DYNAMICALLY DETERMINING RADIO ACCESS TECHNOLOGY FOR ENERGY EFFICIENCY IN 5G MOBILE NETWORKS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ABDULLAH ÖMER YAMAÇ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
COMPUTER ENGINEERING

JUNE 2019

Approval of the thesis:

DYNAMICALLY DETERMINING RADIO ACCESS TECHNOLOGY FOR ENERGY EFFICIENCY IN 5G MOBILE NETWORKS

submitted by **ABDULLAH ÖMER YAMAÇ** in partial fulfillment of the requirements for the degree of **Master of Science in Computer Engineering Department, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences** _______________

Prof. Dr. Halit Oğuztüzün
Head of Department, **Computer Engineering** _______________

Assoc. Prof. Dr. Ertan Onur
Supervisor, **Computer Engineering, METU** _______________

Examining Committee Members:

Assoc. Prof. Dr. Sevil Şen
Computer Engineering, Hacettepe University _______________

Assoc. Prof. Dr. Ertan Onur
Computer Engineering, METU _______________

Assist. Prof. Dr. Pelin Angın
Computer Engineering, METU _______________

Date:

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Abdullah Ömer Yamaç

Signature :

ABSTRACT

DYNAMICALLY DETERMINING RADIO ACCESS TECHNOLOGY FOR ENERGY EFFICIENCY IN 5G MOBILE NETWORKS

Yamaç, Abdullah Ömer
M.S., Department of Computer Engineering
Supervisor: Assoc. Prof. Dr. Ertan Onur

JUNE 2019, 56 pages

The evolution of the Internet of things and information communication services introduces new demands in the 5G area. New types of services and use cases such as massive machine-type communication applications, enhanced mobile broadband and ultra-reliable low-latency services will be created in the coming years. These new services and applications will significantly increase energy consumption. In this thesis, we propose a solution for dynamically configuring the radio access technology by employing cloud radio access networks in 5G to conserve energy. Depending on user locations, remote radio unit (RRU) locations and user demands, the communication stack on the RRU is dynamically determined. While some of the RRUs are turned off in this solution, others are configured to run a protocol stack that consumes less energy while meeting user demands. We define this approach as an optimization problem in this thesis and solve it using the state-of-the-art optimization tools. We show that significant amounts of energy can be conserved by employing this approach.

Keywords: 5G, energy-efficiency, optimization

ÖZ

5G MOBİL AĞLARDA ENERJİ VERİMLİLİĞİ İÇİN RADYO ERİŞİM TEKNOLOJİSİNİN DİNAMİK OLARAK BELİRLENMESİ

Yamaç, Abdullah Ömer
Yüksek Lisans, Bilgisayar Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Ertan Onur

Haziran 2019 , 56 sayfa

Nesnelerin interneti ve bilgi iletişim hizmetlerinin evrimi 5G alanında yeni talepler ortaya koymaktadır. Gelecek yıllarda büyük makine tipi iletişim uygulamaları, gelişmiş geniş mobil bant hizmetleri ve ultra güvenilir düşük gecikmeli kullanım durumları gibi yeni tip servisler ve kullanım durumları oluşacaktır. Bu yeni hizmetler ve uygulamalar enerji tüketimini önemli ölçüde artıracaktır. Bu tezde, 5G'de bulut radyo erişim ağlarını kullanarak radyo erişim teknolojisini dinamik olarak yapılandırmak üzere bir çözüm öneriyoruz. Kullanıcı konumlarına, uzak radyo ünitesi (RRU) konumlarına ve kullanıcı taleplerine bağlı olarak, RRU üzerindeki iletişim protokolü dinamik olarak belirlenir. RRU'ların bazıları bu çözümde kapalı olurken, diğerleri kullanıcı taleplerini karşılamak için daha az enerji tüketen bir radyo protokolü çalıştırmaktadır. Bu yaklaşım, tez çalışmamızda bir optimizasyon problemi olarak tanımlanmış ve en gelişmiş optimizasyon araçları kullanılarak çözülmüştür. Bu çalışmanın sonucu olarak geliştirilen bu yöntem ile önemli miktarda enerjinin korunabileceği gösterilmiştir.

Anahtar Kelimeler: 5G, enerji verimliliği, optimizasyon

This thesis is dedicated to all members of my family:

To my father and mother, Sadık and Neziha Yamaç, whose financial and moral supports to finish my study.

To my lovely wife, Rabia Tuğba Yamaç, whose patient and supports to revise this thesis.

To my brothers - Mustafa, Taha, and Said - whose moral supports.

ACKNOWLEDGMENTS

It is a pleasure to express my deep sense of thanks to my supervisor Assoc. Prof. Dr. Ertan Onur, for all of his efforts during my thesis progress and study. Whenever I need help, only one mail enough to get help from him. Moreover, he works hard to setup WINS-Lab where we can study anytime. Also, I want to thank all of the members of WINS-Lab for technical supports.

It is my privilege to thank my family, for their encouragement and supports.

Finally, my thanks go to all the people who have supported me.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

e	Energy Efficiency
t	Time
BS	Base Station
CP	Control Plane
C-RAN	Cloud Radio Access Network
DDRAT	Dynamically Determining Radio Access Technology
LP	Linear Programming
MILP	Mixed Integer Linear Programming
QoS	Quality of Service
RRU	Remote Radio Unit
SDR	Software Defined Radio
UE	User Equipment
UP	User Plane
USRP	Universal Software Radio Peripheral

CHAPTER 1

INTRODUCTION

In this chapter, we will give an introduction to our thesis. As a first step, we will explain the motivation and the background of our study. Then depending on this motivation, we will define the problem that we solved. After that our solution and contributions will be given verbally. Finally, we will look over the outline of the thesis.

1.1 Motivation

Energy is a term that gives some power to utilities to be able to run. These utilities are varied from the field of transportation to the communication area. They make our lives easier. Therefore, energy is the most valuable thing we should always produce and consume. There are two things we should worry about energy.

The first one is the limited resources. For many years energy is produced by fossil fuels like oil and coal. We still use these kinds of resources [1]. In the coming years, these resources will run out. Therefore, we should be careful about using them.

The other thing is that the production of energy has cost [1]. This cost is not just financial, but also it consumes life resources. If fossil fuels are still used to generate energy, then air and water pollution are generated [2]. Therefore, waste of energy causes more pollution for us and they make difficult to live in the world.

In a nutshell, energy is one of the most important resources that should not be wasted. There are numerous committees to study energy efficiency in the field of all technologies. One of the studies has experimented in this thesis to get better energy efficiency in 5G mobile networks.

1.2 Problem Definition

The number of online devices around us increasing day by day. In 2020, the expected number of Internet-enabled devices running on 5G will be 26 billion [3]. That means the network will become ultra-dense in 5G. These ultra-dense networks will be supported by too many base stations using small cell deployment [4]. Crowded base station deployment will cause some problems such as high energy consumption [5]. If you look at a crucial problem for every aspect of our lives, that is the waste of energy. Hence, energy efficiency is one of the primary design issues for 5G technology [6] [7] [8] [9].

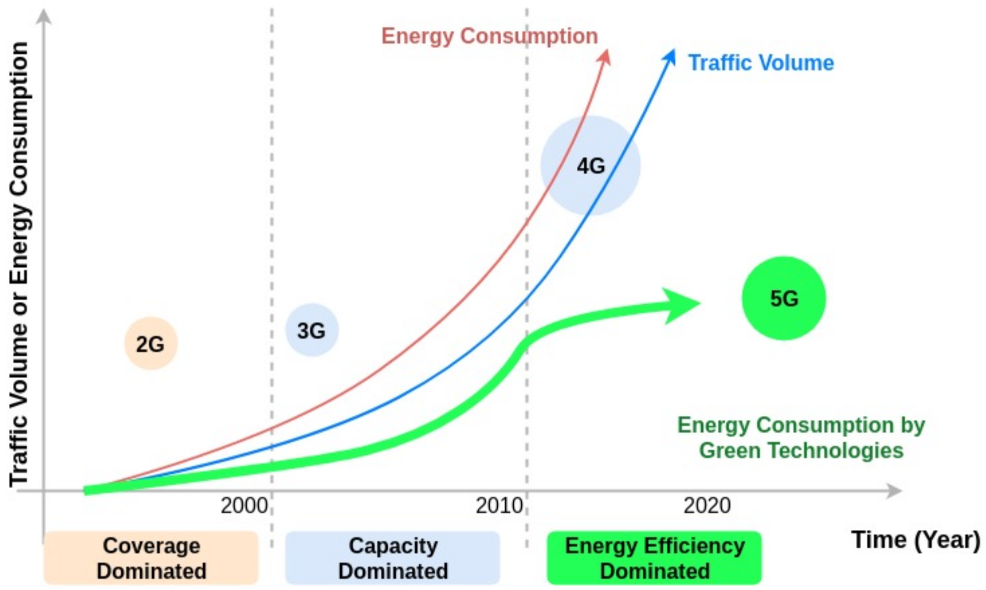

Figure 1.1: Energy consumption forecast by years and technologies.

Over the years, new communication technologies have been developed. With these new communication technologies, energy consumption increases exponentially. In Figure 1.1, it is obvious to see that energy consumption increases exponentially for each new technology [10]. For 5G, this much energy consumption is not desired. Therefore, researchers are studying this concept in the fields of green radio and green mobile communications [5] [11][12] [13].

In conclusion, one of the studies on green communication is explained in this thesis to overcome high energy consumption problem. This problem is solved by optimization tools like MATLAB, Gurobi, and CPLEX. We define an optimization problem that minimizes the energy consumption of the network. In this problem, we are deciding dynamically which radio access technologies should be run for each RRUs. User-cell associations and base stations' on/off status should be found by solving this problem. In the next section, the solution will be explained verbally.

1.3 Methodology

The key idea of this thesis based on the flexibility of the base station. Changing the wireless protocol on the base station is the new idea with new improvements in the area of software-defined radio. Software Defined Radio (SDR) devices enable us to run any protocol on just one device [14]. Each wireless protocol has different features. Some of them consume less energy, but they may have less coverage area [15] [16]. This trade-off can be exploited to decrease energy consumption. Also, these devices can be set in sleep mode to save energy. Then, we can save energy as much as we can do. In short, we have two methods to save energy. One of them is setting a base station in sleep mode. The other one is changing the wireless protocol. We simply call our method as Dynamically Determined Radio Access Technology (DDRAT).

1.4 Contributions

The overall contributions of this thesis are as follows.

- We define base station on-off status and radio access technology running on base stations as an optimization problem. The objective of this problem is to minimize energy consumption. The problem is formulated analytically in this thesis.
- We find the user-cell association concerning base station on-off status and radio access technology. The user-cell association represents which user should be connected to which base stations.

- We use an intuitive solution to decide radio access technology. This intuitive solution makes a comparison between the number of user's decisions. Users prefer to use one of the radio access technologies. Then the most preferred radio access technology is chosen to run on a radio unit.

- We define a heuristic method named as Heuristically and Dynamically Determining Radio Access Technology (HDDRAT). This heuristic method is necessary to speed up the solution time of the optimization problem. In this method, the optimization problem is divided into two parts. In the first part, we decide on the radio access technologies. Then, we find the user-cell associations. Finally, base stations' on-off status are determined. This is the procedure of the heuristic method.

- We use three different tools to solve our optimization problems. These tools are MATLAB, CPLEX, and Gurobi solvers. The algorithms of these solvers are different from each other.

1.5 The Outline of the Thesis

In this section, we will give an outline of the thesis. This thesis includes four chapters.

Chapter 1 is the introduction part of the thesis. In this chapter, motivations, and contributions of the thesis are explained. Additionally, problem definition and solution are also given in this chapter. We finalize this chapter giving the outline of the thesis.

In Chapter 2, we give details about the necessary background information and related works. Background information consists of two parts. The first one is about the if-else case for the optimization problems. The second one is about the mobile communication background. This includes the traditional radio access network and cloud radio access network. The related work section includes studies that find a way to reduce the energy consumption of the network for 5G.

In Chapter 3, we give the details of our study. As a first step, we define a possible architecture to apply our method. This architecture includes two parts: data-plane and control-plane. Next, we define the assumptions of the system and the mathematical representation of the DDRAT. Then, we define the heuristic solution which is called as HDDRAT.

In Chapter 4, we apply DDRAT and HDDRAT to a test case. This case is explained in this section. After that, we show the results of this test case. Then, we discuss the results of the DDRAT, HDDRAT, and solvers.

In Chapter 5, we will conclude our thesis and we will give details about the future work.

CHAPTER 2

BACKGROUND AND RELATED WORK

In this section, we will explain the necessary background information for this thesis. This background information includes optimization problem and mobile networks. Also, we will give details about the related work.

2.1 Background

This section only contains background information about the thesis work. In the optimization problem that is defined in this thesis, needs conditional constraints. These conditional constraints cannot be directly implemented. Therefore, we will explain how we can implement a condition in the optimization problem. The other background information is about mobile network architecture. This information is necessary to explain system architecture in Section 3.2.

2.1.1 IF-ELSE Condition for Mixed Integer Problems

Mixed Integer Linear Programming problems cannot be directly solved if they include conditional statements. Conditions can be represented as multiple statements. These statements enforce the problem depend on the condition state. We need to define an additional parameter to express condition state true or false. To be able to understand this concept clearly, we present an example below.

Assume the problem has the following constraint (2.1.1):

$$\text{if } \alpha > 0 \text{ then } \beta \leqslant 0 \text{ else } \gamma \geqslant 0. \tag{2.1.1}$$

This equation is a simple if-else condition. If α is greater than 0, then β should be less than or equal to 0. If α is less than or equal to 0, then γ should be greater than or equal to 0. This is our sample condition.

As a first step, we need to define some variables. These variables are shown in Table 2.1.

Table 2.1: Variable definitions for the sample conditional statement.

