UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

MASTER THESIS

TFG TITLE: Fast heuristic algorithm for 5G network energy consumption optimization

DEGREE: Master's degree in Applied Telecommunications and Engineering Management

AUTHORS: Min Wang

ADVISOR: Enrica Zola

DATE: October 23, 2017

Title : Fast heuristic algorithm for 5G network energy consumption optimization

Authors: Min Wang

Advisor: Enrica Zola

Date: October 23, 2017

Overview

This study focuses on 5G network, which deploys small cells to form multi-hop topologies using high capacity backhaul wireless links to provide localized capacity. Nowadays, high energy efficiency is very important because powering on unnecessarily a massive amount of macro cells or small cells may lead to increased expenses, CO_2 emission and environmental destruction. Based on a given Mixed-integer Linear Programming (MILP) that solves the energy consumption optimization problem in a 5G network, this research proposes a heuristic algorithm based on integer relaxation that accelerates the resolution of the MILP. The heuristic algorithm could diminish the route options by striking out the impossible links or links with lower possibility to be used. Our numerical evaluations demonstrate that the proposed algorithm can find very good solutions in short time and has similar performance in terms of energy efficiency over a large number of traffic scenarios.

ACKNOWLEDGEMENTS

This master thesis can not be successful without the help and support of many people. I would like to express my heartfelt gratitude to my advisor, Professor Enrica Zola, who gave me many valuable suggestions, guidance, and innovative ideas. Thanks to the University of Polytechnic of Catalonia for providing me a lot of resources. Also many thanks to my classmates of MASTEAM 2016 for constant encouragement and support. Last but not the least, my gratitude also extends to my family who have been assisting, supporting and caring for me all of my life.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AL Access Link

BH Backhaul

CPLEX IBM ILOG CPLEX Optimization Studio

eNB eNodeB

FDM Frequency-division Multiplexing

LP Linear Programming

LSAS Large Scale Antenna Systems

M2M Machine-to-Machine

MCA MultiCriteria analysis

MILP Mixed-integer Linear Programming

MIMO Multiple-input Multiple-output

NFV Network Functions Virtualization

OFDM Orthogonal Frequency Division Multiplexing

OPL Optimization Programming Language

PRB Physical Resource Block

SDN Software-defined Networking

SoA State of the Art

SOCP Second-order Cone Program

TDD Time Division Duplex

TDM Time-division Multiplexing

UE User Equipment

UI User Interface

CHAPTER 1. GOALS

1.1. Scope of thesis

This study focuses on 5G network energy consumption. Based on a given MILP that solves the energy consumption optimization problem in a 5G network [2] [20], this research proposes a heuristic algorithm based on integer relaxation that accelerates the resolution of the MILP. This research evolves several disciplines, which are optimization, 5G network, linear programming, heuristic method and so on.

1.2. Objectives

Nowadays, the world is changing rapidly especially in the field of telecommunications. The next generation, 5th generation wireless systems, aims at higher capacity than current 4G, allowing a higher density of mobile broadband users, and supporting device-to-device, ultra reliable, and massive machine communications. This research principally concentrates on time efficiency of energy consumption optimization for 5G network. It has 2 objectives as follow:

(1) Propose a heuristic algorithm

Heuristic algorithm is the core part of this research. It aims at maintaining a reasonable and acceptable energy savings for 5G network, and it is meant to significantly decrease running time of energy optimization model.

(2) Algorithm validation and evaluation

To evaluate the performance of heuristic algorithm, many scientific experiments are explored and compared. Then it is important to analyse those results and draw out their advantages and disadvantages.

1.3. Methodology

As mentioned in section 1.2., this research has 2 objectives. There are many different methodologies when it comes to implementing and achieving different objectives.

Static analysis and dynamic analysis are good ways to work on this project at the beginning as it requires many research readings and investigations. Static analysis chiefly concentrates on theoretical analysis to understand the logics and principals behind research papers, which have fundamental knowledge about 5G and energy consumption. Dynamic analysis is also a good way to understand an optimization model. It is very impactful to learn a new programming model by changing its codes dynamically and analysing its different results, which are caused by those changes. It is also very conducive for understanding the relations between different parts of codes in the project.

Practice is the sole criterion of truth. Controlled trial and experiment are two good methods aiming at validating performance of programs, researches and conclusions. The control variable (or scientific constant) in scientific experimentation is the experimental element which is constant and unchanged throughout the course of the investigation. The control variable strongly influences experimental results, and it is held constant during the experiment in order to test the relative relationship of the dependent and independent variables. The control variable itself is not of primary interest to the experimenter [1]. The control variable method is a primary method in this research for evaluating the algorithm performance.

1.4. Project schedule

To guarantee the success of this project, a deliberate and flexible schedule is very worthwhile and favourable. As shown in Fig 1.1, this master thesis evolves seven stages and the whole project lasts for approximately eight months since 1st March 2017.

At the beginning, as a freshman of the research, many project preparation work, like reading State of the Art (SoA), is requisite and necessary. This stages starts on 1st March and ends on 17th April. During a period of 10th April to 16th May, the energy consumption model needs to be deeply comprehended and understood. The model is proposed by Professor Enrica Zola in [2]. That learning the implementation of this model is also involved in this stage. Furthermore, a powerful software tool named CPLEX [15] is used to execute the model. The CPLEX is the software development tool for this project.

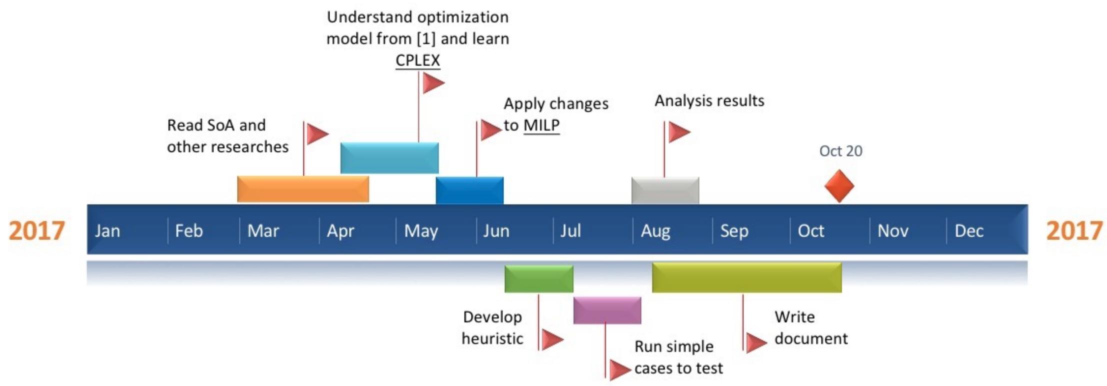


Figure 1.1: Schedule

After the preparation work, this research applies changes to MILP model in order to relax the integer constraints on some variable, thus reducing the resolution time of the problem. This stage also adapts the model from $Mbps$ based to Physical Resource Block (PRB) based. In this way, the model would be able to find routes based on users' PRB demands.

The next stage is the most important stage for this research. A heuristic algorithm is proposed to re-establish the binary conditions for those relaxed variables. This stage costs one month to complete the heuristic algorithm, which is from 13th June to 10th July.

After heuristic algorithm is finished, some simple tests are used to validate the correctness of the algorithm from July. On August, performance of the heuristic algorithm is analysed from many different aspects. At last, the paper work would be done by the end of October.

CHAPTER 2. INTRODUCTION

This chapter introduces the basic knowledge and background of this research including linear programming, CPLEX and energy consumption in 5G network, etc.

2.1. 5G network issues

As next generation, 5G network has much more advantages compared with 4G. Many new technologies like Software-defined Networking (SDN), Network Functions Virtualization (NFV) and fog computing are excogitated to integrate exist infrastructures and networks to provide advanced services. From the viewpoint of users, 5G has much higher bit rates than that of 4G, for instance users can download movies in seconds.

But 5G also has some problems to be addressed. [4] describes five technologies that could lead to both architectural and component disruptive design changes: device-centric architectures, millimeter wave, massive Multiple-input Multiple-output (MIMO), smarter devices, and native support for machine-to-machine communications.

Four more challenges from higher level are discussed in [5]. The first challenge is new business models focused on vertical markets. 3G and especially 4G technologies were designed primarily for the superfast mobile internet. 5G continues on in this direction, but also wants to target what are known as vertical markets like automotive sector and industry 4.0. The second challenge is spectrum harmonisation. 5G is emerging as a technology that will use both low frequencies , high frequencies and, for the first time ever in consumer networks, very high frequencies referred to as “millimetre wave” frequencies. The third challenge is increasingly small cells. 5G will probably bring about a sizeable increase in data traffic, and which will use millimetre wave frequencies whose propagation capabilities are weak – will no doubt require the widespread deployment of low-power base stations (small cells). The last challenge is net neutrality issues, which is an overriding principle that guarantees equal treatment for all data traffic on the internet. In particular, it excludes any form of discrimination with respect to the source, the destination or the content of data flows. Despite the challenges mentioned above, this research focuses on energy consumption challenge.

2.2. 5G network optimization model

Optimization, also called mathematical programming, refers to the study of decision problems in which one seeks to minimize or maximize a function by systematically choosing the values of variables within their allowed sets. In this section, the reasons and energy consumption factors of 5G networks will be discussed. Some interesting researches related to this topic would be introduced also.

Energy efficiency is defined as the number of bits, which can be transmitted per Joule of energy. 5G should support a 1000 times traffic increase in the next 10 years timeframe, with an energy consumption by the whole network of only half that is typically consumed by today’s networks. This leads to the requirement of an energy efficiency increase of x2000 in the next 10 years timeframe [3].

5G is an advanced telecommunications technology, which will be deployed in every corner of the world. It will consume large amount of electronic energy. The costs of the energy would be expensive for both service providers and customers. Additionally, it will bring huge challenges to our environment.

