance.
However, the NMBS that is modified the Minim Bin Slack (MBS) which tries to find a set

of users that fit into bins capacity as much as possible to do load balancing among them. Simulation results show that the NMBS algorithm is better than the BFD and traditional network by reducing the number of active BBUs and saving energy in residential and office area during day time. In business area, the proposed algorithm saves up to 90%, 60% and 20% of BBUs utilized by low, average and peak traffic load respectively, compared to A traditional network.

Moreover, it saves up to 50%, 25% and 10% of active BBUs of low, average and peak traffic load respectively, compared to BFD algorithms for the same area. In addition, for residential, the NMBS algorithm saves up to 90%, 70% and 50% of active BBUs of low, average and peak traffic load respectively, compared to traditional network. It saves up to 50%, 25% and 30% of BBUs used by low, average and peak traffic load respectively, compared to BFD algorithms.

Moreover, the results also show more BB processing functionS moved from the BS to the cloud, with more power savings are gained because of more cooperative and sharing resources between BBUs in the same BBU pool. Furthermore, the average daily power consumption of the business area is reduced by 62% using the NMBS algorithm while the BFD reduced by 53%, compared to the traditional network. The peak daily power consumptions for NMBS and BFD algorithm of the residential area are reduced by 63% and 29% from traditional scheme.

Moreover, there are three common types of optical fibre network, namely, Point To Point (PTP), Active Optical Network (AON) and Passive Optical Network (PON). These types of network are proposed to be used as a fronthaul for C-RAN architecture.

In **Chapter Four**, network planning and deployment is a crucial issue for the Next Generation Network (NGN) and has a significant effect on the network capacity, cost and energy saving. There are many challenges within the proposed C-RAN architecture. One of these challenges is latency and throughput in the fronthaul link.

There are many factors contribution to the overall link latency between the User Equipment (UE) and its related BBU unit in the C-RAN structural design. The significant factor is Hybrid Automatic Repeat reQuest (HARQ) protocol to the latency in the LTE network. In LTE network design, the HARQ did not consider for propagation delay between UE and eNB. Therefore, this chapter shows the effect of the wireless connection between the UE and RRH on distance of optical fibre fronthaul link between the BBU pool and RRHs. All components which have influence on fronthaul delay (i.e. propagation and processing delay) are calculated to find the maximum optical fiber fronthaul with respect to the RRHs coverage area. The BBU pool placement in the network is important to consider the latency constraint with respect to the all served RRHs.

In addition, this chapter analyses real LTE cellular network to determine the optimal BBU pool location, dimension pool area and minim required number of BBU pool in the network. Calculation of C-RAN planning and mechanism of the BBU pool placement are considered by many parameters such as a geographical cell distribution, average cells coverage area, and time delay of HARQ. Quasi-Newton Method (QNM) algorthim is used to find the optimal location for BBU pool placement which is resultant a position of the centre of minimum distance in the pool serving area.

The simulation results analysis are based on two main parts; C-RAN latency analysis as a homogenous network, and real case study for a real heterogeneous network. The results show that the multi pooling is a best solution for the proposed actual heterogeneous LTE network and the minimum required member of pools with respect to the fronthaul constrains was five. The Particle Swarm Optimization (PSO) algorithm has been proposed in this work to partition the network for multi pool.

In **Chapter Five**, The main challenges in multiple pools C-RAN architecture are the partitioning of the network for a required number of BBU pools, their positions and the number of connected RHHs per each pool. In this chapter, an algorithm for partitioning a single network into a required number pools as well as finding the optimal BBU pool positions over the DC-RAN architecture is proposed. Under this concept the set of RRH positions is considered in terms of a set of feasible locations and the number of BBU pools in a specific network.

The multiple pooling based PSO clustering algorithm is adopted to solve the RRH pooling configuration problem, with the optimal BBU pool location allocation, after first, determining their optimal number. That is, the Bayesian Information Criterion (BIC) criterion is used to narrow the search problem of identifying the range of the candidate multiple pools numbers in the search for the optimal multiple pools configuration. Subsequently, the measure of spread technique of the RRH numbers among the candidate multiple BBU pool configurations is successfully used to select the unique optimal multiple pool configuration for the proposed network.

Finally, Voronoi tessellation interaction of the activated main RRHs of DC-RAN facilitates allocating the pools areas as well as the number of connected RRHs with each BBU pool. It shows that there is a significant change in the number of active RRHs within each pool area as a result of using the CRE criterion.

6.2 Future Work

This thesis is significantly contributing to modelling, analysis and reduction of power consumption in whole the C-RAN architecture. Furthermore, planning task of the C-RAN architecture is studied and analysed with respect to the 5G requirements. However, there are some suggestions for future work that can be summarized as follows:

1. Network resources utilisation in time-varying load may lead to traffic imbalances that lead to degrading Quality of Services (QoS) of the system. Consequently, future work shall optimise the QoS parameter of C-RAN by finding the solution of load balancing. Dynamic re-mapping technique for reconfiguration of the BBUs to RRHs proper shall be used. Furthermore, a C-RAN self-optimist is proposed for future work to enhance the network QoS of the system by load balancing among BBUs in BBU pool with minimum possible handovers.