Symbols	Definitions
z	additional binary (1 or 0) variable to meet the condition
L_α	Lower bound on α
L_β	Lower bound on β
L_γ	Lower bound on γ
U_α	Upper bound on α

In Table 2.1, z is the additional variable to represent the conditional state. This value can be only 0 or 1. $z = 1$ represents the conditional statement is true and β should be less than or equal to 0. $z = 0$ represents the conditional statement is false and γ should be greater than or equal to 0. The other variables are the boundary limits of the conditional statement.

The conditional statement represented in Equation (2.1.1) can be expressed using the following four equations:

$$\alpha - z * U_\alpha \leqslant 0. \tag{2.1.2}$$

$$\alpha - (1 - z)(L_\alpha - 1) > 0. \tag{2.1.3}$$

$$\beta - (1 - z)L_\beta \geqslant 0. \tag{2.1.4}$$

$$\gamma - z * L_\gamma \geqslant 0. \tag{2.1.5}$$

These equations are explained as follows:

- If $z = 1$ ($\alpha > 0$) then equations (2.1.2) ($\alpha \leqslant U_\alpha$) and (2.1.5) ($\gamma \geqslant L_\gamma$) are redundant, and the **then** condition (2.1.4) ($\beta \geqslant 0$) is enforced.
- If $z = 0$ ($\alpha \leqslant 0$) then equations (2.1.3) ($\alpha > (L_\alpha - 1)$), and (2.1.4) ($\beta \geqslant L_\beta$) are redundant, and the **else** condition (2.1.5) ($\gamma \geqslant 0$) is enforced.

This method is adopted from studies [17] and [18].

2.1.2 Traditional Radio Access Network

Mobile networks divide a region into small cells as shown in Figure 2.1. Each cell is covered by base stations. These base stations can be separated into two segments which are Remote Radio Units (RRUs) and Base Band Units (BBUs).

RRU is the remote radio unit that is responsible for signals transmission. Base Band Unit (BBU) is the remaining part which includes signal operations. This is the traditional radio access network. In this architecture, each cell requires its own RRU and BBU with routing functionality, cooling system and power management. A tremendous increase in the base stations' deployment causes high expenditure in this network architecture.

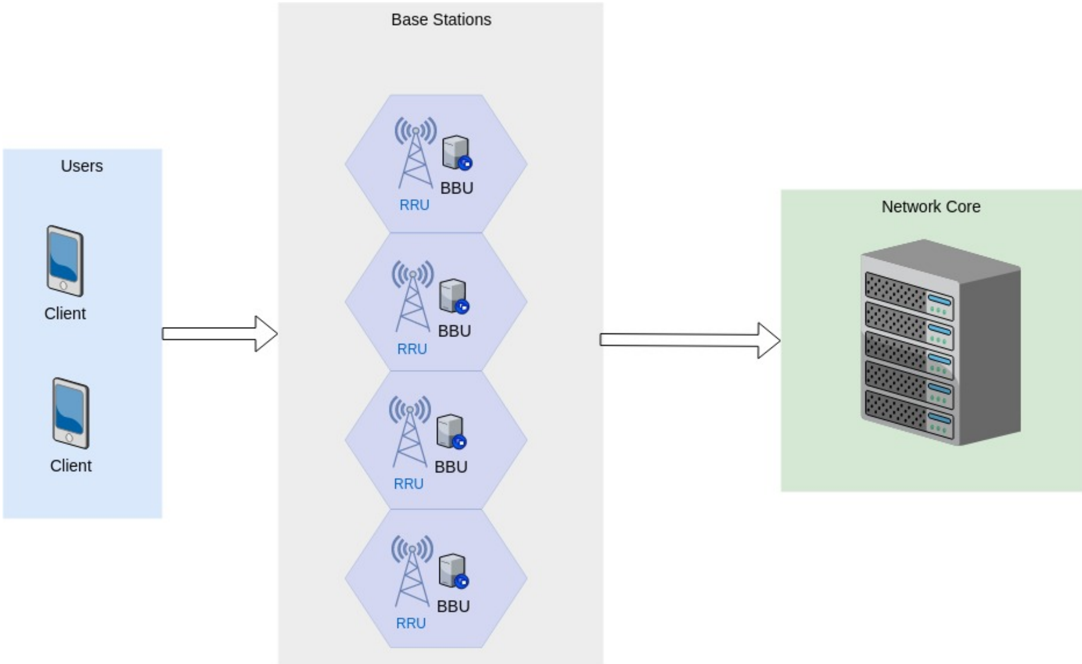

Figure 2.1: Each cell is covered by base stations. These base stations include RRU and BBU. This is the traditional architecture.

2.1.3 Cloud Radio Access Network

In this architecture, RRUs and BBUs are separated and BBUs are centralized. In Figure 2.2, we have two new terms that are fronthaul and backhaul. Fronthaul is responsible for communication between RRUs and BBUs. Backhaul is responsible for communication between BBUs and Network Core. This is the Cloud Radio Access Network (C-RAN).

Cloud Radio Access Network (C-RAN) is a potential candidate for next-generation radio access network architecture that has lower expenditure than traditional radio access network [19]. C-RAN has also the ability to reduce electricity costs by centralizing baseband units to the center side [20] [21]. Moreover, depending on traffic load BBU resources can be dynamically allocated [22]. Then network costs also can be reduced.

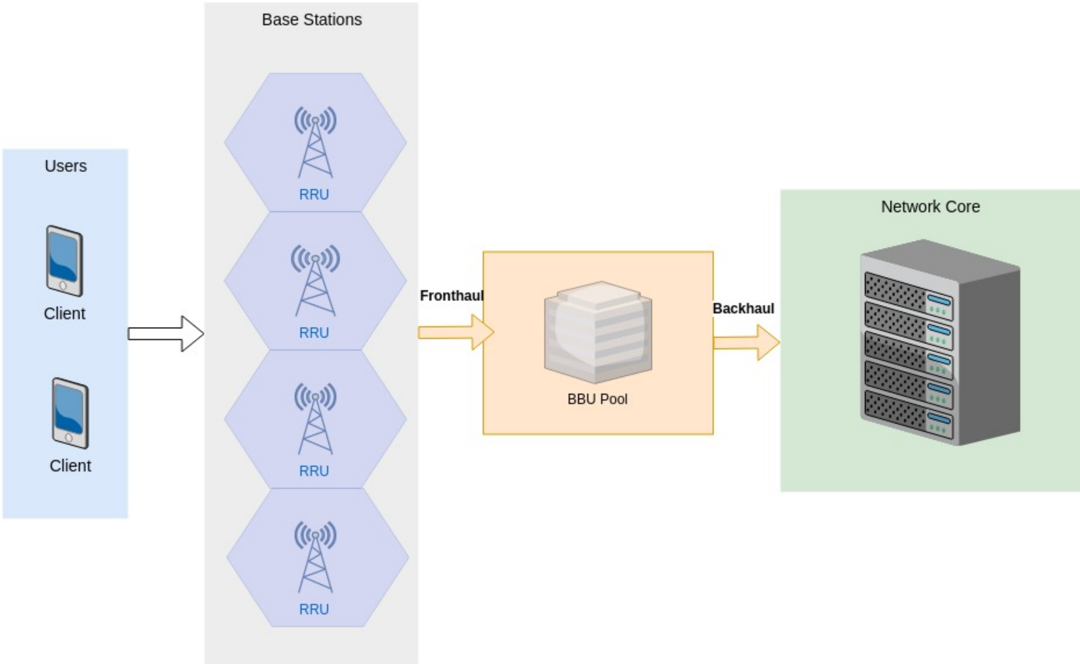

Figure 2.2: Each cell is covered by base stations. These base stations include only RRUs and BBU is centralized. This is the C-RAN architecture.

2.2 Related Work

Energy efficiency has emerged as a design problem in communication networks [7]. In the last decade, energy efficiency is getting more important than other performance metrics such as data-rate or throughput. One of the reasons for this fact is the deployment of the small cells in 5G [23]. The computation power of the base stations increases more than 50 percent of the energy when the small cells are deployed [23]. Studies about energy efficiency in this field are explained below.

The first kind of study is about switching base stations on/off. The idea of switching base stations on/off is to turn off the base station when it is not necessary. In one study, researchers show that 20-30% of energy can be conserved by using base station on/off scheduling when the traffic load is observed [24]. The turn-off decision is done in several ways and energy expenditure can be reduced by 72% [25]. One of them is done by operators depend on the traffic load. The other one is done by some algorithms that are applied depending on the traffic load and time [26] [27] [28] [29]. The last one is done statically by observing the traffic load [30]. Of course, these results can be varied depending on the simulation environment or the local region that method is applied [31].

Instead of only turning off the base stations, some other variations of the turn on/off methods are also studied. One of them is the sleep method and it can be controlled in the following ways [32].

- Duty cycled: Each BS follows a specific duty cycle of sleep/ON scheduling.
- Adaptive Duty Cycled: The duty cycle of the sleep interval is dynamically adjusted based on the traffic condition or prediction.
- On-demand (Low Power Wake-Up Receiver) LP-WUR (Always-on): The LP-WUR wakes up the main transceiver for data transmission when a wake-up package has been successfully received
- On-demand LP-WUR (Duty Cycled): During the ON state of the LP-WUR, the LP-WUR wakes up main transceiver for the data transmission when a wake-up signal comes in.

The other way to apply base station on/off method is only changing the coverage area of base stations and turn off some of them [30]. To be able to do this, better user-cell associations can be found [33] [34] [35] [36] [37]. These user-cell associations are helpful to determine necessary cell coverage. Then, the required power for transmission is applied and some of the base stations can be turned off. The authors in [38] apply game theory to find the best coverage area. Finding optimal user association is the key term of these papers. One of the works uses clustering to get more benefit [39]. Another proposal in [25] uses a greedy approach to apply the BS on/off scheduling. There are lots of studies about the base station on/off strategy. This is also one of the goals of this thesis.

Switching base stations on/off may cause several issues. These issues are switching costs and transmission power adaptation. One of the solutions to these problems can be solved using the Minimum Energy Cost Algorithm [40]. There are additional technical challenges in this subject. They can be listed as follows:

- When a base station is turned-off, network providers should not be worried about the coverage.
- Controlling a large number of base stations becomes harder.
- If there is a connection between a user and a base station that will be turned off, the connection state should be carried always [41].

As stated in the background section, C-RAN architecture has a lower cost than the traditional method. In addition to this, a functional split is also applied to the C-RAN architecture [42]. The network layers can be split for the C-RAN architecture to reduce cost [43].

In this thesis, we are focusing on the user association to determine the base station on/off status. Also, user association will be optimized by changing radio access technology. In conclusion, we will get the benefits from the properties of different radio access technologies.

CHAPTER 3

DYNAMICALLY DETERMINING RADIO ACCESS TECHNOLOGY

In this chapter, we will define our method as an optimization problem. Analytical model of the problem and the system architecture is given here.

3.1 System Model

Dynamically Determining Radio Access Technology (DDRAT) is a multi-decision mechanism which decides the state of the base stations' on/off status and the radio access technology running on the RRUs. This multi-decision mechanism is implemented as an optimization problem. This problem has three variables to represent decisions.

One of the variables is the state of the base stations which are on or off. The other variable represents the running radio access technology on the RRUs. The last variable shows the user-cell associations. We use the last variable to find the previous two variables. Also, these associations are used in the objective function of the optimization problem to find consumed energy and deployment. Details of these variables will be given in Section 3.4.

Our objective is minimizing power consumption which is directly related to the consumed energy. This power consumption model is the summation of the dynamic power consumption and static power consumption. We should consider some constraints like coverage, bandwidth and the number of users while minimizing power consumption in our optimization problem. These details will be given in Section 3.4

There should be a flexible architecture to apply the DDRAT mechanism. This architecture is designed based on C-RAN technology. In addition to using separated BBU and RRU, we split Control Plane (CP) and Data Plane (DP).

Separation of Control Plane (CP) and User Plane (UP) makes necessary parameters such as positions and demands of users are available. These parameters are needed by optimization solvers to optimize energy. CP makes all necessary coordinations like connection state information and necessary parameters for optimization solvers. Moreover, CP provides complete coverage of UEs and drives small cells. Then UP only focuses on data transfer. For more details, readers may refer to Section 3.2. Separation of CP and UP causes additional base stations, but CP power consumption can be neglected concerning the power consumption of UP.

In DDRAT, we try to decrease power consumption by solving the optimization problem. Finding the result of the optimization problem may take a long time. This process should be in the milliseconds' range for the communication networks, but the search space of the problem is increasing exponentially. This is due to the user-cell associations variable. All of the possibilities of these associations are tested in the DDRAT. Therefore, the complexity is $O(2^{M \times N})$. To speed up DDRAT we implemented a new method which is Heuristic DDRAT (HDDRAT). The time differences between these two methods are discussed in the result section. Details of the HDDRAT will be given in Section 3.5.

3.2 The Architecture

In this section, we define the system architecture evolved from the C-RAN. This architecture is used to apply DDRAT and HDDRAT mechanism. The control plane and the user plane of the C-RAN are separated.

User Plane (UP) is shown in Figure 3.1. This architecture has two elements which are RRU and BBU-Pool. RRUs are the RF part of the architecture. SDR devices such as USRPs can be placed as RRUs. These devices operate on a reasonable range of frequencies. During the runtime, frequencies can be altered. This means that at any time we can run any protocol on the RRUs. That is the main reason to use SDR devices.

The other element of the UP is BBU-Pool. It can be named as Central Unit (CU). BBU pool is a cloud and centralized system. Baseband operations are processed in here. Cloud system have also virtualization technology to be able to migrate functions between machines. For each radio access technology, the cloud has different machines and resources can be shifted between them.

This is the user plane architecture and it enables us to run different wireless communication protocols without changing hardware.