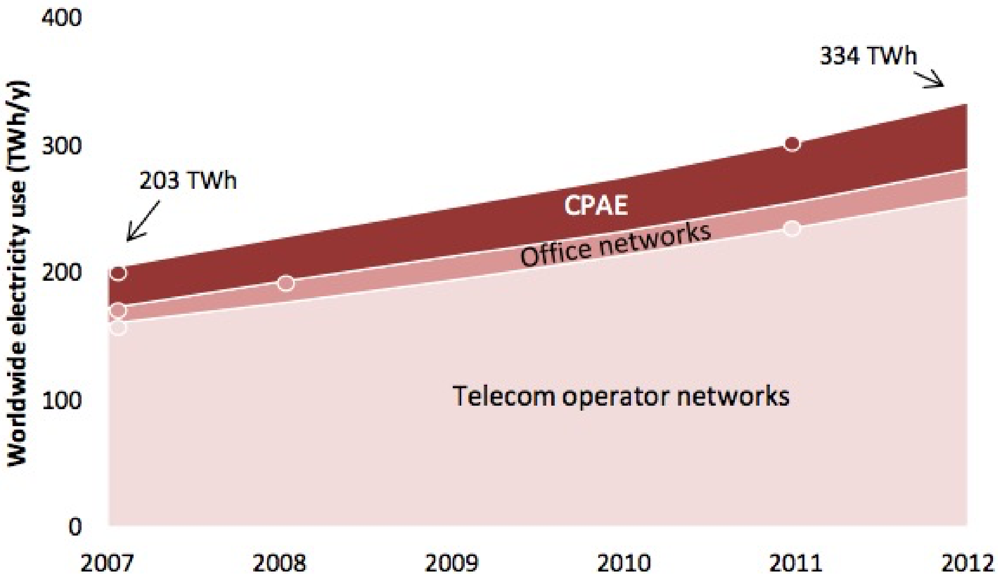


Figure 2.1: Trends in worldwide ICT electricity consumption from 2007 to 2012 [6].

First of all, 5G will bring drastic energy efficiency improvement and develop energy harvesting everywhere. This energy chase will cover terminal devices, network elements, and the network as a whole including data centers [7]. In network electricity, as shown in Fig 2.1, most electricity was consumed by network infrastructures like macro cells and small cells. In the future, electricity consumption will increase continuously [6]. It is easy to deploy more cells, but it is hard to achieve optimal Internet services without using more power. So this calls for much higher energy efficiency. Energy consumption savings of 5G network will bring obvious economical benefits to service providers as operating costs would be reduced exponentially. 5G network relies on a large amount of cells. Reducing energy consumption by turning on minimum amount of cells would also extend the life cycle of the cells and decrease maintaining costs. Indirectly, customers are willing to accept the lower costs for the same or higher quality of services.

Furthermore, the environment can be well protected by saving electricity energy. Practically all parts of the electricity system can affect the environment, and those impacts depend on how and where the electricity is generated and delivered. In general, the environmental effects include: emissions of greenhouse gases and other air pollutants, etc [8]. And the best way to protect environment, is to increase energy efficiency as building new infrastructures would demand unaffordable expenses for most nations.

2.2.1. Researches of 5G energy consumption optimization

Nowadays, energy consumption of 5G network has been an edge-cut topic for decades and it is raising more public attentions as 5G network is getting mature. To pursue enegy savings, researchers made many efforts from different perspectives such as beamforming, Time Division Duplex (TDD), antenna and so on.

The authors in [2] propose an optimization model that minimizes the total power consumption of 5G HetNets deployments while providing the required capacity and coverage. The model jointly optimizes the user association, routing in the multihop backhaul and decides to power on or off the small cells to serve the user demands. Numerical evaluation show significant power savings over a large range of traffic demand distributions while keeping the blocking probability low.

Fatma Ezzahra Salem [9], proposed a research paper concluding energy consumption optimization for 5G network with large scale antenna systems. They focused on the use of an advanced base station power model, which allowed to quantify the power consumption of a reference scenario comprising multiple sites with standard base station antennas, and then compare it to a Large Scale Antenna Systems (LSAS) solution implementing multilevel beamforming. As a result, More scenarios can be devised for leveraging the potential of multilevel beamforming in making mobile networks more energy efficient such as reducing the transmission power when using beamforming or load balancing using adequately designed codebooks.

Eeva Lähetkangas [11], investigates the enablers and limits of TDD latency by analyzing the performance of Orthogonal Frequency Division Multiplexing (OFDM) in different channel environments and discussing on the consequent frame length limits. We then provide a description on how the achieved short TDD latency can further be utilized to enable remarkably low energy consumption. The short physical layer latency enabling fast transitions between sleep and active modes brings significant gains in terms of power consumption.With the same power and battery assumptions the proposed 5G concept has approximately 7-40 times lower energy consumption compared to Machine-to-Machine (M2M) optimized LTE design.

Xumin[12], presents an energy-efficient architecture named SD-EHN for 5G green communications. Energy harvesting networking is enhanced by supporting flexible energy scheduling and improving overall energy efficiency of the network. We investigate a mobile data gathering scenario in SD-EHN. We propose an energy trading model for nodes using stochastic inventory theory and a Nash bargaining game. Numerical results indicate that our proposed SD-EHN supports flexible energy scheduling, which improves energy efficiency and achieves energy saving.

2.3. Linear Programming (LP)

2.3.1. What is LP

In 1975, L.V.Kantorovich, a soviet economist, won a Nobel prize for proposing a model framework to reveal market balance and market optimization, which is written in a famous book, Mathematics in Economics: Achievements, Difficulties, Perspectives [10]. The first LP method, generalized simplex method, is published by an US mathematician, G.B.Antzing, laying a foundation of LP research in 1974. From then on, LP researches are flourishing.

Linear programming is a established branch of operations research, which is widely popularized in economic and human resource optimization. Specifically, LP is regarded as the most useful method to derive the optimal minimum or maximum solutions of objective problems, which are subjected to one or many linear constraints. Currently, LP is getting more and more important in industrial optimization with puissant power of computer.

$$\begin{aligned} Maximize \quad & z = 5x + 15y \\ Subject \quad to \quad & -x + 6y \leq 30 \\ & x + 3y \leq 24 \\ & x \leq 8 \\ & x \geq 0, y \geq 0 \end{aligned} \tag{2.1}$$

A simple example of LP is shown in Eq 2.1. The purpose is to maximize z and z is related to x and y. In four equations shown, x and y are connected with specific rules, which are termed constraints. Those constraints mark a convex polytope where the objective function is to be optimized.

2.3.2. Applications of LP

LP is extensively applied in enterprise management to optimize productivity and interests. With the tremendous development of technology like computer science and telecommunications, a great amount of companies in the world have chosen LP as a leading management support and it is proved extremely advantageous and valuable. Overall, there are 5 aspects of LP applications involved in companies.

Production planning. Companies require many resources to produce commodities. That how to dispatch and distribute those resources would be a pivotal topic for most companies. Production plan covers human resource, material resource and financial resource. Before LP was invented, production plan is resolved highly relying on project manager's personal experience and a sensation of work, which are verified inefficient, unscientific and unstable. For example, [13] introduced a methodology for automated production planning of semiconductor manufacturing based on iterative LP optimization and discrete-event simulation calculations. They demonstrated in experiments on an industry data set that a relatively small number of iterations is required to develop a production plan correctly characterizing future flow times as a function of factory load and product mix. The methodology makes possible automated production planning of semiconductor manufacturing on an engineering work station.

Labor force plan. Labor is getting more expensive especially in high-tech companies. That how to enable the companies with healthy and competitive strength by minimum labor force, is a strait for most high-tech companies.

Transportation. Metropolis emerges bigger and bigger in our moderated world. Daily movements of citizens bring huge challenges for governments and metro systems. The LP is an excellent way to analysis the subway supports and public bus routines, etc. On the other hand, shipping for overseas companies to transport goods from one place to another can be designed based on LP in order to adapt to shipping cost changes influenced by inevitable factors like oil price.

Product materials savings. LP can obviously improve product material savings by optimizing the material consumption especially for some material price sensitive industrials. Some prices of materials change dynamically and LP can ensure the best material savings according to daily changing prices and guarantee the quality of the product.

Investment. Investment is an efficient way to accelerate the economic developing speed involving finance, technique and management skills. The linchpin to make an investment decision is to evaluate the balance between profits and risks. LP can be applied to solve investment problems by avoiding the risks.

2.3.3. Mixed Integer Linear Problem (MILP)

MILP is a small branch of LP. It is characterized by forcing some variables to be floating numbers instead of integer numbers. In this research, some variables in the model are in real number such as energy consumption. But others are set as integer for special purposes like indicating the on-off of the cells .

$$
\begin{aligned}
Minimum \quad & Y = 0.18X_{corn} + 0.27X_{milk} + 0.55X_{bread} \\
Subject \quad to \quad & 107X_{corn} + 500X_{milk} \leq 50000 \\
& 107X_{corn} + 500X_{milk} \geq 500 \\
& 72X_{corn} + 121X_{milk} + 65X_{bread} \leq 2250 \\
& 72X_{corn} + 121X_{milk} + 65X_{bread} \geq 2000 \\
& X_{corn} > 0, \quad X_{milk} > 0, \quad X_{bread} > 0
\end{aligned}
\tag{2.2}
$$

An example of MILP is shown in Eq. 2.2. We can see that some variables are floating numbers.

2.3.4. Tools for LP

As LP is such a powerful tool to improve our society from many different aspects, there are more than 50 softwares developed to server business and academic needs. Fortunately, many softwares are open source or free for academical uses including ADMB, OpenMDAO, GLPK and so on.

(a) ADMB

(b) CPLEX

Figure 2.2: ADMB and CPLEX

ADMB [14] is a nonlinear optimization framework, using automatic differentiation. OpenMDAO is a multidisciplinary design, analysis, and optimization (MDAO) framework, written in the python programming language, developed by NASA Glenn Research Center, with support from the NASA Langley Research Center. GLPK is a GNU Linear Programming Kit for LP realization.

In this research, the tool used is CPLEX [15], which is developed by IBM and free for academic purposes. The CPLEX Optimizer was named for the simplex method as implemented in the C programming language, although today it also supports other types of mathematical optimization and offers interfaces other than C. The interface of CPLEX is shown in Fig 2.3.