   Furthermore, study the influences of the DC-RAN on handover for the proposed network. The problem formulation could be defined as Key Performance Indicators (KPIs) for the number of users and handovers in the system that subject to RRH loads constraint. Moreover, a PSO, Genetic Algorithm (GA) and Simulating Angling (SA) should be proposed as algorithms to evaluate the system performance. Additionally, study the influences of the DC-RAN on handover and power consumption calculation for the proposed network.

2. As traffic load in mobile communication system continues to grow because of sharp increase in smart devices such as smart phone, and emerging new application and services. This increasing in network is a challenge for current and future cellular network due to the increase in complexity for management, operation and high upgrade. Although, C-RAN that is proposed by many companies as this work mentioned in chapter two to solve many problems, there are still several issues. The C-RAN/Fronthaul will no be able to handle such increasing traffic load requirement in 5G network.

   Future work could optimize the split function between BBU and RRH, several functional split options are considered with respect to fronthaul capacity, RAN virtualization gain, Coordinated MultiPoint (CoMP) effect, etc to solve these issues. In addition, using the Analogue Radio over Fibre (A-RoF) instead of Digital RoF (D-RoF) which has the ability to face the increasing data rate demand for the 5G.

3. It is expected for the next generation a massive traffic backhaul between BBU pools and Core Network (CN) that needs ultra-high processing capacity for core network. This would result in an increase of CApital EXpenditures (CAPEX) and OPerating EXpenditures (OPEX) when trying to handle the growing signalling overhead. In order to mitigate this problem, it is proposed for future work to split some functions of CN and move into BBU pool. Moving some functions to BBU pool can reduce the signaling delay, proceeding effort in CN, and operating cost. The moved some functions of CN to the BBU pools can be called 5G Distributed Core Network (5G-DCN) as shown in Fig. 6.1.

4. Mission-critical Internet of Things (IoT) applications include autonomous driving (self-driving), remote controlled machine, etc of ultra-real-time services require low end-to-end latency about less than 1ms. The best method to achieve minimal latency communications is to eliminate backhaul delay as discussed above (5G-DCN) which is closest to mobile users, and placing application servers right next to it.

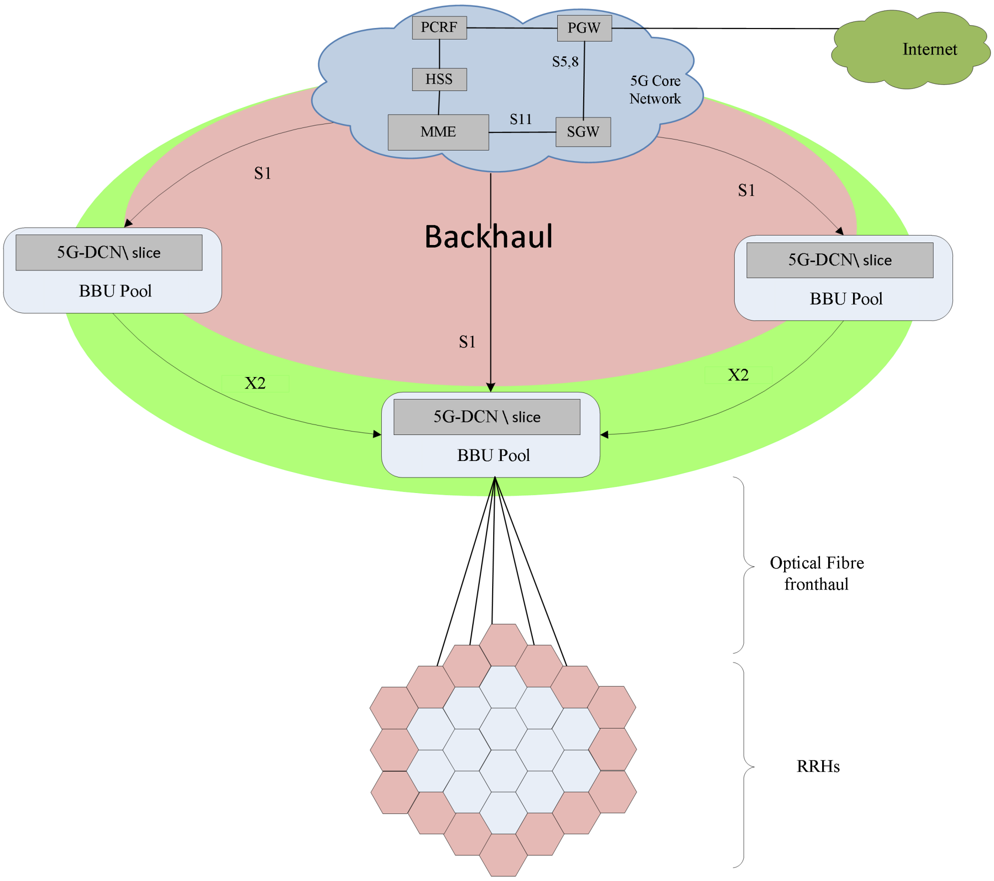


Fig. 6.1 Proposed cellular network architecture for the future work

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