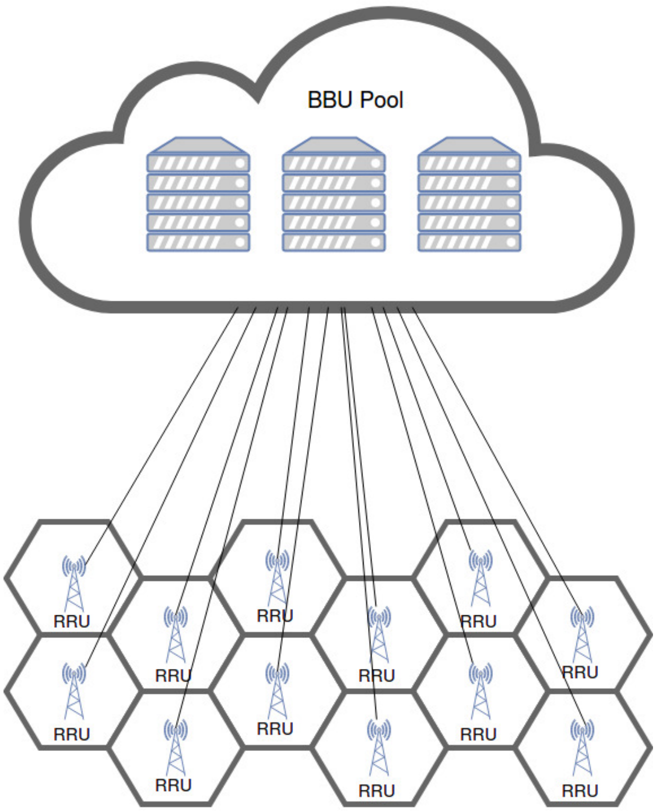

Figure 3.1: Each RRU is connected to the BBU pool. I/Q samples are transferred between RRU and BBU. These I/Q samples' characteristic changes depending on the running radio access technology on RRU.

Control Plane (CP) architecture is simpler than the UP. CP covers the whole area to handle the coverage issue. In Figure 3.2, one CP RRU and multi UP RRUs are shown. All UEs must communicate to CP to notify their locations. UP RRUs are also connected to the CP RRU. All of the control protocols are done by CP RRUs.

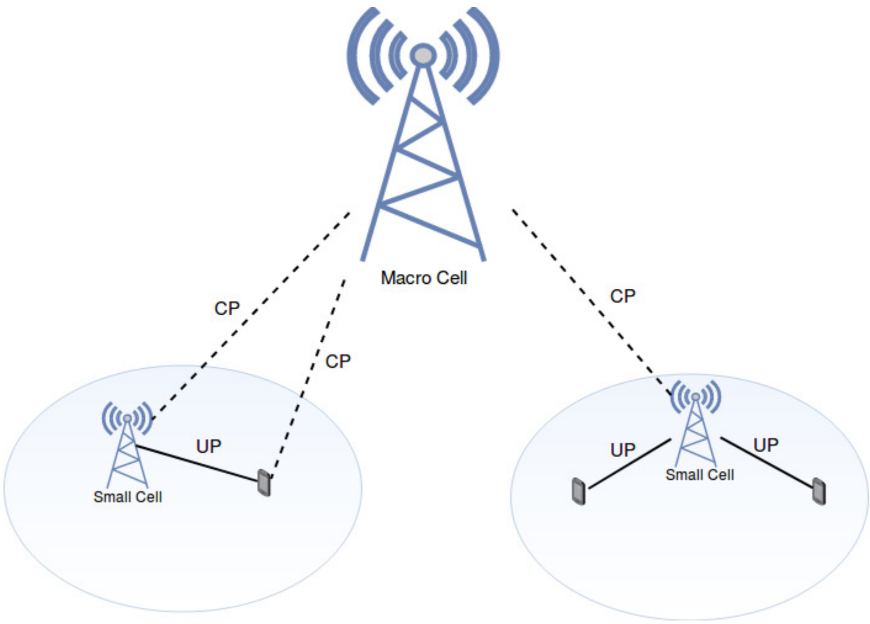

Figure 3.2: CP architecture includes macrocells and microcells. CP communications are done by macrocells. Data is transferred by the small cells. Small cells are also connected to macrocells to be able to control these small cells.

3.3 Assumptions

To be able to simplify our study, some assumptions should be considered. These assumptions are listed below.

- The positions of the UEs do not change during the observation period.
- UEs should support at least two technologies.
- There are two types of radio access technology that an RRU may run.
- RRU antenna type should support at least two radio access technologies.
- At the backbone capacity is not an issue, this system can handle full performance.

3.4 Analytical Model

In this section, we will express DDRAT and HDDRAT methods mathematically. The parameters are also explained. After this chapter, DDRAT and HDDRAT methods will be ready to apply.

3.4.1 Power Model

Energy efficiency is directly related to power consumption. Total power consumption is the summation of the static power consumption (P_{static}) and dynamic power consumption ($P_{dynamic}$) (3.4.1):

$$P_{total} = P_{static} + P_{dynamic}. \tag{3.4.1}$$

Static Power Consumption and Dynamic Power Consumption models are defined as:

$$P_{static} = \left(\frac{P_{TX}}{\mu_{PA}} C_{TX,static} + P_{SP,static} \right) (1 + C_{PS}). \tag{3.4.2}$$

and

$$P_{dynamic} = \left(\frac{P_{TX}}{\mu_{PA}} (1 - C_{TX,static}) C_{TX,NL} + P_{SP,NL} \right) N_L (1 + C_{PS}). \tag{3.4.3}$$

These models are adapted from [44]. Table 3.1 shows the general symbol definitions. Table 3.2 shows the static power symbol definitions and Table 3.3 shows the dynamic power symbol definitions.

Table 3.1: General parameters of the power model are defined in this table. They are used for both static and dynamic power calculations.

Symbols	Definitions
P_{total}	Total power consumption (W)
P_{static}	Static power consumption (W)
$P_{dynamic}$	Dynamic power consumption (W)
P_{TX}	Maximum TX power (W)
μ_{PA}	Power amplifier efficiency (%)
C_{PS}	Power supply loss

Table 3.2: Static power parameters are defined here. These parameters are used to calculate static power.

Symbols	Definitions
$C_{TX,static}$	Static TX power
$P_{SP,static}$	Static signal processing power (W)

Table 3.3: Dynamic power parameters are defined here. These parameters are used to calculate dynamic power.

Symbols	Definitions
$C_{TX,NL}$	Dynamic TX power per link
$P_{SP,NL}$	Dynamic signal processing per link (W)
N_L	Number of active links

3.4.2 Mathematical Representations of DDRAT

The mathematical representation of the optimization problem explained in this section. Table 3.4 summarize the meaning of the symbols and parameters that are used in this problem.

Table 3.4: The definition of the problem parameters and the symbols of the problem are explained in this table.

Symbols	Definitions
$\mathbf{A}_{N\times 2M}$	User equipment and cell association with respect to RAT
$\mathbf{O}_{1\times 2M}$	RRU on/off State
$\mathbf{T}_{M\times 1}$	RRU and RAT association
$\mathbf{K}_{1\times 2M}$	Maximum number of users
$\mathbf{C}_{N\times 2M}$	Maximum coverage matrix (m)
$\mathbf{B}_{1\times 2M}$	Maximum bandwidth matrix (# of links)
$\boldsymbol{\beta}_{N\times 2M}$	Randomly assigned bandwidth for each UEs
$\mathbf{D}_{N\times 2M}$	Distance between User Equipments and Remote Radio Unit (m)
$\mathbf{P}_{1\times M}$	RRU position coordinates
$\mathbf{Q}_{1\times N}$	UE position coordinates
M	Total number of remote radio units
N	Total number of user equipments
$\circ$	Hadamard Product
ϵ	Positive number that approaches to zero

Association Matrix (A) is the technology depended RRU and UE association matrix. This matrix is the concatenation of the two additional matrices $\mathbf{A_1}$ and $\mathbf{A_2}$ (3.4.4). Matrix $\mathbf{A_1}$ corresponds to the first technology and this is a UE-RRU association matrix. Rows are the UE identification number and columns are the RRU identification number. Similar to the $\mathbf{A_1}$ matrix, $\mathbf{A_2}$ corresponds to the second technology. These $\mathbf{A_1}$ and $\mathbf{A_2}$ matrices are populated according to (3.4.5) and (3.4.6). Therefore, $\mathbf{A}$ is an N x $2M$ binary matrix and only two technologies are supported.

N represents the total number of UEs and M represents the total number of RRUs. That is,

$$\mathbf{A}_{N\,\text{x}\,2M} = [\mathbf{A_1}\ \mathbf{A_2}], \tag{3.4.4}$$

, where

$$\mathbf{A_1}_{ij} = \begin{cases} 1, & \text{if } i^{th} \text{ UE is connected to } j^{th} \text{ RRU and uses technology I,} \\ 0, & \text{otherwise.} \end{cases} \tag{3.4.5}$$

$$\mathbf{A_2}_{ij} = \begin{cases} 1, & \text{if } i^{th} \text{ UE is connected to } j^{th} \text{ RRU and uses technology II,} \\ 0, & \text{otherwise.} \end{cases} \tag{3.4.6}$$

RRU On-Off Decision Vector (O) is the RRU on-off decision vector. The size of the vector is the same as the number of RRUs. This vector shows which RRU is on and which RRU is off (3.4.7):

$$\mathbf{O}_i = \begin{cases} 1, & \text{if } i^{th} \text{ RRU is in operation mode.} \\ 0, & \text{if } i^{th} \text{ RRU is in off state.} \end{cases} \tag{3.4.7}$$

Technology Decision Vector (T) is the radio access technology decision vector. The size of the vector is the same as the number of RRUs. This vector is filled as:

$$\mathbf{T}_i = \begin{cases} 1, & \text{if ith RRU uses Technology I,} \\ 0, & \text{if ith RRU uses Technology II,} \end{cases} \tag{3.4.8}$$

and only two radio access technologies are supported.

Maximum Number of Users (K) is a vector and stores the maximum number of users for each RRUs. Assume k_1 and k_2 are user limits with respect to technology I and II (3.4.9), then

$$\mathbf{K} = [k_1 \mathbf{1}_{1\,\text{x}\,M}\ k_2 \mathbf{1}_{1\,\text{x}\,M}]. \tag{3.4.9}$$

Coverage Matrix (C) is the N x $2M$ matrix and stores the maximum coverage area of technologies. Assume that c_1 and c_2 are the maximum coverage range constants (in meters) concerning technology I and II, then

$$\mathbf{C}_{N \text{ x } 2M} = [c_1 \mathbf{1}_{N \text{ x } M} \; c_2 \mathbf{1}_{N \text{ x } M}]. \tag{3.4.10}$$

Bandwith Matrix (B) is the N x $2M$ matrix and stores the maximum bandwidth capacity of the technologies. Here, b_1 and b_2 are the maximum bandwidth units with respect to technology I and II. $\boldsymbol{\beta}$ is a vector and stores randomly assigned user demands with respect to UEs. Values of $\boldsymbol{\beta}$ represent the number of assigned channels to users:

$$\mathbf{B}_{N \text{ x } 2M} = [b_1 \mathbf{1}_{N \text{ x } M} \; b_2 \mathbf{1}_{N \text{ x } M}]. \tag{3.4.11}$$

Distance Matrix (D) is the N x $2M$ Euclidian distance matrix between RRU and UE is calculated. To make calculation easy, the distance matrix is the concatenated two times. In the (3.4.12), function d(P, Q) represents the pairwise Euclidian distance between P and Q. Rows correspond to UEs and columns for RRUs. Distance calculations are done in meters and distance matrix can be represented as follows:

$$\mathbf{D}_{N \text{ x } 2M} = [d(\mathbf{P}, \mathbf{Q}) \; d(\mathbf{P}, \mathbf{Q})]. \tag{3.4.12}$$

Hadamard Product ($\circ$) is an operation that takes two matrices of the same dimensions and produces another matrix of the same dimension as the operands where each element i, j is the product of elements i, j of the original two matrices.

To be able to save energy, power consumption should be minimized. The objective function of this system is the total power (3.4.13). The total power has two parts which are defined as static power consumption and dynamic power consumption. Dynamic power consumption is directly related to the user association (variable $\mathbf{A}$). Static power consumption is just related to the on-off state of the RRU (variable $\mathbf{O}$). If an RRU does not operate (off state), the static power of this RRU should be zero. All of these things are represented in the problem and we define the DDRAT problem as follows:

$$\min_{\mathbf{A},\mathbf{O},\mathbf{T}} \mathbf{1}_{1\,\mathrm{x}\,N}(\boldsymbol{P_{dynamic}} \circ \mathbf{A})\mathbf{1}_{2M\,\mathrm{x}\,1} + (\boldsymbol{P_{static}} \circ \mathbf{O})\mathbf{1}_{1\,\mathrm{x}\,M} \tag{3.4.13}$$

$$\text{subject to} \begin{cases} \mathbf{A}\mathbf{1}_{2M\,\mathrm{x}\,N} = \mathbf{1}_{N\,\mathrm{x}\,1} & (3.4.14) \\ \mathbf{A} \circ \mathbf{D} \leqslant \mathbf{C} & (3.4.15) \\ \mathbf{1}_{1\,\mathrm{x}\,N}\mathbf{A} \leqslant \mathbf{K} & (3.4.16) \\ \mathbf{1}_{1\,\mathrm{x}\,N}(\mathbf{A} \circ \boldsymbol{\beta}) \leqslant \mathbf{B} & (3.4.17) \\ \mathbf{A_1}^T\mathbf{1}_{N\,\mathrm{x}\,1} - \mathbf{A_2}^T\mathbf{1}_{N\,\mathrm{x}\,1} + N\mathbf{T} \geqslant \mathbf{0}_{M\,\mathrm{x}\,1} & (3.4.18) \\ \mathbf{A_2}^T\mathbf{1}_{N\,\mathrm{x}\,1} - n\mathbf{T} \leqslant \mathbf{0}_{M\,\mathrm{x}\,1} & (3.4.19) \\ N(\mathbf{1}_{M\,\mathrm{x}\,1} - \mathbf{T}) - \mathbf{A_1}^T\mathbf{1}_{N\,\mathrm{x}\,1} + \mathbf{A_2}^T\mathbf{1}_{N\,\mathrm{x}\,1} \geqslant \mathbf{0}_{M\,\mathrm{x}\,1} & (3.4.20) \\ N(\mathbf{1}_{M\,\mathrm{x}\,1} - \mathbf{T}) - \mathbf{A_1}^T\mathbf{1}_{N\,\mathrm{x}\,1} \leqslant \mathbf{0}_{M\,\mathrm{x}\,1} & (3.4.21) \\ \mathbf{1}_{N\,\mathrm{x}\,1}^T\mathbf{A} \leqslant N\mathbf{O} & (3.4.22) \\ N(\mathbf{O} - \mathbf{1}_{1\,\mathrm{x}\,2M}) - \mathbf{1}_{1\,\mathrm{x}\,N}\mathbf{A} \leqslant \boldsymbol{\epsilon}_{2M\,\mathrm{x}\,1}. & (3.4.23) \end{cases}$$

The objective function is explained in the previous paragraph. We will explain the constraints here. There are two conditions in these constraints. One of them is implemented using constraints (3.4.22) and (3.4.23) to check whether an RRU is on or off. The other conditional logic is based on the chosen technology. If an RRU runs technology I, none of the UEs can connect to the same RRU using technology II. This logic is implemented using constraints (3.4.18), (3.4.19), (3.4.20) and (3.4.21). For more details of the implementation of these logics check Section 2.1. Other constraints are explained below.