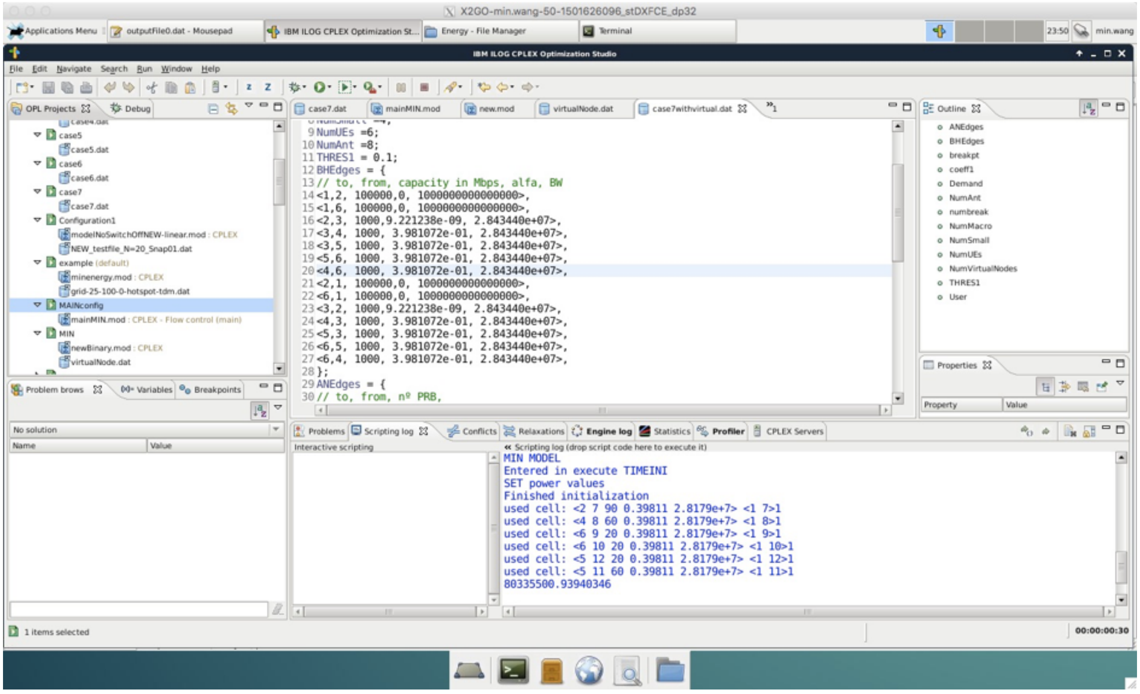


Figure 2.3: Interface of CPLEX

In the left part of Fig 2.3, it shows the resources of each configuration, which can run as a linear programming solver with model file and data file. The middle part is editing zone for editing codes of model file and data file. The right part shows the essential parameters and lower part displays the execution results or debugging.

2.4. Heuristic

In computer science, artificial intelligence, and mathematical optimization, a heuristic is a technique designed for solving a problem more quickly when classic methods are too slow, or for finding an approximate solution when classic methods fail to find any exact solution. This is achieved by trading optimality, completeness, accuracy, or precision for speed. In a way, it can be considered a short-cut [16].

Heuristic technique is extremely popular in many different areas like psychology, management science mathematics and so forth. In computer science area, 2 kinds of heuristic method are diffusely used and they are approved excellent methods. The first one is heuristic analysis [18], which is a method employed by many computer antivirus programs designed to detect previously unknown computer viruses, as well as new variants of viruses already in the ”wild”. Heuristic analysis is an expert based analysis that determines the susceptibility of a system towards particular threat/risk using various decision rules or weighing methods. MultiCriteria analysis (MCA) is one of the means of weighing. This method differs from statistical analysis, which bases itself on the available data or statistics.

The second one is heuristic evaluation [19], which is a usability inspection method for computer software that helps to identify usability problems in the User Interface (UI). It specifically involves evaluators examining the interface and judging its compliance with recognized usability principles (the ”heuristics”). These evaluation methods are now widely taught and practised in the new media sector, where UIs are often designed in a short space of time on a budget that may restrict the amount of money available to provide for other types of interface testing.

In general, heuristic algorithms can no guarantee that the best solution will be found, but they usually have their own advantages regardless the inaccuracy they have. Many heuristic algorithms are proposed to solve very famous and classical problems. One of the most famous research is [17]. It discusses a highly effective heuristic procedure for generating optimum and near-optimum solutions for the symmetric traveling-salesman problem. The procedure is based on a general approach to heuristics that is believed to have wide applicability in combinatorial optimization problems.

Another important research that uses heuristic method to improve 5G network energy consumption is published in [20]. It proposes a mathematical model that jointly solves the user association and backhaul routing problem in the aforementioned context, aiming at the energy efficiency maximization of the network. Due to the high complexity of the optimal solution, they also propose an energy efficient heuristic algorithm (Joint), which solves the discussed joint problem, while inducing low complexity in the system.

The majority work of this research is based on the research in [2] [20], which delivered an excellent energy consumption model for 5G network. In chapter 3, the energy consumption model of 5G network would be expounded.

CHAPTER 3. 5G NETWORK ENERGY CONSUMPTION OPTIMIZATION

3.1. Scenario analysis

5G network costs huge energy consumption owing to a large amount of small cells and macro cells. Energy consumption would make enormous pressures to both resources like electricity and environment. Nowadays, that how to minimize energy consumption has been a cutting edge research topic for several years.

This chapter is a brief introduction about energy consumption model, which is proposed in [2]. Based on the architecture of 5G network in reality, the model can select the best route for energy saving by turning off superfluous and unneccessary cells. It assumes that a fixed 5G network consists of many macro cells and small cells, which can support User Equipment (UE)s. The network at least contains one macro cell, but small cell is optional. And details of this model can be found in [2]. This model is the basics of our research.

3.2. Flow constraint

For the flow route, the flow conservation constraint states that for each UE u and each link (i,j), the sum of the flows $f^u_{(i,j)}$ that exit a node i has to be the same as the sum of the flows entering i, except if i is the source or the sink. This can be written as:

$$\sum_j f^u_{(i,j)} - \sum_j f^u_{(j,i)} = \begin{cases} R^u, & if \quad i = source \\ -R^u, & if \quad i = u(sink) \\ 0, & \quad otherwise \end{cases} \qquad (3.1)$$
$$\forall u \in U, \forall i \quad and j \in M \cup S \cup U$$

where R^u represents the total rate that UE u is allocated after optimization (i.e., it equals the demanded rate d_u when the blocking probability of user u is zero). It assumes that the flow for each UE u must follow a single path route; thus, the non-splittable flow constraint can be written as:

$$\sum_j x^u_{(i,j)} - \sum_j x^u_{(j,i)} = \begin{cases} 1, & if \quad i = source \\ -1, & if \quad i = u(sink) \\ 0, & \quad otherwise \end{cases} \qquad (3.2)$$
$$\forall u \in U, \forall i \quad and j \in M \cup S \cup U$$

where $x^u_{(i,j)}$ is a decision variable that is 1 when u uses link (i,j) and 0 otherwise.

We have to ensure that the flow for UE u on link (i,j) is zero when that link is not used (i.e., $x^u_{(i,j)}$ is 0); on the other hand, the flow assigned to UE u is limited by the maximum capacity $c(i,j)$ on that link:

$$f^{u}_{(i,j)} \leq x^{u}_{(i,j)} c_{(i,j)}, \forall u \in U, \forall (i,j) \in \mathcal{L} \tag{3.3}$$

Also, the single association rule states that each UE u must be connected to only one cell in the network:

$$\sum_{(i,u) \in \mathcal{L}_{\mathcal{AL}}} x^{u}_{i,u} = 1, \forall u \in U \tag{3.4}$$

where $\mathcal{L}_{\mathcal{AL}}$ represents the subset of all the Access Link (AL).

When more than one UE connect to the same cell, they have to share the capacity on that AL. Each UE will be assigned a given number of PRBs, according to its demand and availability. We can thus write the capacity constraint for an AL as follows:

$$\sum_{u \in U} \sum_{(i,u) \in \mathcal{L}_{\mathcal{AL}}} f^{u}_{(i,u)} \leq C^{max}_{i}, \forall i \in M \cup S \tag{3.5}$$

where C^{max}_{i} is the maximum capacity of cell i in the AL according to the available PRBs. Similarly, the data of different users that flows on a given Backhaul (BH) link must share the maximum capacity of that link:

$$\sum_{u \in U} f^{u}_{(i,u)} \leq C_{(i,j)}, \forall (i,j) \in \mathcal{L}_{\mathcal{BH}} \tag{3.6}$$

where $\mathcal{L}_{\mathcal{BH}}$ represents the subset of BH links.

In addition, the set of interference links defined as I has to share the maximum capacity of a single channel, where TDD and Time-division Multiplexing (TDM) approaches are needed to separate transmissions on different time slots. Otherwise, simultaneous transmissions on adjacent BH links can be handled through Frequency-division Multiplexing (FDM), for which channel assignment is required so to avoid interference. The following constraint ensures that the capacity of each BH link is shared among adjacent interference BH links:

$$\sum_{u \in U} \left(\frac{f^{u}_{(i,j)}}{c_{(i,j)}} + \sum_{(k,l) \in I_{(i,j)}} \frac{f^{u}_{(k,l)}}{c_{(k,l)}} \right) \leq 1, \forall (i,j) \in \mathcal{L}_{\mathcal{BH}} \tag{3.7}$$

3.3. Power model

Energy consumption is calculated by summing all the energy consumption of each cells (including macro cells and small cells). The formula of energy consumption on each cell is shown as:

$$p_i = p^{AL}_{i} + p^{BH}_{i} \tag{3.8}$$

where p_i is the power consumption of $cell_i$, p^{AL}_{i} is the power consumption of AL and, p^{BH}_{i} is the power consumption of BH link of $cell_i$. For accurately, we have the total energy consumption as follow:

$$p_{total} = \sum_{k=1}^{n} p_i \tag{3.9}$$

where equals sum of all cells form number 1 to k. To calculate p_i^{AL} for each cell, the formula is shown as follow:

$$p_i^{AL} = p_{0_i}^{AL} + \Delta_{p_i} p_{out_i}^{AL} \tag{3.10}$$

where $p_{0_i}^{AL}$ represents the minimum non-zero output power 0_i of the AL transceiver at cell i. is the slope of the load-dependent power consumption and can take different values based on the type of antenna used. $p_{out_i}^{AL}$ is the power consumption of the transceiver for the AL between cell i and all the associated UE:

$$p_{out_i}^{AL} = \frac{p_{max_i}^{AL}}{N_{ant_i} N_{PRB_i}} \sum_{u \in U} \frac{f_{iu}^u}{BW_{PRB} \log_2 1 + SINR_{iu}} \tag{3.11}$$

where $p_{max_i}^{AL}$ is the maximum transmission power of the AL transceiver at cell i; N_{ant_i} is the number of antennas at cell i for the AL (i.e., if MIMO is used); N_{PRB_i} is the maximum number of PRBs at cell i; f_{iu}^u is the flow rate that user u gets from cell i; the denominator in the second fraction stands for the spectral efficiency.

$$p_i^{BH} = \sum_{j \in m \bigcup s} \left(p_{0_i}^{BH} x_{(i,j)}^u + p_{out_i}^{BH} \frac{\sum_{u \in U} f_{(i,j)}^u}{c_{(i,j)}}\right) \tag{3.12}$$

where $p_{o_i}^{BH}$ represents the minimum non-zero output power of each BH transceiver at cell i;

3.4. Activation Constraint

The energy consumption model shown above is only about the energy part which is not realistic due to the 5G network should be able to ensure better service. To ensure better services like achieving needed rates for UE and physical PRBs, we have many constraints for routing the traffics that can satisfy the service quality also.

Two binary variables are defined to indicate whether the $AL(s_i^{AL})$ and $AL(s_i^{BH})$ links are powered on or off at cell i. AL in eNodeB (eNB) should be always on as it provide connection to Internet:

$$s_i^{AL} = 1, \forall i \in M \tag{3.13}$$

The AL of a small cell will be powered on if and only if the power consumption of the transceiver at cell i is not zero:

$$s_i^{AL} \le p_{out_i}^{AL}, \forall i \in S \tag{3.14}$$

The following constraints set a similar rule of the BH links:

$$s_i^{BH} \le p_i^{BH} * BIG, \forall i \in M \cup S \tag{3.15}$$

BIG is a big number (ie.., 10^8).

Also, cell i should be switched on only when there is at least one active link going out of it:

$$
\begin{aligned}
s_i^{AL} &\leq \sum_{u \bigcup U} \sum_{(i,j) \in L_{AL}} x^u_{(i,j)} \\
s_i^{BH} &\leq \sum_{u \bigcup U} \sum_{(i,j) \in L_{BH}} x^u_{(i,j)} \\
&\forall i \in M \cup S
\end{aligned}
\tag{3.16}
$$

Finally, a link $x(i,j)$ can only be used by the UE when the transmitting cell i is on:

$$
\begin{aligned}
\sum_{u \bigcup U} x^u_{i,j} \leq s_i^{AL} * BIG, \forall (i,j), \in L_{AL} \\
\sum_{u \bigcup U} x^u_{i,j} \leq s_i^{BH} * BIG, \forall (i,j), \in L_{BH}
\end{aligned}
\tag{3.17}
$$

In the end , the maximum number of PRBs per cell is 100.

CHAPTER 4. ENERGY CONSUMPTION OPTIMIZATION MODEL IMPLEMENTED WITH CPLEX

4.1. CPLEX

The IBM ILOG CPLEX Optimizer solves integer programming problems, very large linear programming problems using either primal or dual variants of the simplex method or the barrier interior point method, convex and non-convex quadratic programming problems, and convex quadratically constrained problems (solved via second-order cone programming, or Second-order Cone Program (SOCP)) [15].

The architecture of the project is shown in Fig 4.1. There are 2 main files, one for model and another for data. The model file is written in C programming language with CPLEX standards. The data file contains all the initialization data like 5G network architecture and user demands and so forth. All the files will be illustrated in details in section 4.2 and section 4.3. The flow control procedure is to do the flow management that can manipulate and create a new data file based on heuristic method. Then, based on the energy consumption model expressed in Chapter 3, CPLEX would search out the best route in 5G network to save energy.

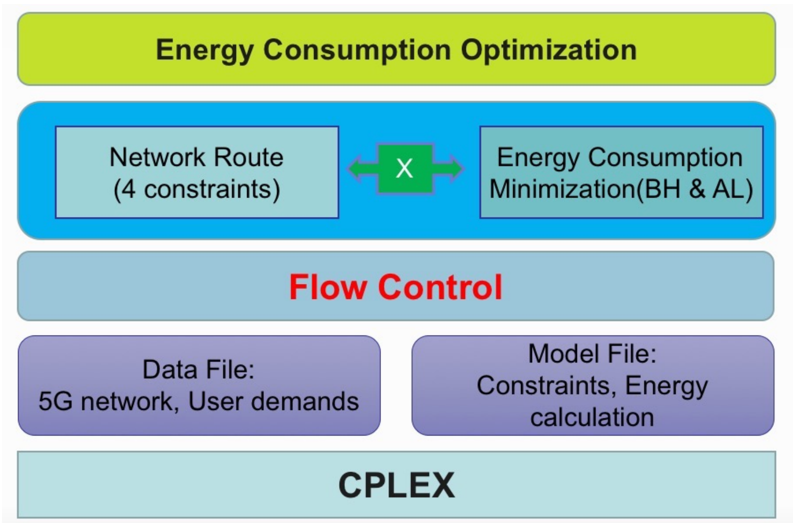


Figure 4.1: Architecture of the project

4.2. Data structure

The data file used in the project is for initializing the 5G networks and user demands. Data structures are defined in Table 4.1. The vital data in the file are $BHEdges$ and $ANEdges$, which transform the structures of 5G network into two lists. The $BHEdges$ list reveals BH links between cells. The $ANEdges$ list describes prospective cells that each user can connect to. Hence, they can be utilized to make route decisions. The parameter $User$ labels each UE into a number, which is also an identification.

Table 4.1: Data file in CPLEX

name	type
$NumMacro$	(int) The number of Macro cells in the network
$NumSmal$	(int) The number of Small cells in the network
$NumUEs$	(int) The number of users
$BHEdges$	(List) [SourceNode(int), DestinationNode(int)]
$ANEdges$	(List) [SourceNode(int), DestinationNode(int)]
$User$	(List) [User Number(int)]
$Demand$	(List) [SourceNode(int),UserNumber(int), Demand(float, In Mbps)]

Another important parameter is $Demand$, which is a triplet. The elements of the triplet are a source node, an user and its bit rate demand. In general, source node is number 1 in this research insomuch as most scenarios have one macro cell only. A simple instance of data file is unfolded in Fig 4.2. As shown in Fig 4.2, integer type parameters like $NumMacro$, $NumSmall$, $NumUEs$ and $NumAnt$ are included. Then it is followed by a list of BH links, a list of AL links and a list of UEs.

```
/*********************************************
 * OPL 12.5 Data
 * Author: min.wang
 * Creation Date: Jun 5, 2017 at 11:07:46 PM
 *********************************************/
NumMacro =1;
NumSmall =2;
NumUEs =1;
NumAnt =8;
BHEdges = {
<1,2, 250,9.221238e-09, 2.843440e+07>,
<2,3, 250, 3.981072e-01, 2.843440e+07>,
};
ANEdges = {
<3,4, 250, 3.981072e-01, 2.817947e+07>,
<1,4, 250, 3.981072e-01, 2.817947e+07>,
};
User = {
<1, 4>,
};
Demand = {
<1, 4, 250>,
};
numbreak = 7;
breakpt = [8, 16, 24, 30, 3.250000e+01, 3.350000e+01, 3.450000e+01];
coeff1= [3.187500e+01, 8.160000e+03, 2.088960e+06, 1.761608e+08,
2.000104e+09, 6.074001e+09, 1.214800e+10];

```

Figure 4.2: Sample data file

4.3. Model parameter

In the model file, to organize the data from data file and set up constraints, there are many parameters needed as shown in the Table 4.2.

Table 4.2: Model parameters

name	type
x	(vector, int, 0...1) The most important parameter in the program, indicating whether cells are on or not, regarded as route vector
sbh	(vector, int, 0...1) 1 means BH on that node
san	(vector, int, 0...1) 1 means AN on that node
$maxPRBSmall$	Max number of PRBs at small cell, fixed to 100.
$maxPRBMacro$	Max number of PRBs at macro cell, fixed to 100.
$NtrxAnSmall$	Number of transmission chains for small cells, fixed to 8.
$NtrxAnMacro$	Number of transmission chains for macro cells, fixed to 8.
$zeroAnSmallPower$	Power consumption at the minimum non-zero output power
$AnPower$	Power consumption of each small cell
$BhPower$	Power consumption of each macro cell
$PslopeSmall$	Slope for the load dependent power consumption

In the table, the most important variable is x, which is not only concerned about the route decisions but also relates to energy consumption optimization. And our heuristic algorithm introduced in chapter 5 is based on relaxation of this parameter. The variable x is also named as COI (Cell On-off Indicator) as it can decide whether the cell is on or not for energy savings.

4.4. Use cases analysis

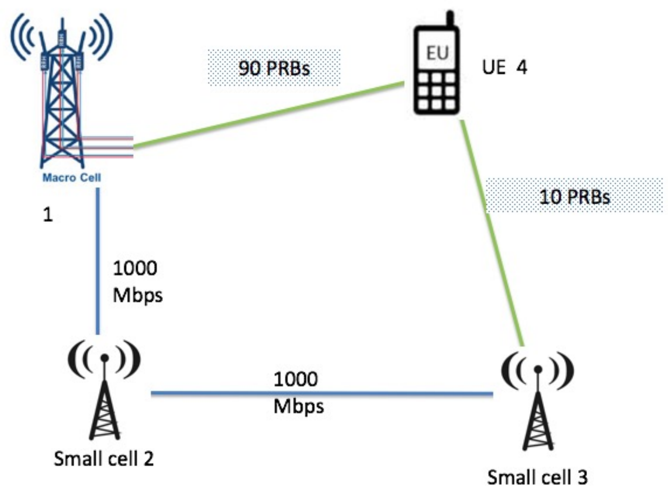


Figure 4.3: Use case 1

Based on the implementation of section 4.2. and 4.3., we used three 5G scenarios to demonstrate the model and to help deeply understand on how the model works. And many parameters are discussed in details. The most important parameter, COI, would be the strategic point of the heuristic algorithm.

fromnode	tonode	source	sink	Value
1	2	1	4	0
2	3	1	4	0
1	4	1	4	1
3	4	1	4	0

Figure 4.4: Use case 1 - Variable x

For now, the model, data and parameters expressed will be shown in many detailed examples to better grasp the model. In general, all the 5G network used has macro cells, small cells and UEs. The connection capacity between cells are evaluated by bit rates for energy consumption calculation. Likewise, connections between cells and UEs are measured by the number of PRBs. It means the exact number of PRBs those users need when the corresponding cells are chosen and connected.

Nodes (size 4)	Value
1	1
2	0
3	0
4	0

(a) Parameter san

Nodes (size 4)	Value
1	0
2	0
3	0
4	0

(b) Parameter sbh

Figure 4.5: Use case 1 - Parameter san and sbh

Use case1: In Fig 4.3, big antenna with number 1 is a macro cell connecting to small cell labelled 2 with $1000Mbps$ capacity. Given UE 4 demand, this user can connect to the macro using 90 PRBs. Small cell 3 has the same connections as macro cell 1, but the PRBs used to satisfy the same demand from UE 4 would be only 10 (e.g., better SNR conditions). Small cell 2 does not connect to UE directly, but is has two BH links separately connecting to other two cells.