- Constraint (3.4.14): Each UE must be connected to exactly one RRU.
- Constraint (3.4.15): All of the UE should be in the coverage area.
- Constraint (3.4.16): The number of user capacity of each RRU is limited by the connected UE.
- Constraint (3.4.17): Bandwidth capacity of each RRU is limited.

3.5 The Heuristic Model

The running time of the DDRAT may take a long time. This process should be in the milliseconds' range for the communication networks, but the search space of the problem is increasing exponentially. This is due to the user-cell associations variable. All of the possibilities of these associations are tested in the DDRAT. Therefore the complexity is $O(2^{M \times N})$. To speed up DDRAT we implemented a new method which is Heuristic DDRAT (HDDRAT). HDDRAT will be explained in this section.

This heuristic method is generated intuitively. As a first step, on-off state variable ($\mathbf{O}$) is converted from binary to floating-point. The result of this process gives an idea about the running RATs. The other variables are not meaningful; because of the floating-point value of the on/off state. An RRU cannot be half-open, but we got the radio access technology types running on the RRUs.

Using the RAT types, we can reinitialize the coverage, bandwidth and capacity constraints depend on the found radio access technology types. Then we need to decide only base station on/off status. To be able to this, we will calculate a new user-cell association matrix. This matrix can be calculated in another optimization problem. This problem is defined as follows:

$$\min_{\mathbf{A}} \mathbf{1}_{1 \text{ x } N}(\boldsymbol{P_{dynamic}} \circ \mathbf{A})\mathbf{1}_{M \text{ x } 1} \tag{3.5.1}$$

$$\text{subject to} \begin{cases} \mathbf{A}\mathbf{1}_{2M \text{ x } N} = \mathbf{1}_{N \text{ x } 1} & (3.5.2) \\ \mathbf{A} \circ \mathbf{D} \leqslant \mathbf{C} & (3.5.3) \\ \mathbf{1}_{1 \text{ x } N}\mathbf{A} \leqslant \mathbf{K} & (3.5.4) \\ \mathbf{1}_{1 \text{ x } N}(\mathbf{A} \circ \mathbf{B}) \geqslant \boldsymbol{\beta}. & (3.5.5) \end{cases}$$

The objective function of the problem is about only determining the aforementioned association matrix. Bandwith (3.5.5), coverage (3.5.3), and capacity limits (3.5.4) are changed according to found technology types. The result of this problem gives the association matrix. Then unused RRUs can be turned off. This is the HDDRAT method.

CHAPTER 4

EXPERIMENTS, RESULTS, AND DISCUSSIONS

In this section, we will make an experiment of our methods DDRAT and Heuristic DDRAT. This experiment is done using optimization tools which are MATLAB, Gurobi, and CPLEX. DDRAT and Heuristic DDRAT are implemented in MATLAB. Other optimization tools are used as an add-on to MATLAB IDE. The results are compared and discussed in this section.

4.1 Experimentation

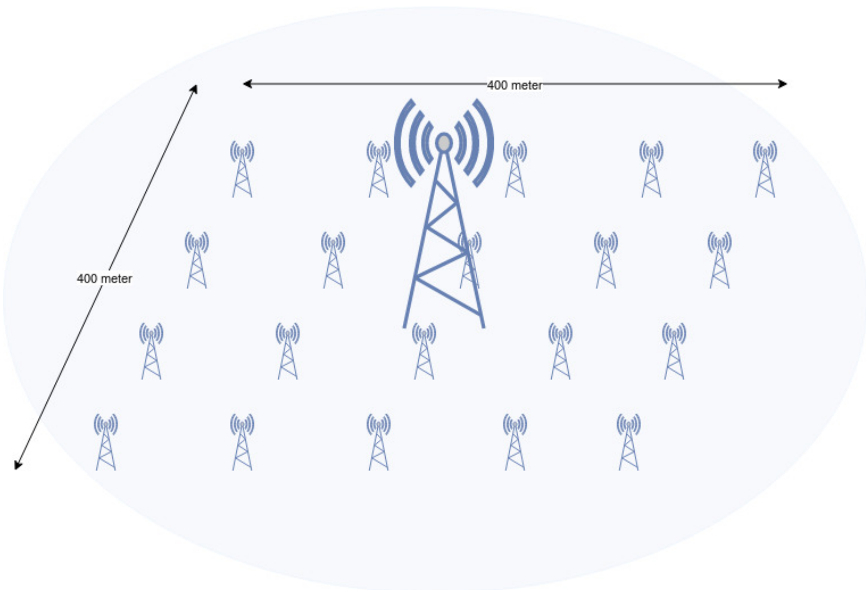

Figure 4.1: Test scenario deployment. RRUs are randomly placed and the area is $400 \times 400\ m^2$. One central base station is deployed to handle the control plane operations.

Figure 4.1 shows the experiment scenario deployment. CP and DP are shown in the same figure. In this deployment, the whole area is covered using the worst technology. Without any benefit from the other technology, all of the UEs must be connected. The other thing we should consider is that C-Plane covers whole RRUs. Parametric details of the experiment deployment are given in Table 4.1 and Table 4.2 [45] [46] [47] [44].

Table 4.1: Deployment dependent parameters for the experiment case.

Parameter	Value	Detail
M	24, 36	24 RRUs and 36 RRUs are deployed.
N	5 to 120	UEs are randomly deployed from 5 to 120.

Table 4.2: Technology depended parameters.

Property	**Technology I (Wifi)**	**Technology II (LTE)**
Maximum TX Power	2 W	0.1 W
Number of Active Links	25	16
Max. Coverage Distance Diameter	100 m	30 m

In this experiment case, we will run solvers to find minimum energy consumptions, user-cell associations, and radio access technologies running on the RRUs. Then we will compare all results.

As a first step, we will implement DDRAT, HDDRAT, and Legacy in MATLAB IDE. The legacy method means that no optimization is applied. MATLAB IDE can be extended with CPLEX and Gurobi optimization tools. Therefore, the experiment is tested with CPLEX [48], Gurobi [49], and MATLAB [50] solvers. We can run MATLAB implementation with three tools by only changing the solver functions.

These three solvers are differentiated in small points. MATLAB solver uses the branch-and-bound algorithm for mixed-integer linear problems [51]. Gurobi also uses the same algorithm, but additionally, it has an automatic parallelism feature. CPLEX applies the branch-and-cut algorithm. This method is the combination of the cut plane method and the branch-and-bound method. All these solvers based on the branch-and-bound method, but these small differences affect the processing time of the algorithm. These details will be shown in Section 4.2.

In these implementations, the number of users varies from 5 to 120, each solver is run 100 times. Each user position is randomized and RRUs are stationary. Results are shown within the 95% confidence interval. In the next sections, the results of these simulations will be shown.

4.2 Results and Disscussions

In this part, we will examine and discuss the results of the experiment. Each result will be shown in different subsections. We will compare three methods. These methods are DDRAT, HDDRAT, and Legacy. We will generate these results using MATLAB and three solvers which are CPLEX, Gurobi, and MATLAB.

4.2.1 Power Consumption

In this section, we will examine the power consumption of DDRAT, HDDRAT, and Legacy methods. In the experimentation case, DDRAT solved by three different solvers. The difference between these solvers is also discussed in this section. At the end of this section, we will summarize results.

Firstly, we will show the power consumption results of the DDRAT method solved by three solvers. Then we will observe the HDDRAT method. The power consumption of the Legacy method will be shown for each figure. Finally, we will compare DDRAT and HDDRAT methods.

In the first figure (Figure 4.2), we will discuss the DDRAT method solved by MATLAB. The x-axis of the figure shows the number of users that are connected to the RRUs. The y-axis shows the power consumption in Watt. In this figure, two different number of RRU deployment is shown. We got these results using 24 RRUs deployments and 36 RRUs deployments. To be able to compare power consumption with the Legacy method, we draw also Legacy method power consumption.

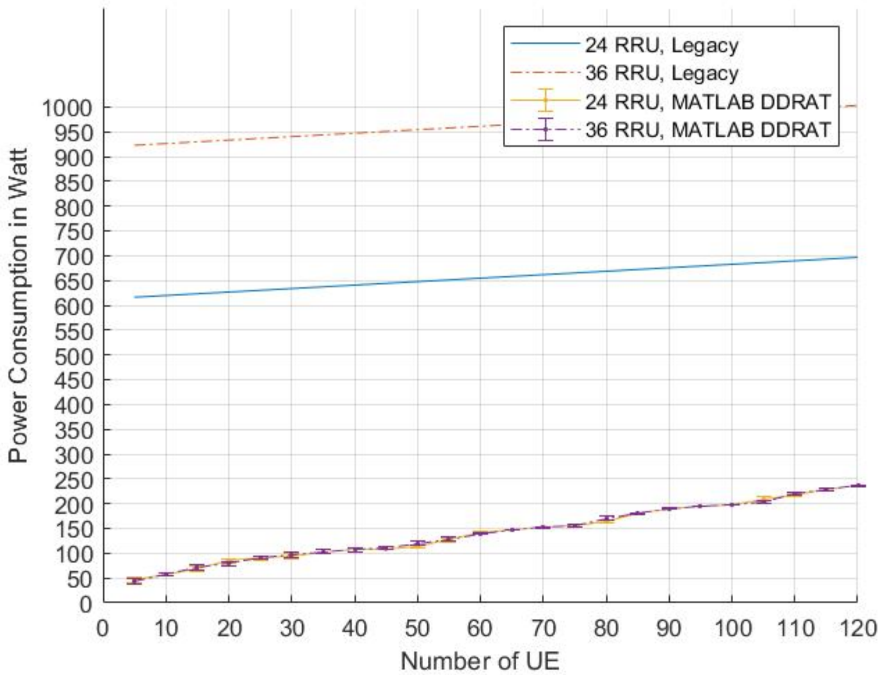

Figure 4.2: DDRAT method solved by MATLAB solver for 24 and 36 RRUs deployments. The power consumption of the Legacy method is also shown.

In Figure 4.2, it is clear that if the number of users increases the power consumption of the Legacy method increases proportionally. This increase is due to the dynamic power consumption. Dynamic power consumption is directly proportional to the number of connected users. The number of deployed RRUs is also directly proportional to the power consumption of the Legacy method. These RRUs increases the static power consumption of the Legacy method. For the DDRAT, unused RRUs are turned off. Therefore, static power is not always directly related to RRUs for the DDRAT method. In our example, the number of deployed RRUs doesn't affect power consumption. For both 24 and 36 deployments, power consumption lines are almost the same. That means additional RRUs are not necessary in this test case.

In Figure 4.3, we discuss the DDRAT method solved by CPLEX. The x-axis of the figure shows the number of users that are connected to the RRUs. The y-axis shows the power consumption in Watt. Two different number of RRU deployment is also shown in this figure. We got these results using 24 RRUs deployments and 36 RRUs deployments. To be able to compare power consumption with the Legacy method, we also draw power consumption of the Legacy method.

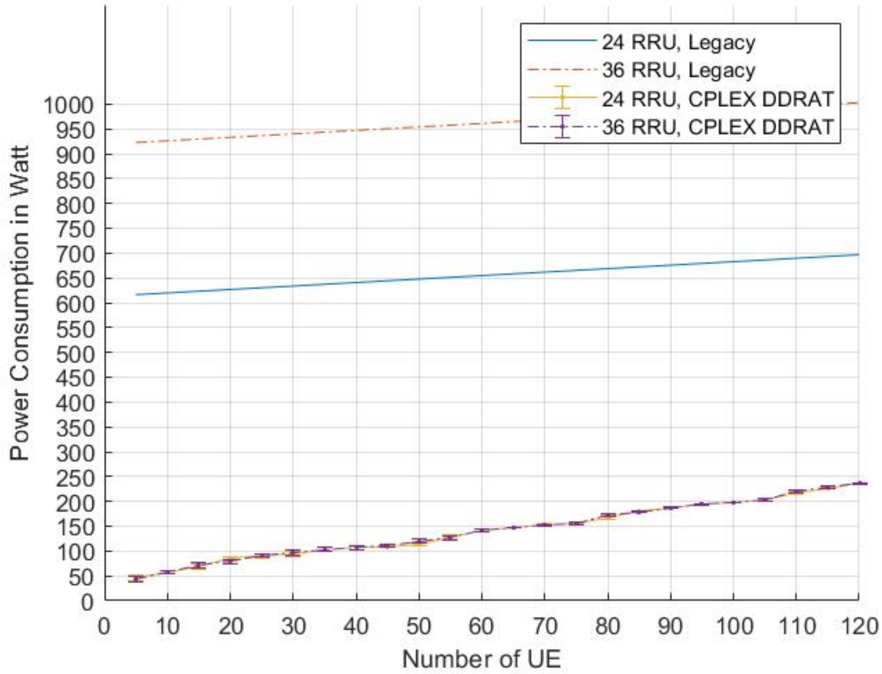

Figure 4.3: DDRAT method solved by CPLEX solver for 24 and 36 RRUs deployments. The power consumption of the Legacy method is also shown.