Enb (size 3)	Value
1	3.98107200000012
2	0
3	0

(a) Parameter $ANPower$

Enb (size 3)	Value
1	0
2	0
3	0

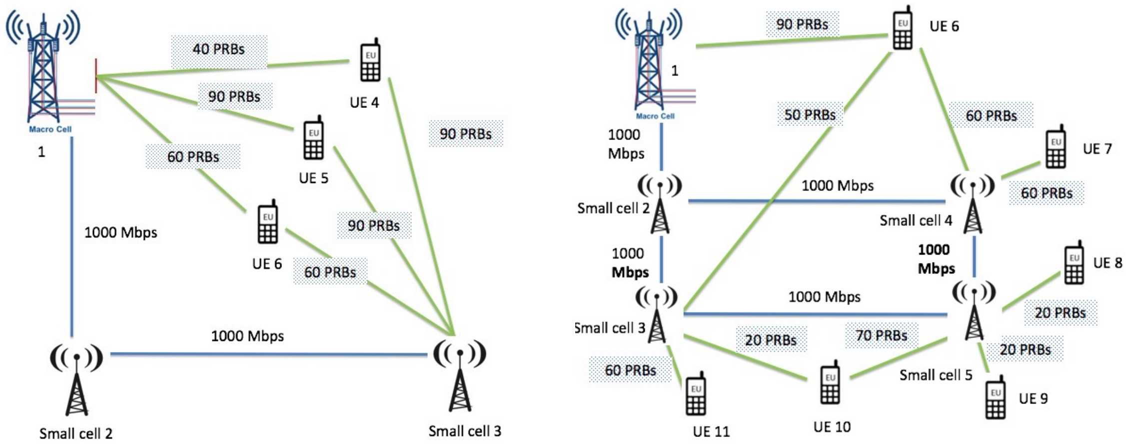
(b) Parameter $BHPower$

Figure 4.6: Use case 1 - Parameter $ANPower$ and $BHPower$

Fig 4.4 below shows the details of variable x, which is generated by CPLEX studio. Variable x is a two-dimensional array. The first dimension is link, which is represented as $BHEdge$ or $ANEdge$ in the data file of the project. Exactly, a link is defined by two factors, which are $fromnode$ and $tonode$ as shown in the figure.

The second dimension of variable x is $User$, which is defined by two factors, $source$ and $sink$. In this research, most scenarios used have one thing in common,which is that they have one macro cell only. So the $source$ would always be 1. And $sink$ is the identification of UE. In this network, the identification of the UE is 4. The key function of x is to indicate if a link is used or not and who is this link serving for when it is being used. As shown in Fig 4.4 , all the COIs are 0 except the third one. It means that the link from macro cell 1 to

UE 4 is used for Internet services. This achieves the purpose of energy saving because it only needs to turn on one macro cell compared with another route solution, which needs to activate 3 cells.



(a) Use case 2 (b) Use case 3

Figure 4.7: Use case 2 and use case 3

The parameter *san* on the left picture of Fig 4.5, is to indicate access connection on the node. The value for node 1 is 1 since only the AL link on node 1 is used for serving UE 4. This is in accordance to the results of variable x. In the right part of Fig 4.5, not a single BH link is used because macro cell is the only used node. Then values of parameter *sbh* are all 0. Based on those route results, the energy consumption as shown in Fig 4.6, is calculated for each cell. The AL link energy consumption of cell 1 is around 3.98W. With the fact that no BH link is used, so energy consumption is 0.

Edges (size 8)		User (size 3)		
fromnode	tonode	source	sink	Value
1	2	1	4	0
1	2	1	5	1
1	2	1	6	0
2	3	1	4	0
2	3	1	5	1
2	3	1	6	0
1	4	1	4	1
1	4	1	5	0
1	4	1	6	0
1	5	1	4	0
1	5	1	5	0
1	5	1	6	0
1	6	1	4	0
1	6	1	5	0
1	6	1	6	1
3	4	1	4	0
3	4	1	5	0
3	4	1	6	0
3	5	1	4	0
3	5	1	5	1
3	5	1	6	0
3	6	1	4	0
3	6	1	5	0
3	6	1	6	0

Figure 4.8: Use case 2 variable x

Nodes (size 6)	Value
1	1
2	0
3	1
4	0
5	0
6	0

(a) Parameter *san*

Nodes (size 6)	Value
1	1
2	1
3	0
4	0
5	0
6	0

(b) Parameter *sbh*

Figure 4.9: Use case 2 - Parameter *san* and *sbh*

To deeply understand this model, two more use cases with more cells and UEs are made. They are shown in Fig 4.7. Use case 2 is slightly more complicated than use case 1 due to more UEs it has. All UEs connect to macro cell 1 and small cell 3 with different PRB demands. According to variable x shown in Fig 4.8.The routes of this 5G network that can satisfy all demands of UEs, are macro cell 1 connects to UE 4 and UE 6, and small cell 3 connects to UE 6. The routes have achieved best energy optimization. As a result, macro cell 1 and small cell 3 are activated to connect to UEs. And BH links between them are activated also. Parameters san and sbh are shown in Fig 4.9. It shows that macro cell 1 and small cell 3 provide AL links. The macro cell 1 and small cell 2 provide BH links. Energy consumption are shown in Fig 4.10. Small cell 2 does not connect any UE, so its $ANpower$ is 0. BH power of small cell 3 is also 0 since is has AL link from UE 5 only.

Enb (size 3)	Value
1	39.81072
2	0
3	35.829648

(a) Parameter $ANpower$

Enb (size 3)	Value
1	1.65392319866078e-8
2	0.714045916214163
3	0

(b) Parameter $BHpower$

Figure 4.10: Use case 2 - Parameter $ANpower$ and $BHpower$

Nodes (size 11)	Value
1	1
2	0
3	1
4	1
5	1
6	0
7	0
8	0
9	0
10	0
11	0

(a) Parameter *san*

Nodes (size 11)	Value
1	1
2	5
3	2
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0

(b) Parameter *sbh*

Figure 4.11: Use case 3 - Parameter *san* and *sbh*

Use case 3 is more complicated than use case 2 by having more small cells and UEs. In the network, there are 1 macro cell, 4 small cells and 6 UEs. The rates of BH links between cells are all $1000Mbps$. The BH links are represented by blue lines. Green lines are AL links connecting cells and UEs. As the maximum number of PRBs per cell is 100. So the solution for this network is that: UE 6 connects to macro cell 1; And UE 7 connects to small cell 4; And UE 8 and UE 9 connect to small cell 5; And UE 10 and UE 11 connect to small cell 3. The BH link between small cell 2 and small cell 4 is off for energy savings. The variable x is not presented as it is to long. Parameter san and sbh is shown in Fig 4.11. $ANpower$ and $BHpower$ are shown in Fig 4.12.

↓ Enb (size 5)	↓ Value
1	35.8296480000011
2	0
3	31.8485760000029
4	23.8864319999978
5	15.9242879999982

(a) Parameter $ANpower$

↓ Enb (size 5)	↓ Value
1	0.00000124...239897814
2	53.5534437160622
3	21.4213774864249
4	0
5	0

(b) Parameter $BHpower$

Figure 4.12: Use case 3 - Parameter $ANpower$ and $BHpower$

4.5. Model improvements for more complex scenarios

The model implemented in section 4.2. and 4.3. can serve networks with one macro cell only. To support networks with more macro cells, many improvements are needed to achieve this purpose. This section shows how the model was adapted for new scenario which has multi macro cells.

4.5.1. Model improvement design

The new model should be able to support many macro cells 5G network, but it also should maintain its feature of supporting previous networks, which have one macro cell only. In reality, like shown in the previous networks, there are one macro cell and many small cells. But with user demands increase, some macro cells and small cells shall be allowed to have a fixed connection to the Internet, so that they can satisfy new demands and provide better service quality. It is necessary for the model to face the upcoming changes by minimum and acceptable expenses. Based on the common features of 5G network and their potential tendency, those improvements are designed on both model side and data side. In the model file, the model must be suitable for all kinds of network despite of how many macro cells they have. In the data file, it would be better to make limited changes on previous networks as huge modifications for existing networks are unrealistic.

Table 4.3: Parameter $virtualnode$

name	type
virtualnode	(int, 0 or 1) The number of virtual node, 0 means this network has no virtual cell, 1 means 1 virtual cell.

In model improvement design, a new concept, $virtualnode$, is introduced. The $virtualnode$ is a special node that does not really exist in the network and it can connect to all macro