The results of Figure 4.3 is similar to Figure 4.2. Because of the branch-and-bound algorithm. Both of the solvers are based on this algorithm.

The last figure about the solvers is Figure 4.4. In this figure, we will examine the DDRAT method solved by Gurobi. The Legacy method is also shown here. Similar to previous figures, two deployment cases are drawn. The x-axis of the figure shows the number of users and the y-axis shows the power consumption in Watt.

The results of Figure 4.4 is similar to Figure 4.2 and Figure 4.3. We have same reason to get similar results. Gurobi uses also the branch-and-bound method.

The power consumption of the HDDRAT method is shown in Figure 4.5. The only difference between the previous figures is that this figure shows the Heuristic DDRAT instead of DDRAT. All other things are the same as the previous figures.

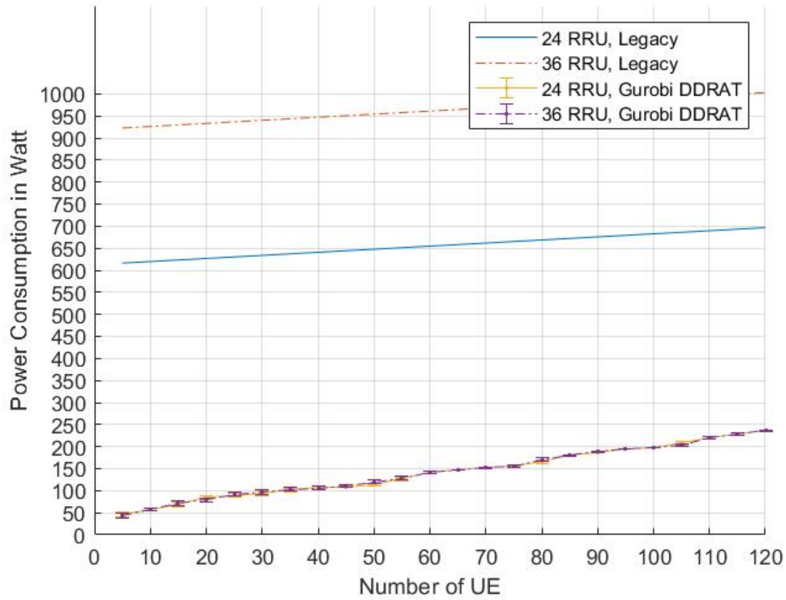

Figure 4.4: DDRAT method solved by Gurobi solver for 24 and 36 RRUs deployments. The power consumption of the Legacy method is also shown.

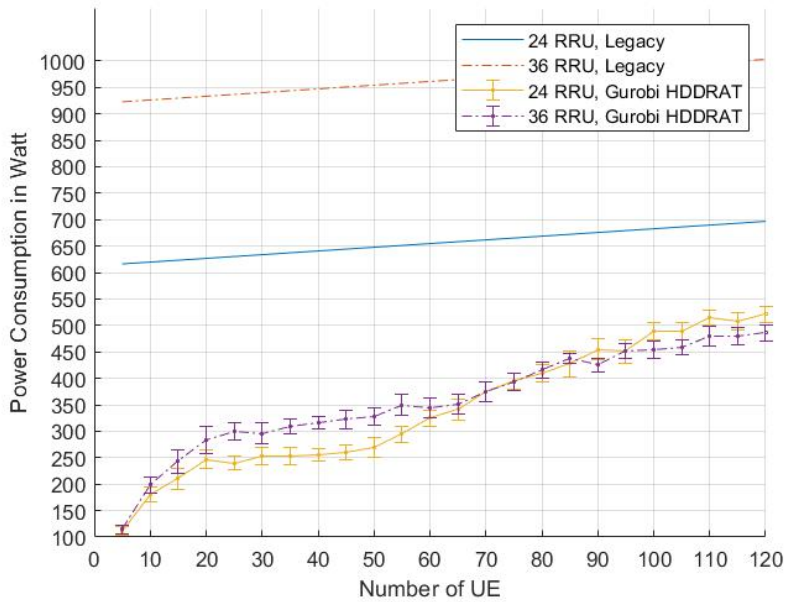

Figure 4.5: Heuristic DDRAT method solved by Gurobi solver for 24 and 36 RRUs deployments. The power consumption of the Legacy method is also shown.

HDDRAT method consumes more power than the DDRAT method, but it consumes less power than Legacy (Figure 4.5). That means this method is still usable although DDRAT consumes less power. The HDDRAT method does not give the optimum result. Therefore, the different number of RRUs deployment results may not give stable power consumption results.

Until now, we explained the power consumption of the DDRAT, HDDRAT, and Legacy methods. In the next figures (Figure 4.6 and Figure 4.7), we will compare the DDRAT and HDDRAT methods for 24 RRUs and 36 RRUs deployments.

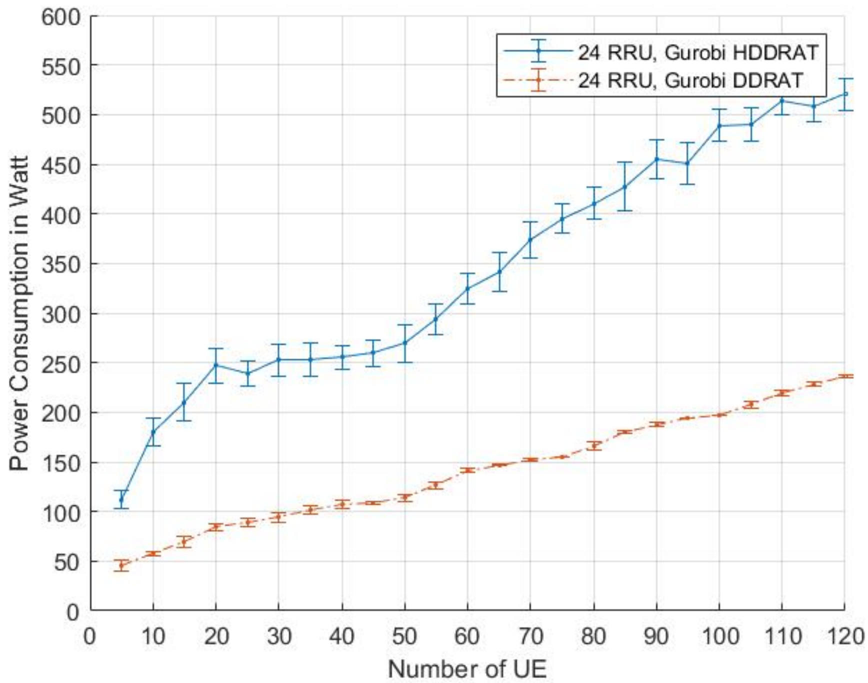

Figure 4.6: Heuristic DDRAT method and DDRAT method applied to the 24 RRUs deployment case for power consumption.

In Figure 4.6, the power consumption of the DDRAT and HDDRAT with 24 RRUs deployments are shown. In Figure 4.7, 36 RRUs deployment results are displayed. For both figures, DDRAT consumes less power. In terms of power consumption, DDRAT consumes less power that's why it gives better results.

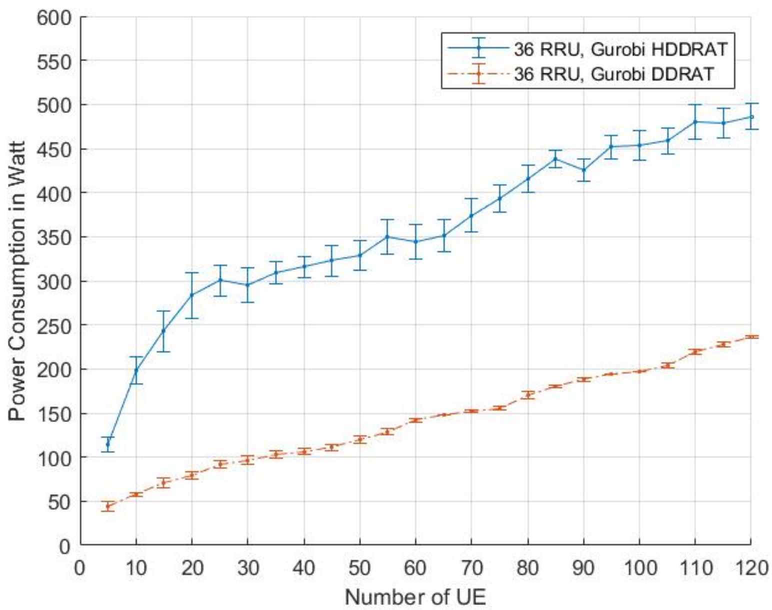

Figure 4.7: Heuristic DDRAT method and DDRAT method applied to the 36 RRUs deployment case for power consumption.

In conclusion, we can summarize the results by looking at Table 4.3 and previous figures. This table includes sample data for three methods that are DDRAT, HDDRAT, and Legacy. The final points can be listed below.

- For a different number of users, the DDRAT method gives the same results for each solver. This is because all of the solvers eventually use the same method which is the branch-and-bound method.

- The other point is that the number of RRU deployment does not always increase power consumption for DDRAT and HDDRAT. User-cell associations are determined using the position of the UEs and coverage of the RRUs. If we have the same associations for different numbers of RRUs, we will consume the same amount of energy. Because we don't use unassociated RRUs. They consume zero power.

- As the final point, we can say that DDRAT gives better results according to HDDRAT in the power consumption perspective. Also, HDDRAT gives better performance respect to Legacy method. That means HDDRAT and DDRAT have benefits on energy consumption (Table 4.3).

Table 4.3: Power consumption results table for 24 RRUs deployment.

Number of UE	DDRAT (W)	HDDRAT (W)	Legacy (W)
20	79.04	283.3	933.1
40	106.2	315.7	947.1
60	141.9	344	961
80	170	415.7	975

4.2.2 Energy Efficiency

In this section, we will see power consumption as energy efficiency. Energy efficiency is calculated as a ratio of the energy saved to the energy consumed in Legacy mode. This value is shown as a percentage value by multiplying 100. Evaluation of the methods is easier using energy efficiency. Similar figures in Section 4.2.1 are also drawn here, but the difference is the y-axis. This axis shows energy efficiency.

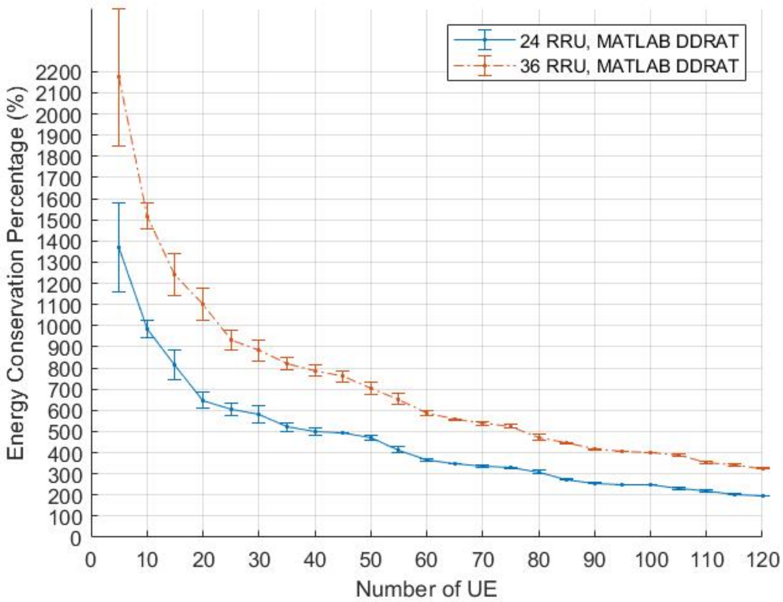

Figure 4.8: The efficiency calculated by MATLAB solver for the DDRAT.

In the first figure (4.8), the energy efficiency of the DDRAT method solved by MATLAB is shown. This efficiency is decreasing with the number of users as expected. If we increase the number of connected users, at some point all of the RRUs must be turned on and the RAT decision converges to one radio access technology. That's why energy efficiency decreases when the number of users increases. The number of RRUs increases efficiency. Although the power consumption of the running RRUs can be constant for different numbers of RRUs deployment, the power consumption of the Legacy method always increases due to the static power of the RRUs.

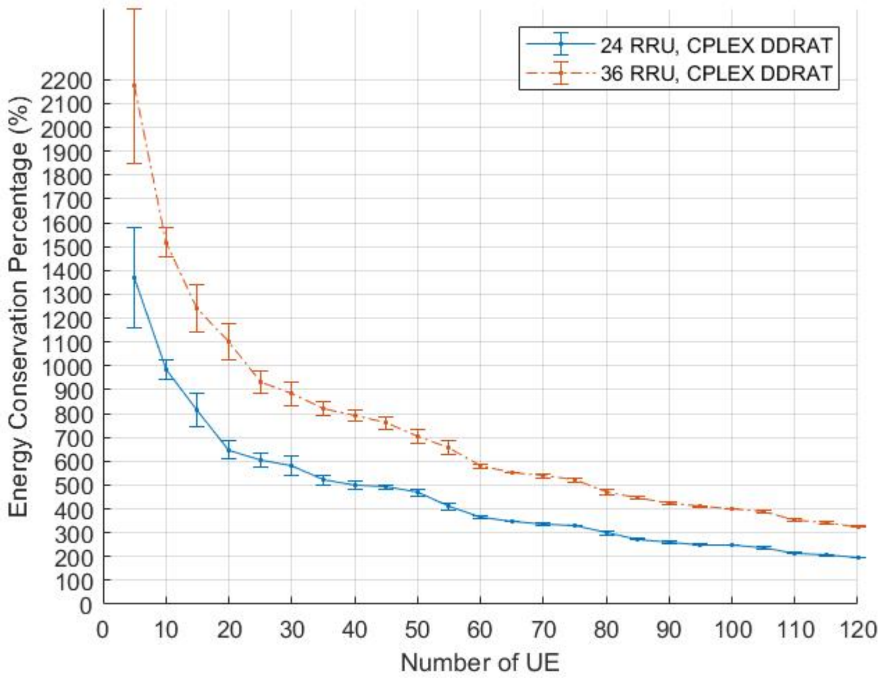

Figure 4.9: The efficiency calculated by CPLEX solver for the DDRAT.