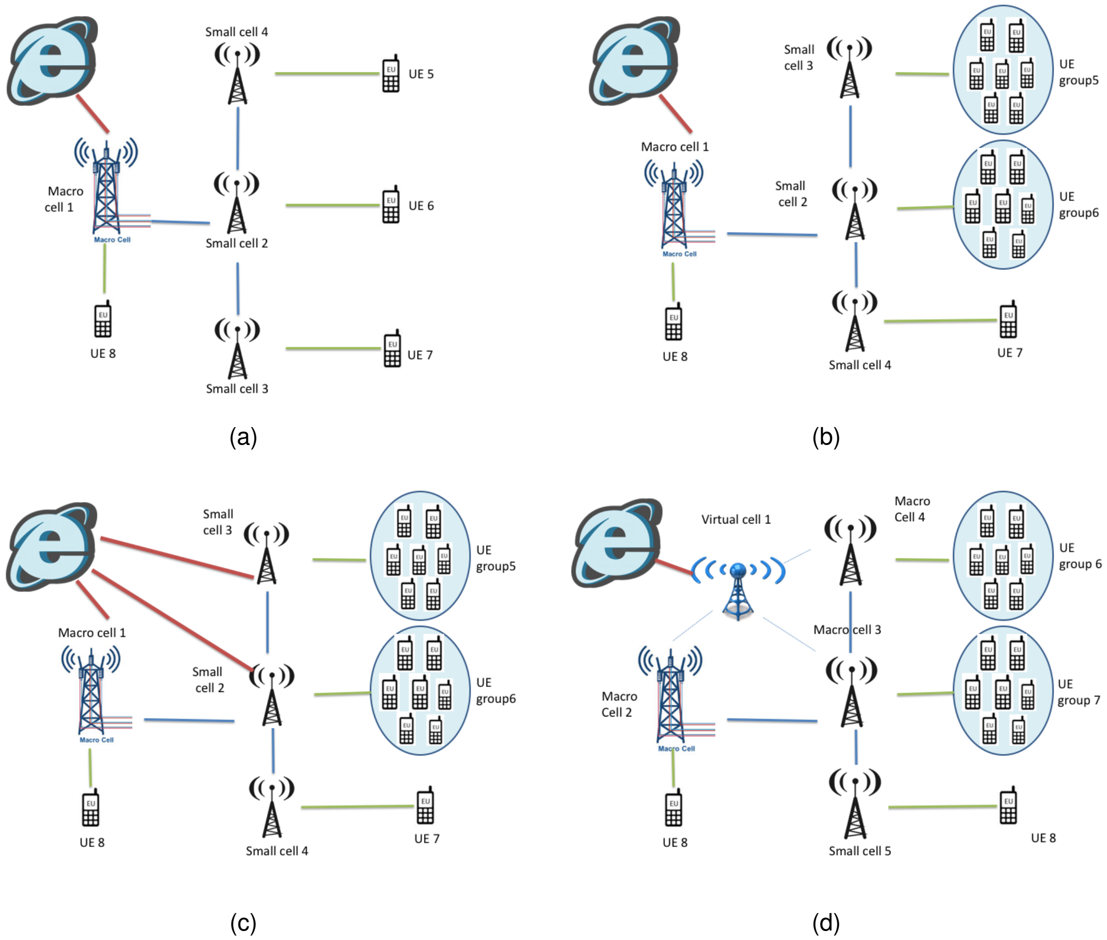


Figure 4.13: Model improvement

cells and some small cells. The function of $virtualnode$ is to visualize multi macro cells networks into one macro cell networks, so that the model can easily adopt it. With the help of $virtualnode$, the network can be regarded as one Internet source network.

An example of $virtualnode$ is shown in Fig 4.13. At the beginning, as shown In sub-figure (a), there is a 5G network with one macro cell, 3 small cells and 4 UEs. Each cell connects to one UE. Only the macro cell can connect to the Internet. In the sub-figure (b), with the increasing demands and more UEs, small cell 2 and small cell 3 are overloaded. It is urgent to promote the performance of those cells to provide better services. In sub-figure (c), small cell 2 and small cell 3 are allowed to have fixed connections with the Internet to support UE groups 5 and UE group 6. In sub-figure (d), to do the energy consumption optimization for our new scenario, a new parameter $virtualnode$ is used to connect macro cell 2, small cell 3 and small cell 4. From the view of this figure (d), it can be viewed as previous networks, which has only one cell connecting to the Internet. This way we do not need to create a new class of nodes (i.e., small cell with/without fixed internet access), but use the initial classification used in previous models (i.e., macro cell and small cells) and determine their possibility to connect to the internet through a fake link to the virtual node (i.e., very high capacity and no power consumption). Then the old model is capable for this new scenario. Some changes are needed for the model file and they are illustrated in subsection 4.5.2.

```
// Number of macro eNB
int NumMacro = ...;
range MacroEnb = 1..NumMacro;
// Number of small cells
int NumSmall = ...;
// Tot number of eNb
int NumEnb = NumMacro + NumSmall;
range Small = NumMacro+1..NumEnb;
range Enb = 1..NumEnb;
int NumUEs = ...;
// Total number of nodes (eNb + UE)
int NumNodes = NumEnb + NumUEs;
//range UEs = NumEnb+1..NumNodes;
range Nodes = 1..NumNodes;
```

Figure 4.14: Previous codes

4.5.2. Model improvement implementation

Model improvement implementation involves two kinds of modification. One is a new parameter added in data file. Another one is numbering system adjustment in model file. Parameter $virtualnode$ is an integer, and the value is either 0 or 1. Details are shown in Table 4.3

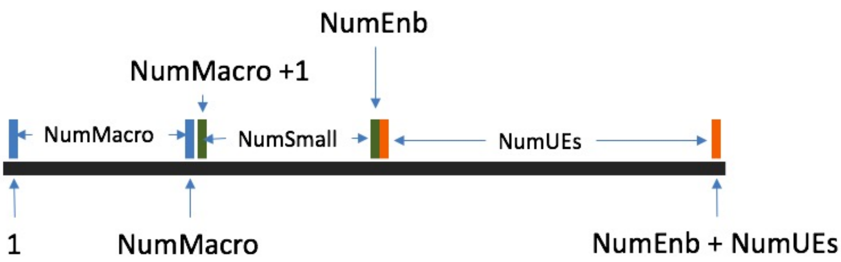


Figure 4.15: Previous numbering system

After adding the new parameter $virtualnode$ to the data file, it should be used in model file. In the original model, the relative parameters are $NumMacro$, $NumSmall$ and $NumUEs$. Although all those parameters remain the same as before, the ranges of all those nodes would be changed after the $virtualnode$ is added. Furthermore the most important parameter will be changed. The original codes of numbering system is shown in Fig 4.14.

The main change for new model is updating numbering system. The codes in Fig 4.14 can be described in a one-dimensional coordinate as shown in Fig 4.15. In the original numbering system, it starts from number 1, then followed by macro cells, so the numbers of macro cells is numbered secondly. After macro cell, small cells are numbered and it starts from $(NumMacro+1)$. The rest of them are UEs, they are numbered until $(NumEnb+NumUEs)$.

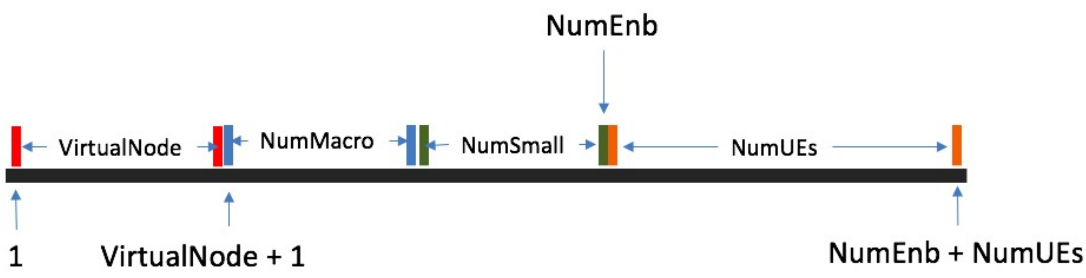


Figure 4.16: Numbering system with virtual node

```
// Number of virtual nodes
int NumVirtualNodes = ...;
// Number of macro eNB
int NumMacro = ...;
range MacroEnb = NumVirtualNodes+1..NumVirtualNodes+NumMacro;
// Number of small cells
int NumSmall = ...;
// Tot num of eNb (including the virtual node)
int NumEnb = NumVirtualNodes + NumMacro + NumSmall;
range Small = NumVirtualNodes+NumMacro+1..NumEnb;
// (including the virtual node)
range Enb = 1..NumEnb;
int NumUEs = ...;
// Total number of nodes (eNb + UE + virtual node)
int NumNodes = NumEnb + NumUEs;
//range UEs = NumEnb+1..NumNodes;
range Nodes = 1..NumNodes;
```

Figure 4.17: Virtual node codes

New numbering system is shown in Fig 4.16. It labels *virtualnode* first, then macro cells, small cells and UEs. The implementation of new numbering system is shown i Fig 4.17.

This chapter expresses details and implementation of energy consumption optimization model. Many use cases are used to show that how the CPLEX tool works. And all the parameters of the model are discussed. In the end, the model is improved to support new feature, which is supporting networks with multi macro cells.

CHAPTER 5. HEURISTIC ALGORITHM DESIGN AND IMPLEMENTATION

5.1. Heuristic algorithm design

Many optimization problems in various fields have been solved by using varied optimization algorithms. Traditional optimization techniques such as linear programming, non-linear programming, and dynamic programming have had major roles in solving these problems. However, their drawbacks generate demand for other types of algorithms, such as heuristic optimization approaches (simulated annealing, tabu search, and evolutionary algorithms) [22]. Still, there are some improvement possibilities for this 5G network energy consumption model.

Heuristic algorithm for fast 5G network energy consumption optimization is based on the model illustrated in chapter 4. It is improved for accelerating the computing speed for complex 5G network to save time. To better explain the heuristic algorithm, integer relaxation method would be introduced in advanced. Then the flow control of the heuristic algorithm will be expounded.

5.1.1. Integer relaxation method

In mathematics, the linear programming relaxation of a 0-1 integer program is the problem that arises by replacing the constraint that each variable must be 0 or 1 by a weaker constraint, that each variable belong to the interval [0,1].

That is, for each constraint of the form: $x_i \in \{0,1\}$, of the original integer program, one instead uses a pair of linear constraints, $0 \leq x_i \leq 1$.

The resulting relaxation is a linear program, hence the name. This relaxation technique transforms an NP-hard optimization problem (integer programming) into a related problem that is solvable in polynomial time (linear programming); the solution to the relaxed linear program can be used to gain information about the solution to the original integer program [21].

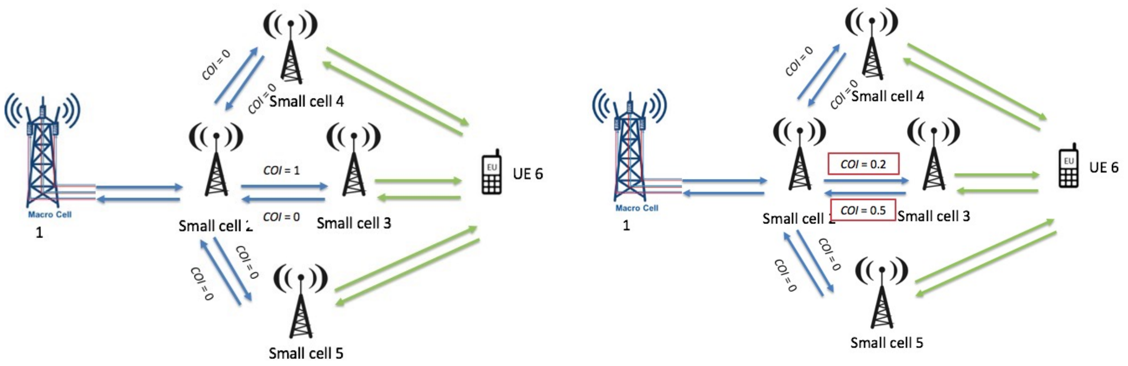
Integer relaxation method is a fundamental method in this heuristic algorithm. A relaxed model is generated on the strength of this method by relaxing 4 flow constraints, which are expressed in section 5.1.2.

5.1.2. Model constraint relaxation improvement

Model constraint relaxation improvement is to achieve the idea of section 5.1.1. To relax the model, some constraints would be changed in order to achieve heuristic procedures. Those changes mainly about route decision rules as they are the essential ways to optimize energy consumption. Four constraints are modified according to the characteristics of 5G network. In the four constraints introduced below, a new concept, $threshold$, is adopted to relax the model. The value of $threshold$ is not fixed. It is estimated according to the scale of the target networks and experiments.

Constraint 1: Path conservation intermediate

Path conservation intermediate constraint is a rule that could keep traffic balance between the middle cells, who are neither source cell nor sink cell, to ensure traffic route appropriately between them. In the model, the COI is 1 if this cell is activated and likewise. So the COIs of both directions should be the same. As shown in figure 5.1 (a), to support the demand of UE 6, the chosen route is through macro cell 1, small cell 2 and small cell 3. So COI of the directed link from small cell 2 to small cell 3 is 1. And COI of the directed link from small cell 3 to small cell 2 is 0. This means the BH link between small cell 2 and small cell 3 is used. And the rest COIs of BH links are 0 since they are not activated, like the BH links of small cell 2 and small cell 4.



(a) Integer (b) Float

Figure 5.1: Path conservation intermediate

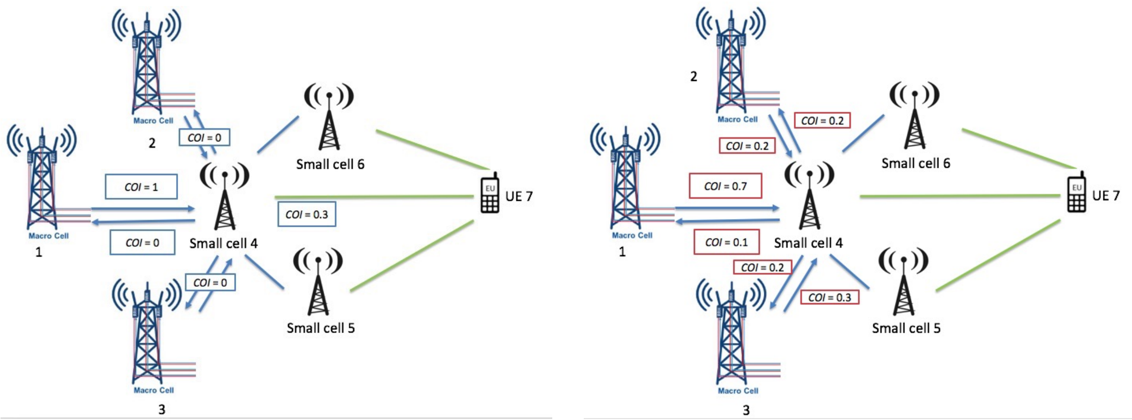
To relax the model and accelerate the computing speed, this constraint is improved by using floating value for COI. As shown in Fig 5.1 (b), the COIs of the directed link between small cell 2 and small cell 3 are 0.2 and 0.5. To acquire those values, the data type of COI is floating number instead of integer. Accurately, the difference between the two COIs of directed BH links should be less than $threhold$. Then COIs can be regulated. New version code is shown in Fig 5.2. In the grey circle, the unimproved codes are shown. It shows that the difference between two COIs of one BH link is enabled as 0 strictly. But in the green circle, the difference is more flexible than previous one as now the range is less than $threshold$ instead of 0.

```
subject to {
   Pathconservation_Intermediate:
   forall (u in User)
       forall (i in Nodes)
        if (i != u.source && i != u.sink)
          sum (<i,j,c, p, se> in Edges) x[<i,j,c, p, se>][u]
        - sum (<j,i,c, p, se> in Edges) x[<j,i,c, p, se>][u] == 0.0;

          sum (<i,j,c, p, se> in Edges) x[<i,j,c, p, se>][u]
        - sum (<j,i,c, p, se> in Edges) x[<j,i,c, p, se>][u] <= 0.0+THRES;
}
```

Figure 5.2: Code of constraint 1

Constraint 2: Path conservation for source

In a 5G network, usually there are many macro cells that each UE can connect directly or through many small cells to obtain Internet services. But only one macro cell can an UE connect for route. Path conservation for source constraint is designed for this purpose. As shown in Fig 5.3 (a), there is a 5G network with 3 macro cells, 3 small cells and 1 UE. The UE can connect to one of these three macro cells for route. In original version constraint, COIs of unused macro cells would be 0 in both directions. As to used macro cell, COI of a BH link directing to a small cell is 1. On the contrary, COI of the opposite direction is 0. An example of original version of constraint is shown in the Fig 5.3 (a). Unused macro cells are number 2 and 3, so the COIs are 0 on all directions. Macro cell 1 is activated, so the COI with the direction towards small cell 4 is 1. And COI on the opposite direction is 0.



(a) Integer (b) Float

Figure 5.3: Path conservation for source

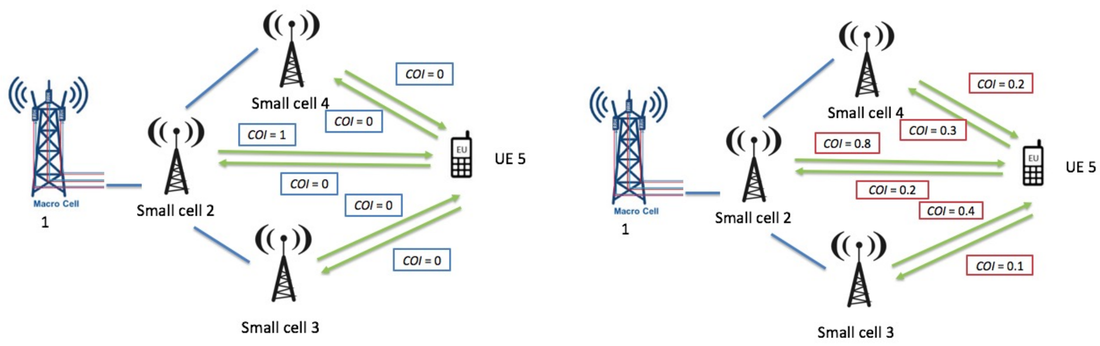
In Fig 5.3 (b), a relaxed path conservation source constraint is proposed. It is obvious that all COIs are floating numbers. To relax this constraint, the same $threshold$ is used as shown in Fig 5.4. Codes of old version is shown in the gray circle. For all users, the difference of COIs, which are for two directions of a chosen link, is 1. In the relaxed constraint, the difference is relaxed as a flexible range, which is less than $(1 - threshold)$.

```
subject to {
   Pathconservation_Source:
   forall (u in User)
     sum (<u.source,j,c, p, se> in Edges) x[<u.source,j,c, p, se>][u]
     - sum (<j,u.source,c, p, se> in Edges) x[<j,u.source,c, p, se>][u] == 1.0;

     sum (<u.source,j,c, p, se> in Edges) x[<u.source,j,c, p, se>][u]
     - sum (<j,u.source,c, p, se> in Edges) x[<j,u.source,c, p, se>][u] >= 1.0-THRES;
}
```

Figure 5.4: Code of constraint 2

Constraint 3: Path conservation for sink

Constraint 2 is for choosing only one of the optional macro cells for route. Then constraint 3, path conservation for sink, is for choosing a small cell as an access point that an UE can connect to. As shown in figure 5.5 (a), there are 1 macro cell, 3 small cells and 1 UE. According to the meaning of COI, it concludes that the chosen small cell is number 2 as the COI of the link, whose direction towards to UE 5, is 1. The COI of the link on opposite direction is 0. The rest small cells are not used, so all the COIs are 0.



(a) Integrate (b) Float

Figure 5.5: Path conservation for sink

The relaxed constraint is shown in Fig 5.5 (b), all the COIs are floating numbers instead of integers. With the same logic, all the COIs can be any floating number. But the difference between COIs of two directions of a AL link, which connects small cell and UE, is strictly maintained to be smaller than threshold. Codes are shown in 5.6, the difference is set to be smaller than $(1-threshod)$ as shown in green circle. And previous value is 1 as shown in gray circle.

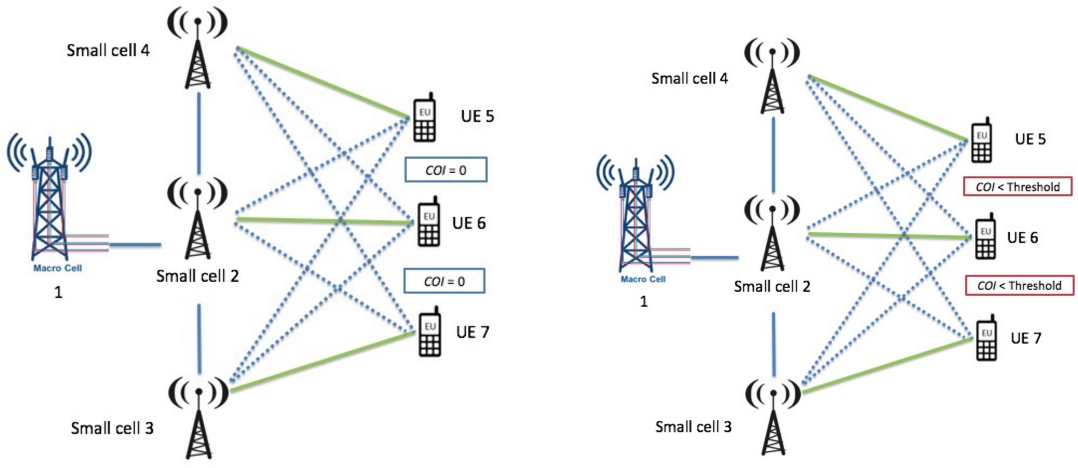
```
subject to {
    Pathconservation_Sink:
    forall (u in User)
      sum (<j,u.sink,c, p, se> in Edges) x[<j,u.sink,c, p, se>][u]
      - sum (<u.sink,j,c, p, se> in Edges) x[<u.sink,j,c, p, se>][u] == 1.0;

      sum (<j,u.sink,c, p, se> in Edges) x[<j,u.sink,c, p, se>][u]
      - sum (<u.sink,j,c, p, se> in Edges) x[<u.sink,j,c, p, se>][u] >= 1.0-THRES;
}
```

Figure 5.6: Code of constraint 3

Constraint 4: Only user can use access link:

This constraint is designed for ensuring that AL links can only be used by accessible UEs. Those accessible UEs are written and fixed in the data file under $ANlink$ keywords indicating the optional cells that UEs can connect to. For most UEs, they can not connect to all the cells, and usually they have limited options like three or four possible cells as candidate cells. So the COIs of the rest cells which are not in the list of $ANlink$, should be 0. As shown in Fig 5.7 (a), green lines between small cells and UEs represent candidate links and their COIs can be 1 if they are chosen as route links. The blue dotted lines represent that those links are not optional links wrote in the data file of the project under $ANlink$ parameter, and all COIs of them are 0.