In the second figure (4.9), the energy efficiency of the DDRAT solved by CPLEX is shown. This figure is similar to the previous one. The results are the same for three solvers. In the next figure (4.10), the energy efficiency of the DDRAT solved by Gurobi is presented. In Figure 4.11, the energy efficiency of the HDDRAT is presented.

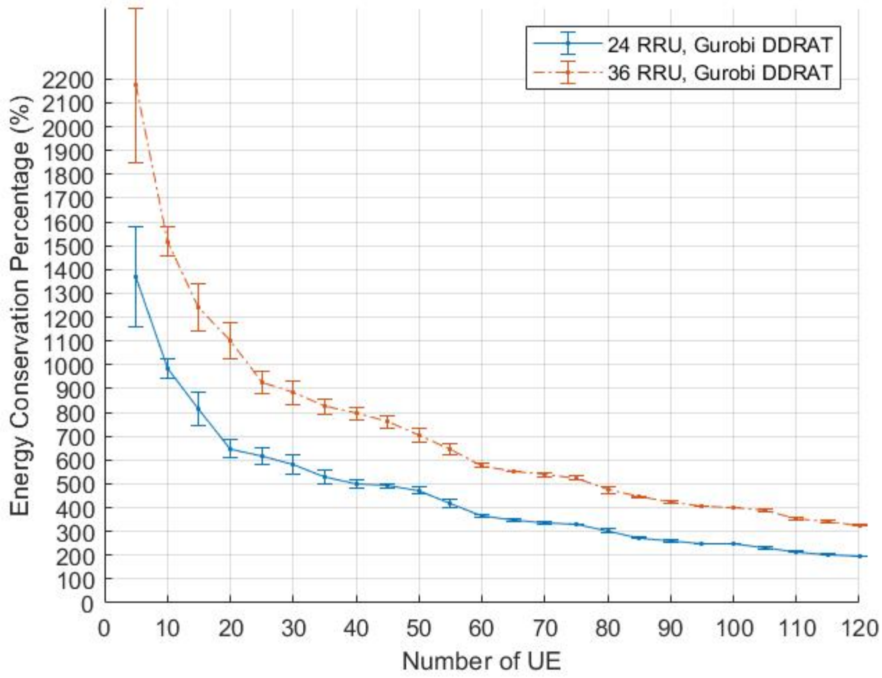

Figure 4.10: The efficiency calculated by Gurobi solver for the DDRAT.

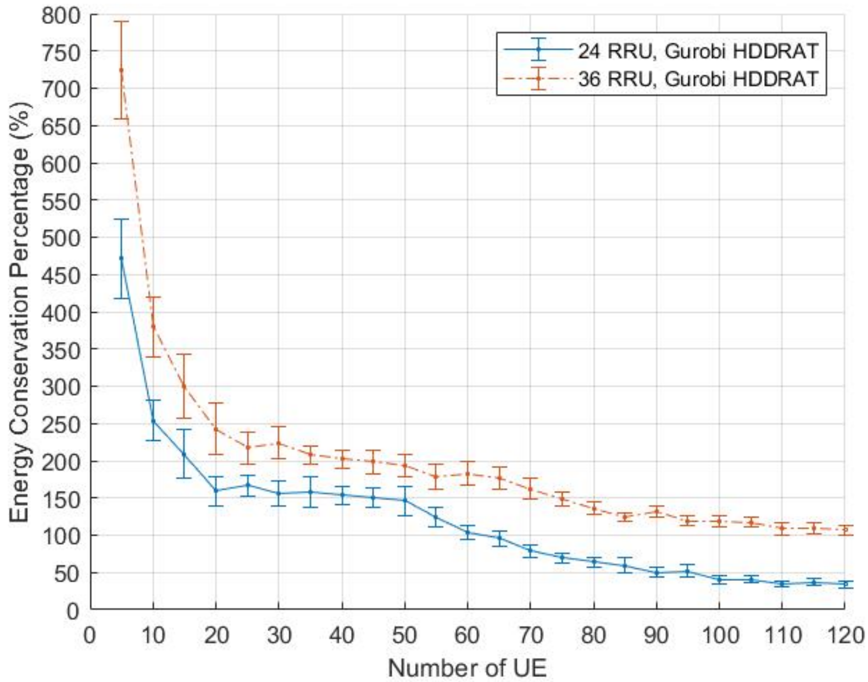

Figure 4.11: The efficiency calculated by Gurobi solver for the HDDRAT.

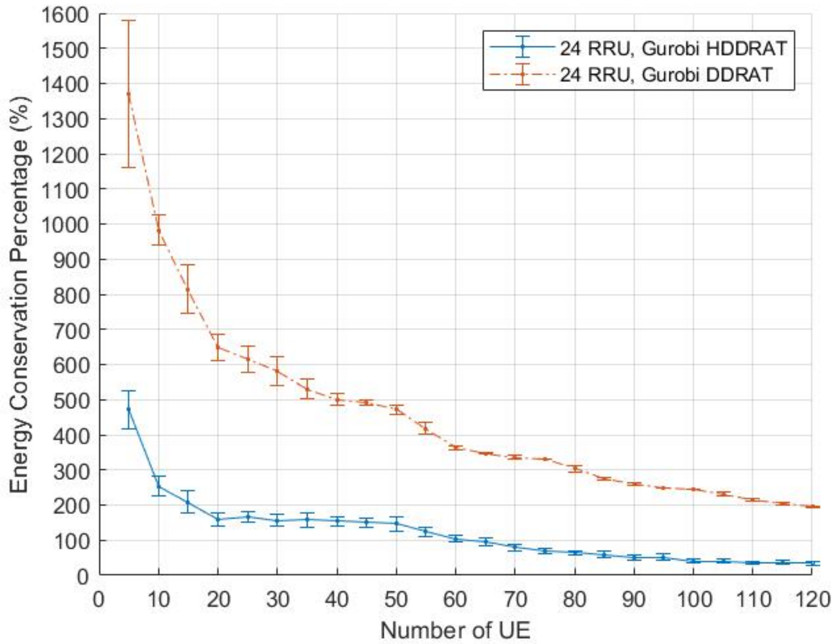

Figure 4.12: Heuristic DDRAT method and DDRAT method applied to the 24 RRUs deployment case for energy efficiency.

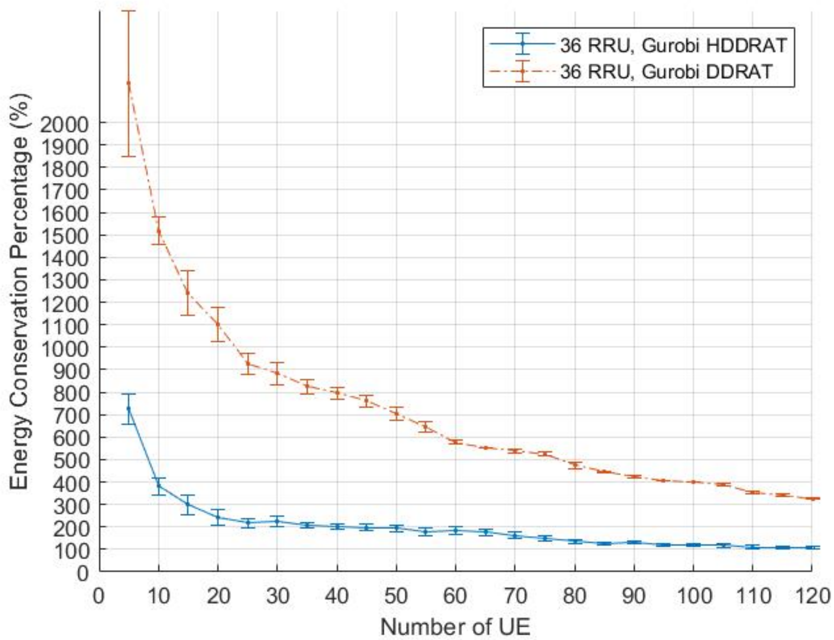

Figure 4.13: Heuristic DDRAT method and DDRAT method applied to the 36 RRUs deployment case for energy efficiency.

In the last two figures, we compare the DDRAT and HDDRAT methods. DDRAT has better performance as expected in Section 4.2.1.

4.2.3 Processing Time

In this section, we will examine the processing time of the DDRAT and HDDRAT methods. All measurements of processing times are done by a personal computer with a 2.2 GHz processor. The processing time or the solution time of these methods is one of the very important measurement factors to apply these methods in the communication area. This processing time to solve the problem should be in the milliseconds' range for the communication area. In this section, we will experiment that are these methods applicable or not?

For all figures discussed in this section, the x-axis of figures shows the number of UEs and the y-axis shows the elapsed time to solve the problem in second.

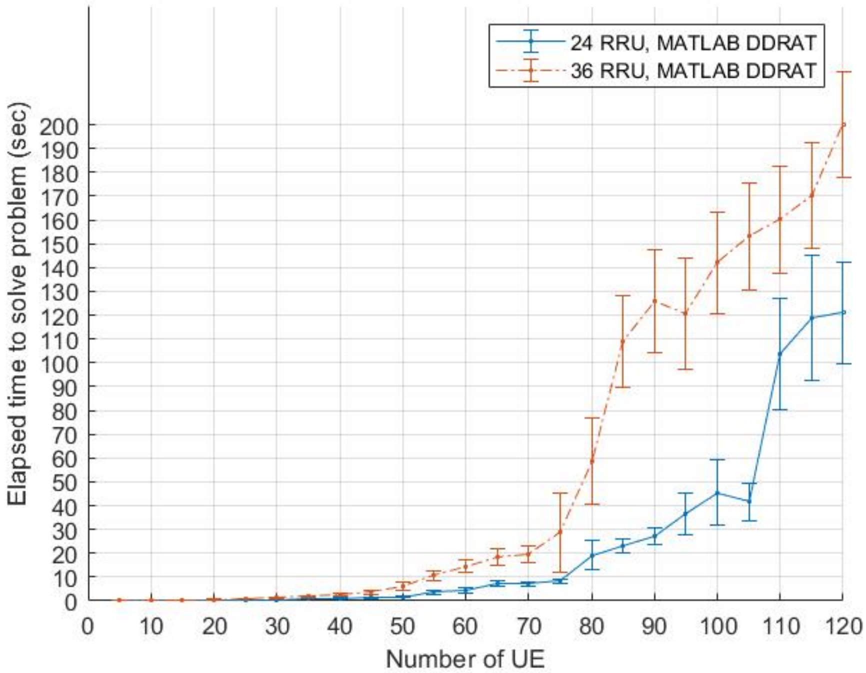

Figure 4.14: The processing time of the MATLAB solver for the DDRAT method.

In the first figure (4.14), the processing time of the DDRAT solved by MATLAB is shown. In this figure, we can see that the processing time of the DDRAT increases exponentially when the number of users increases. Also, the number of RRUs increases this time.

In the next figure (4.15), the processing time of the DDRAT solved by CPLEX is presented. In this figure, we can conclude that the processing time of the CPLEX solver is slower than the MATLAB. Although CPLEX has a multi-thread mechanism, it gives a worse result due to its main algorithm (branch-and-cut).

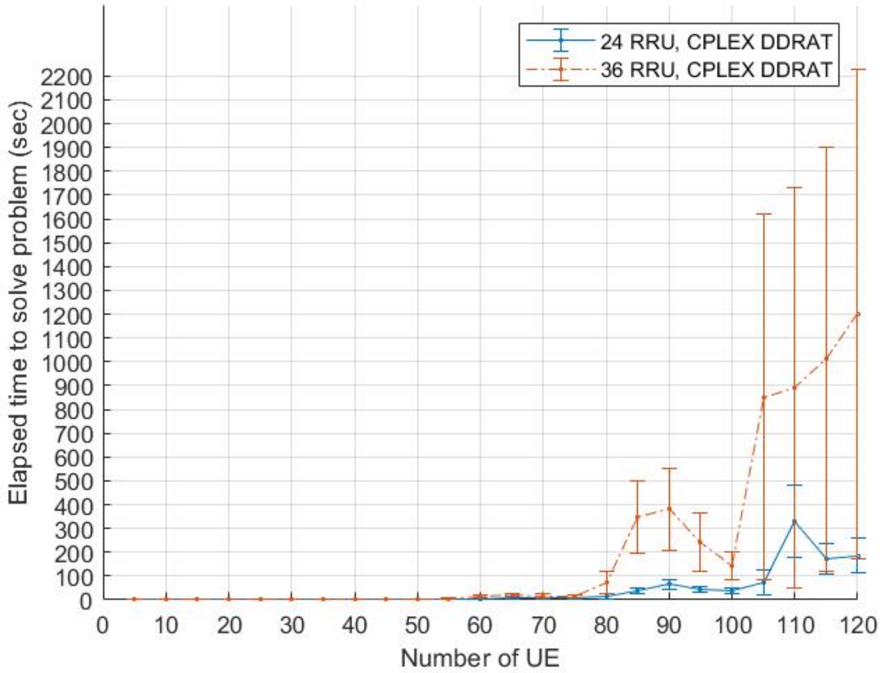

Figure 4.15: The processing time of the CPLEX solver for the DDRAT method.

The following figure (4.16), is about the DDRAT method solved by Gurobi. Gurobi has the best results between three solvers that are MATLAB, CPLEX, and Gurobi. These results are shown in Figure 4.14, 4.15, and 4.16. Gurobi has a parallelism feature on the branch-and-bound algorithm. That's why Gurobi has better performance.

In Figure (4.17), we will observe the Heuristic DDRAT that is implemented due to the slowness of the DDRAT method. HDDRAT increases the performance substantially comparing to the DDRAT method. The processing time of the HDDRAT is in the range of milliseconds. This is the reason why we implement HDDRAT method.

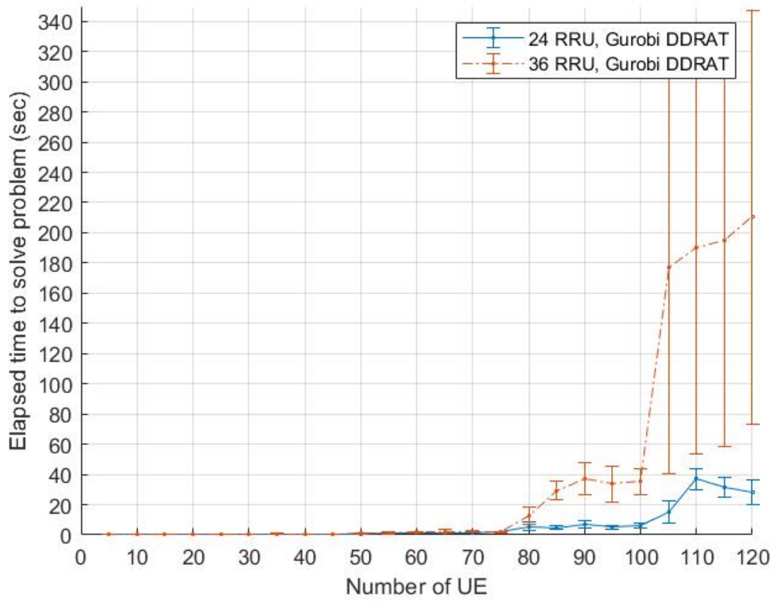

Figure 4.16: The processing time of the Gurobi solver for the DDRAT method.

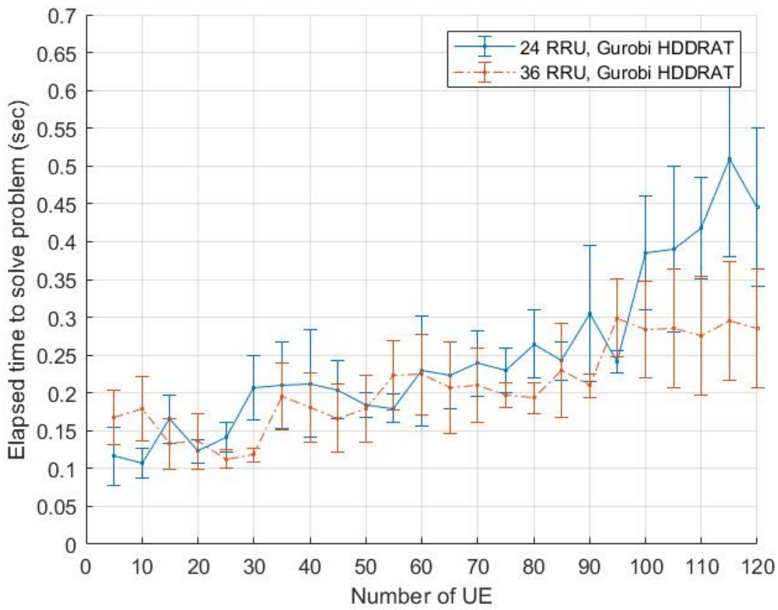

Figure 4.17: The processing time of the Gurobi solver for the HDDRAT method.

Figure (4.18) and Figure (4.19) are drawn to observe both DDRAT and HDDRAT method. Although DDRAT gives better energy efficiency, the processing time of the DDRAT algorithm worse than the HDDRAT. In these figures, we can say that the processing time difference increases when the number of RRUs increases.

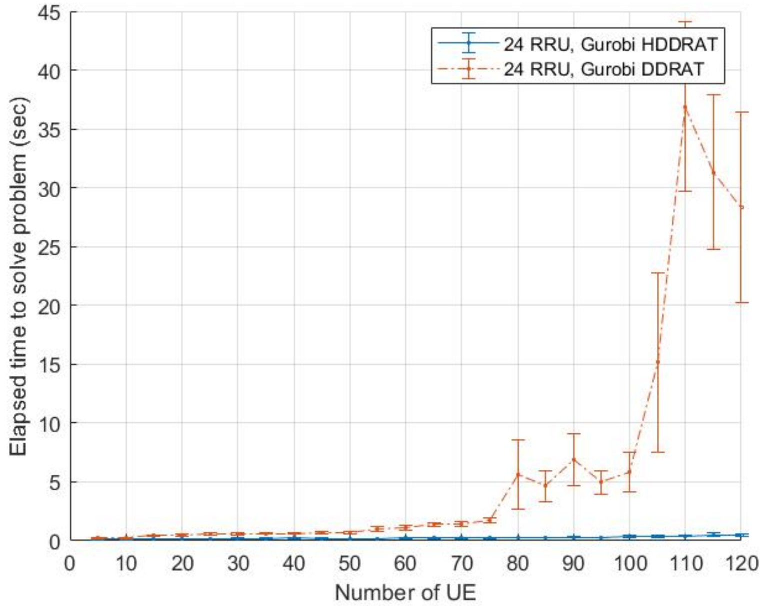

Figure 4.18: The comparison between HDDRAT and DDRAT using 24 RRUs deployment.

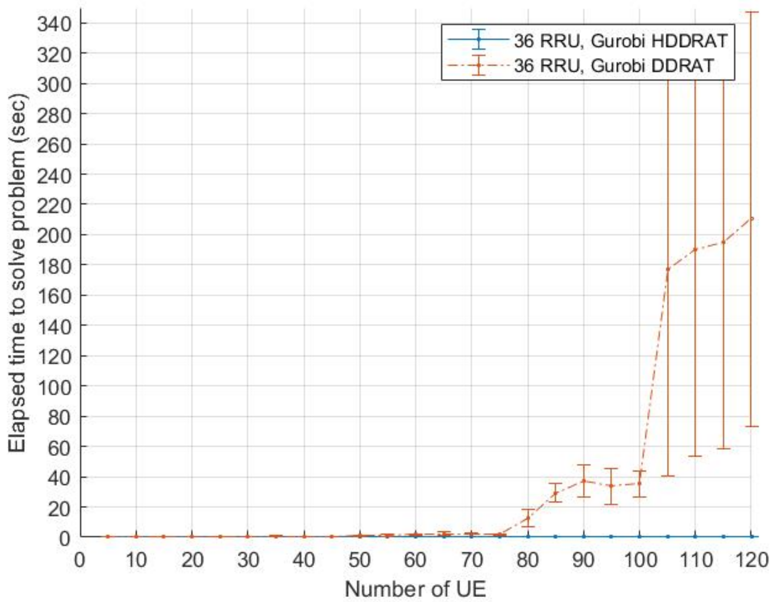

Figure 4.19: The comparison between HDDRAT and DDRAT using 24 RRUs deployment.

In conclusion, the number of RRUs directly affect the processing time of the DDRAT and the HDDRAT. Also, HDDRAT is faster than DDRAT although the HDDRAT method saves less energy.

4.2.4 Efficiency per unit running time (γ)

In previous sections, we observed the energy efficiency and the processing time of the DDRAT and the HDDRAT. DDRAT gives better results in energy efficiency, but it gives worse results in the processing time. Therefore, in this section, we will define a new comparison metric which is γ. To formulate this comparison measure, energy efficiency and the processing time is used. Both variables are important for this study. The purpose of this study maximize energy efficiency and minimize calculation time. Therefore the γ should be directly proportional to the efficiency and inversely proportional to the time (4.2.1). That means a higher value of γ gives better results in real life which concerns time and efficiency concurrent. γ can be represented as follows:

$$\gamma = \frac{e}{t}, \tag{4.2.1}$$

where e represents energy efficiency and t representes the processing time.

In Figure 4.20, the HDDRAT method has higher γ values than the DDRAT method has. That means we can prefer the HDDRAT method instead of the DDRAT method. The difference between these methods can be seen more clearly in Figure 4.21. If the number of RRUs increases, we can prefer HDDRAT more comfortably (Figure 4.22).

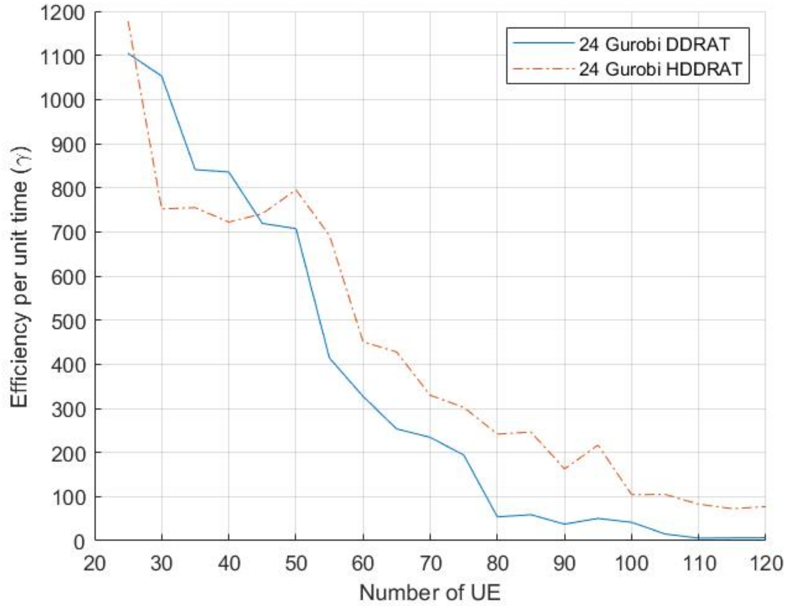

Figure 4.20: The efficiency per unit running time of the DDRAT and the HDDRAT. 24 RRUs are deployed.

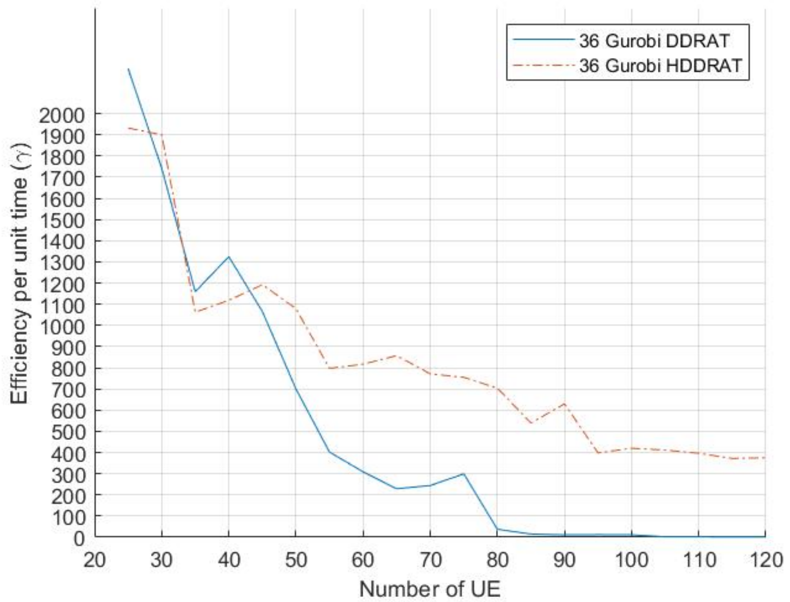

Figure 4.21: The efficiency per unit running time of the DDRAT and the HDDRAT. 36 RRUs are deployed.

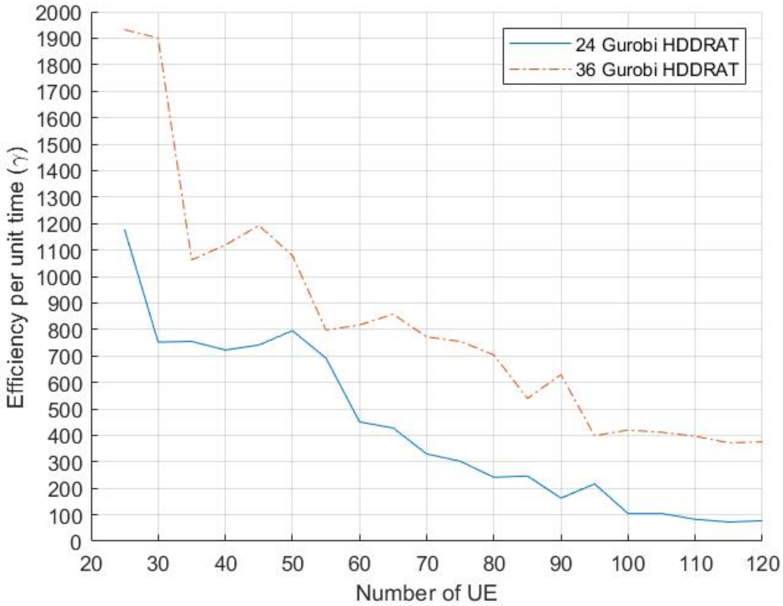

Figure 4.22: The efficiency per unit running time of 24 RRUs deployments and 36 RRUs deployments.

In a nutshell, for the small number of UEs, the DDRAT method gives better results. This is due to the small execution time. For the large number of UEs, the execution time increases exponentially. Therefore the HDDRAT method gives better results for the large number of UEs.

CHAPTER 5

CONCLUSIONS

In this chapter, we will conclude our study and give details about future works.

5.1 Conclusion

With the increasing number of base stations, energy consumption will be one of the design problems in 5G mobile networks. There are various studies such as base station on/off strategies, splitting the functionality of the base stations, and changing coverage area of the base stations to solve this problem. In this study, we will also propose a method to decrease energy consumption. We call this method as Dynamically Determining Radio Access Technology (DDRAT).

DDRAT provides a solution to increase energy efficiency simultaneously using the base station on/off strategy and dynamically changing the radio access technology of the base stations. We define a modified C-RAN architecture to change radio access technology dynamically. During the runtime, changing the radio access technologies running on the remote radio units produce better results about energy efficiency because of the different features of the radio access technologies.

DDRAT incredibly increases energy efficiency around 200 %. The amount of gain depends on the number of RRU deployment, the number of connected users (UEs), and the type of used radio access technologies. This DDRAT method is run by MATLAB, CPLEX, and Gurobi solvers to examine the effects of the solvers. All these solvers give the same result to minimize energy consumption, but they are different about the processing time. Due to the better parallelism feature, Gurobi has the best results about the solution time. Although Gurobi is faster than others, the processing time of DDRAT takes so much time for the communication networks. To speed up DDRAT method, we define a Heuristic Dynamically Determining Radio Access Technology (HDDRAT).

HDDRAT divides the progress of DDRAT into two parts. In the first part, HDDRAT decides radio access technologies using relaxation on the base station on/off status. In the second part, HDDRAT finds the user-cell associations and base station on/off status. These are the steps of the HDDRAT.

HDDRAT and DDRAT are compared in terms of energy efficiency and processing time. DDRAT is better at energy efficiency, but HDD is better at processing time. This contradiction forces us to define a new comparison metric (γ). We defined γ proportional to the energy efficiency and inversely proportional to the processing time. This comparison metric shows that HDDRAT method is the more realistic method to apply real-life scenarios.

Real-life scenarios of the communication systems are much complex than our test cases. In this thesis, we simplified the problem to generate a new concept which is dynamically changing radio access technology in 5G. This study shows that remarkable energy can be saved using DDRAT. DDRAT has a disadvantage on the processing time and this problem can be also solved using some heuristic methods such as HDDRAT.

5.2 Future Work

Future works of this study are listed as follows:

- This study is a simplified version of the real-life system. We can extend this study by improving the DDRAT model. There are lots of parameters that can be added as constraints to the DDRAT and HDDRAT. Backhaul and fronthaul capacities are the two of them. Adding these parameters increases the processing time. Therefore additional heuristic methods may be necessary.
- Another new concept of 5G is multi-connection to base stations. That means

users can connect multi-base stations concurrently. Our models can be extended for multi-RAT systems.

- In our study, two radio access technologies are used. This number of radio access technologies can be extended to a large value.
- HDDRAT method does not give the minimum energy consumption. Therefore this method can be improved.
- The impact of all parameters used in DDRAT model can be discussed.

REFERENCES

[1] M. Ram, M. Child, A. Aghahosseini, D. Bogdanov, and A. Lohrmann, "Comparing electricity production costs of renewables to fossil and nuclear power plants in G20 countries," tech. rep., GreenPeace, 07 2017.

[2] P. Epstein, J. Buonocore, K. Eckerle, M. Hendryx, B. Iii, R. Heinberg, R. Clapp, B. May, N. Reinhart, M. Ahern, S. Doshi, and L. Glustrom, "Full cost accounting for the life cycle of coal," *Annals of the New York Academy of Sciences*, vol. 1219, pp. 73–98, 02 2011.

[3] J. Rivera and R. van der Meulen, "Gartner says the internet of things installed base will grow to 26 billion units by 2020," December 12, 2013. URL: `https://www.gartner.com/newsroom/id/2636073`.

[4] X. Ge, S. Tu, G. Mao, C. Wang, and T. Han, "5G Ultra-Dense Cellular Networks," *IEEE Wireless Communications*, vol. 23, pp. 72–79, February 2016.

[5] X. Ge and W. Zhang, *Challenges of 5G Green Communication Networks*. 5G Green Mobile Communication Networks, 05 2019.

[6] K. N. R. S. V. Prasad, E. Hossain, and V. K. Bhargava, "Energy Efficiency in Massive MIMO-Based 5G Networks: Opportunities and Challenges," *IEEE Wireless Communications*, vol. 24, pp. 86–94, June 2017.

[7] S. Buzzi, C. I, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A Survey of Energy-Efficient Techniques for 5G Networks and Challenges Ahead," *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 697–709, April 2016.

[8] C. Wang, F. Haider, X. Gao, X. You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Communications Magazine*, vol. 52, pp. 122–130, February 2014.

[9] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. M. Grant, H. Haas, J. S. Thompson, I. Ku, C. Wang, T. A. Le, M. R. Nakhai, J. Zhang, and L. Hanzo, "Green radio: radio techniques to enable energy-efficient wireless networks," *IEEE Communications Magazine*, vol. 49, pp. 46–54, June 2011.

[10] S.Amirtharaj and T.Sabapathi, "Augmentation of Smart Grid Capability by Communication Networks," *International Journal of Pure and Applied Mathematics*, vol. 120, August 2018.

[11] G. Han, L. Wan, J. J. P. C. Rodrigues, H. Wu, and D. Zhang, "IEEE Access Special Section Editorial: Green Communications and Networking for 5G," *IEEE Access*, vol. 6, pp. 79263–79271, 2018.

[12] K. Davaslioglu and R. D. Gitlin, "5G green networking: Enabling technologies, potentials, and challenges," in *2016 IEEE 17th Annual Wireless and Microwave Technology Conference (WAMICON)*, pp. 1–6, April 2016.

[13] S. Guo, D. Zeng, L. Gu, and J. Luo, "When Green Energy Meets Cloud Radio Access Network: Joint Optimization Towards Brown Energy Minimization," *Mobile Networks and Applications*, vol. 24, pp. 1–9, 02 2018.

[14] J. Wang, K. Wang, B. Han, S. Zhang, C. Wen, and S. Jin, "SDR Implementation of a 5G-Oriented Ultra-Dense Distributed MIMO Prototype System," in *2018 10th International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1–6, Oct 2018.

[15] L. Zou, A. Javed, and G. Muntean, "Smart mobile device power consumption measurement for video streaming in wireless environments: WiFi vs. LTE," in *2017 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, pp. 1–6, June 2017.

[16] M. Condoluci, L. Militano, A. Orsino, J. Alonso-Zarate, and G. Araniti, "LTE-direct vs. WiFi-direct for machine-type communications over LTE-A systems," in *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 2298–2302, Aug 2015.

[17] "Mixed-integer-programming-if-then-with-logical-and-operation." URL: `https://stackoverflow.com/questions/41559428`.

[18] "If-then-else for MILP." URL: http://www.yzuda.org/Useful_Links/optimization/if-then-else-02.html.

[19] J. Wu, Z. Zhang, Y. Hong, and Y. Wen, "Cloud radio access network (C-RAN): a primer," *IEEE Network*, vol. 29, pp. 35–41, Jan 2015.

[20] S. Namba, T. Warabino, and S. Kaneko, "BBU-RRH switching schemes for centralized RAN," in *7th International Conference on Communications and Networking in China*, pp. 762–766, Aug 2012.

[21] B. Al-Oquibi, O. Amin, H. Dahrouj, T. Y. Al-Naffouri, and M. Alouini, "Energy efficiency for cloud-radio access networks with imperfect channel state information," in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 1–5, Sep. 2016.

[22] M. F. Hossain, A. Mahin, T. Debnath, F. Mosharrof, and K. Islam, "Recent Research in Cloud Radio Access Network (C-RAN) for 5G Cellular Systems - A Survey," *Journal of Network and Computer Applications*, vol. 139, 04 2019.

[23] X. Ge, J. Yang, H. Gharavi, and Y. Sun, "Energy Efficiency Challenges of 5G Small Cell Networks," *IEEE Communications Magazine*, vol. 55, 02 2017.

[24] M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Optimal Energy Savings in Cellular Access Networks," in *2009 IEEE International Conference on Communications Workshops*, pp. 1–5, June 2009.

[25] J. Wu, J. Liu, and H. Zhao, "Dynamic small cell on/off control for green ultra-dense networks," in *2016 8th International Conference on Wireless Communications Signal Processing (WCSP)*, pp. 1–5, Oct 2016.

[26] C. Peng, S. Lee, S. Lu, and H. Luo, "GreenBSN: Enabling Energy-Proportional Cellular Base Station Networks," *IEEE Transactions on Mobile Computing*, vol. 13, pp. 2537–2551, Nov 2014.

[27] E. Oh, K. Son, and B. Krishnamachari, "Dynamic Base Station Switching-On/Off Strategies for Green Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 12, pp. 2126–2136, May 2013.

[28] A. Bousia, A. Antonopoulos, L. Alonso, and C. Verikoukis, “"Green" distance-aware base station sleeping algorithm in LTE-Advanced,” in *2012 IEEE International Conference on Communications (ICC)*, pp. 1347–1351, June 2012.

[29] M. F. Hossain, K. S. Munasinghe, and A. Jamalipour, “Toward self-organizing sectorization of LTE eNBs for energy efficient network operation under QoS constraints,” in *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1279–1284, April 2013.

[30] A. Conte, A. Feki, L. Chiaraviglio, D. Ciullo, M. Meo, and M. A. Marsan, “Cell wilting and blossoming for energy efficiency,” *IEEE Wireless Communications*, vol. 18, pp. 50–57, October 2011.

[31] C. Peng, S.-B. Lee, S. Lu, H. Luo, and H. Li, “Traffic-driven power saving in operational 3G cellular networks,” in *Proceedings of the Annual International Conference on Mobile Computing and Networking, MOBICOM*, pp. 121–132, 09 2011.

[32] H. Xu, W. Yu, A. Hematian, D. Griffith, and N. Golmie, “Performance Evaluation of Energy Efficiency with Sleep Mode in Ultra Dense Networks,” in *2018 International Conference on Computing, Networking and Communications (ICNC)*, pp. 747–751, March 2018.

[33] C. Luo and J. Liu, “Load Based Dynamic Small Cell On/Off Strategy In Ultra-Dense Networks,” in *2018 10th International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1–6, Oct 2018.

[34] M. Feng, S. Mao, and T. Jiang, “BOOST: Base station ON-OFF switching strategy for energy efficient massive MIMO HetNets,” in *IEEE INFOCOM 2016 - The 35th Annual IEEE International Conference on Computer Communications*, pp. 1–9, April 2016.

[35] X. Lin and S. Wang, “Joint user association and base station switching on/off for green heterogeneous cellular networks,” in *2017 IEEE International Conference on Communications (ICC)*, pp. 1–6, May 2017.

[36] B. Maaz, K. Khawam, S. Tohme, S. Lahoud, and J. Nasreddine, “Joint User Association, Power Control and Scheduling in Multi-Cell 5G Networks,” in *2017*

IEEE Wireless Communications and Networking Conference (WCNC), pp. 1–6, March 2017.

[37] W. Yu, H. Xu, A. Hematian, D. Griffith, and N. Golmie, "Towards energy efficiency in ultra dense networks," in *2016 IEEE 35th International Performance Computing and Communications Conference (IPCCC)*, pp. 1–8, Dec 2016.

[38] X. Xu, C. Yuan, W. Chen, X. Tao, and Y. Sun, "Adaptive Cell Zooming and Sleeping for Green Heterogeneous Ultradense Networks," *IEEE Transactions on Vehicular Technology*, vol. 67, pp. 1612–1621, Feb 2018.

[39] L. Tang, W. Wang, Y. Wang, and Q. Chen, "An Energy-Saving Algorithm With Joint User Association, Clustering, and On/Off Strategies in Dense Heterogeneous Networks," *IEEE Access*, vol. 5, pp. 12988–13000, 2017.

[40] N. Yu, Y. Miao, L. Mu, H. Du, H. Huang, and X. Jia, "Minimizing Energy Cost by Dynamic Switching ON/OFF Base Stations in Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 15, pp. 7457–7469, Nov 2016.

[41] M. Feng, S. Mao, and T. Jiang, "Base Station ON-OFF Switching in 5G Wireless Networks: Approaches and Challenges," *IEEE Wireless Communications*, vol. 24, pp. 46–54, Aug 2017.

[42] S. Matoussi, I. Fajjari, N. Aitsaadi, R. Langar, and S. Costanzo, "Joint Functional Split and Resource Allocation in 5G Cloud-RAN," in *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, pp. 1–7, May 2019.

[43] D. Harutyunyan and R. Riggio, "Flexible functional split in 5G networks," in *2017 13th International Conference on Network and Service Management (CNSM)*, pp. 1–9, Nov 2017.

[44] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power consumption modeling of different base station types in heterogeneous cellular networks," in *2010 Future Network Mobile Summit*, pp. 1–8, June 2010.

[45] M. Klapez, C. A. Grazia, and M. Casoni, "Quantifying Sleep-Related Energy Savings in Indoor LTE HetNets Radio Access," *2018 International Conference on Selected Topics in Mobile and Wireless Networking (MoWNeT)*, 2018.

[46] S. F. Hasan, N. H. Siddique, and S. Chakraborty, "Femtocell versus WiFi – A Survey and Comparison of Architecture and Performance," *2009 1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology*, 2009.

[47] F. Ltd., "Fujitsu LS100 Product Description." available: `https://www.fujitsu.com/ca/en/Images/FemtoCellLS100.pdf`.

[48] "Cplex." available: `https://www.ibm.com/analytics/cplex-optimizer`.

[49] "Gurobi." available: `https://www.gurobi.com/`.

[50] "Matlab." available: `https://www.mathworks.com/help/optim/ug/intlinprog.html`.

[51] J. Linderoth and A. Lodi, "MILP software," *Wiley Encyclopedia of Operations Research and Management Science*, vol. 5, 01 2011.