The relaxation of this constraint is as similar as previous constraints 1 to 3, the unused links are allowed to be non-zero by having them smaller than $threshold$ as shown in Fig 5.8. In the gray circle, all the COIs of unmentioned links are set to be 0. They are allowed to be values in a flexible range as shown in green circle.



(a) Integrate (b) Float

Figure 5.7: Only user can use AN link

```
subject to {
  OnlyUserCanUseItsANLink:
  forall(u in User) forall(<i,j,b,p, se> in ANEdges)
     if (j != u.sink) x[<i, j, b, p, se>][u] == 0.0;

     if (j != u.sink) x[<i, j, b, p, se>][u] <= 0.0+THRES;
}
```

Figure 5.8: Code of constraint 4

5.1.3. Flow control of the algorithm

The idea of heuristic algorithm is diminishing the route options by striking out the impossible links or links with lower possibility to be used. In a word, their COIs are smaller than threshold. The flow control of this algorithm is shown in Fig 5.9. There are 6 steps in Fig 5.9 and the essential part is about how to make the threshold decision.

First of all, running the relaxed model with original data file is required to obtain values of the parameters illustrated in chapter 4. This step is executed in CPLEX studio. Then values of parameters like COI, SBH and so on, would be obtained . The most important indicator is parameter COI.

The next step is designing thresholds for our heuristic algorithm. This is very essential as it is the key part for accelerating optimizing speed. There are 2 types of threshold, one is for optimization model ($mThreshold$, in model file), another one is for making on-off decision ($dThreshold$, in flow control file). The $mThreshold$ is related with many constraints, which are explained in section 5.1.2. In this research, $mThreshold$ is 0.01 and $dThreshold$ is 0.001 for the networks mentioned. Those values are decided according to our tested experiments.

The $dThreshold$ would be compared with all the COIs of AL links to make on-off decision. Only the AL links with the COIs, which are greater than $dThreshold$, can be kept. As to BH links, normally BH links are used by many different UEs. Some BH links , who are

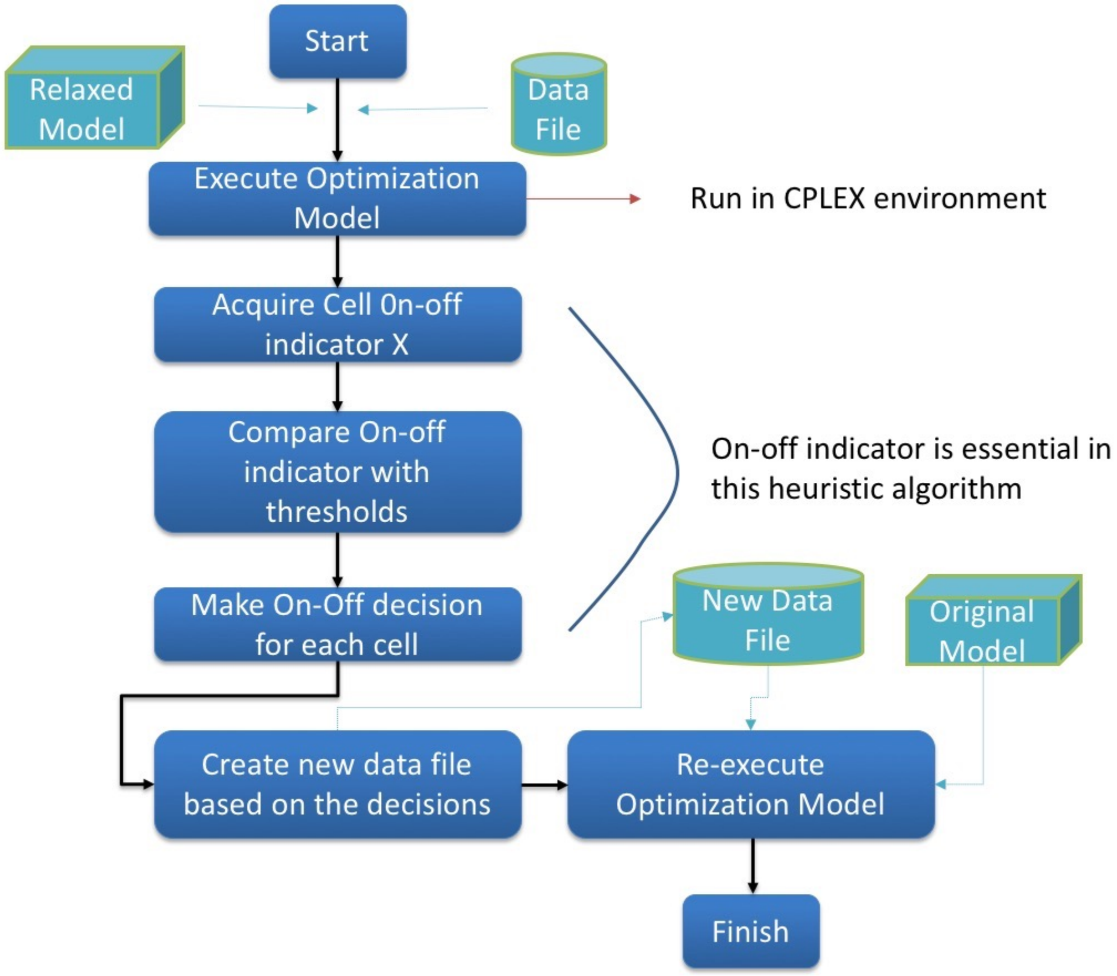


Figure 5.9: Flow chart of heuristic algorithm

impossible to be used by any cell, would be discarded. Each BH link has many COIs to show that who are this BH link serving for. Specifically, it means that a BH link would be deleted if the sum of its COIs are 0. On the contrary, if a BH link is used by at least one UE , then it will be saved in data file.

In the renew data step, the decided AL links and BH links, whose COIs are greater than threshold, would be saved into a new data file for re-executing in next step. That is, the new data file will have a subset of UE whose association needs to be solved, as other UEs have already been associated in the previous step of the relaxation algorithm. Also, a subset of BH and AL links appear in the new data file, as some of them have already been assigned or deleted in the previous step. Some other parameters would be also remained such as $NumVirtualNodes$, $NumMacro$ and so on. Re-executing is the final step of the flow control. CPLEX would run the original model (i.e., the exact one without integer relaxation) with the new data file and the final results would be shown when CPLEX is finished.

```
var source = new IloOplModelSource("new.mod");
var data =   new IloOplDataSource(datafile);
var cplex =  new IloCplex();
var def =  new IloOplModelDefinition(source);
var opl =  new IloOplModel(def,cplex);
opl.addDataSource(data);
opl.generate();
```

Figure 5.10: Flow control initiation

5.2. Heuristic algorithm implementation

To implement the heuristic algorithm, some operations are needed to control the flow of the model to execute the steps as shown in Fig 5.9. Flow control enables control over how models are instantiated and solved in CPLEX using IBM ILOG Script: (1) Solving several models with different data in sequence or iteratively; (2) Running multiple "solves" on the same base model, modifying data, constraints, or both; (3) Decomposing a model into smaller more manageable models, and solve these to arrive at a solution to the original model (model decomposition). A script is a sequence of commands. These commands could be of various types such as declarations, simple instructions or compound instructions. IBM ILOG Script is different from Optimization Programming Language (OPL) modeling language. IBM ILOG Script is an implementation of JavaScript, including extension classes for OPL using which Model elements can be accessed and modified in Flow Control. All IBM ILOG Script extension classes for OPL start with Ilo, (for example $IloOplModel$, $IloCplex$, $IloCP$) [23]

```
if (cplex.solve()) {
  ofile.write("BHEdges="{\n");
    for (var b in opl.BHEdges) {
        var temp = 0;
        for (var u in opl.User){
        temp = temp + opl.x[b][u];
        }
        if(temp == 0){
            writeln("Not used cell, will be discarded");
        }else{
            writeln("In use cell, save.")
            ofile.write(b);
            ofile.write("\n");
    }}}
```

Figure 5.11: BH link decision

Three parts of essential codes are displayed below. First part is about initializing flow control as shown in Fig 5.10. $IloOplModelSource$ is an instances of this class represent the input source for an OPL model; $IloOplDataSource$ represents a source from which an OPL model can read data; $IloCplex$ is the class used to create and solve a large variety of Mathematical Programming models; $IloOplModelDefinition$ is an instances of this class hold the internal representation of a model source; $IloOplModel$ is an instances of this class represent an OPL model. This class associates a model definition with data sources and an optimization engine. The method $generate()$ generates the problem and uses the optimization engine to extract it. It is the main purpose of an OPL model instance. It reads data, performs preprocessing, and creates the Concert $IloModel$ object to represent the resulting problem. The problem is then extracted using the associated engine.

```
for (var e in opl.ANEdges) {
    for(var u in opl.User){
        if(e.tonode == u.sink){
           writeln(e.fromnode,";", u.sink,";", opl.x[e][u]);
             if( opl.x[e][u]> dThreshold){
               writeln("row should be saved", e, u, opl.x[e][u]);
               ofile.write(e);
               ofile.write("\n");
}}}}
```

Figure 5.12: AN link decision

Second part displays the codes of making BH link decisions in Fig 5.11. It is necessary to check if a final solution is solved by CPLEX engine in the first step. Then it uses a loop to go through each BH link for checking the sum of associated COIs. If the sum is 0, then this BH link would be discarded as the BH link has very low possibility to be used. Likewise, if the sum is non-zero, then saving this BH link by writhing and storing it to the new data file.

The codes in Fig 5.12 are to make AL link on-off decision. Two loops are used to travel through all COIs. The parameter, $dThreshold$ is compared with all the COIs. The links, whose COIs are greater than $dThreshold$, would be saved. And rest of them are cancelled and deleted.

5.3. Scenario network validation

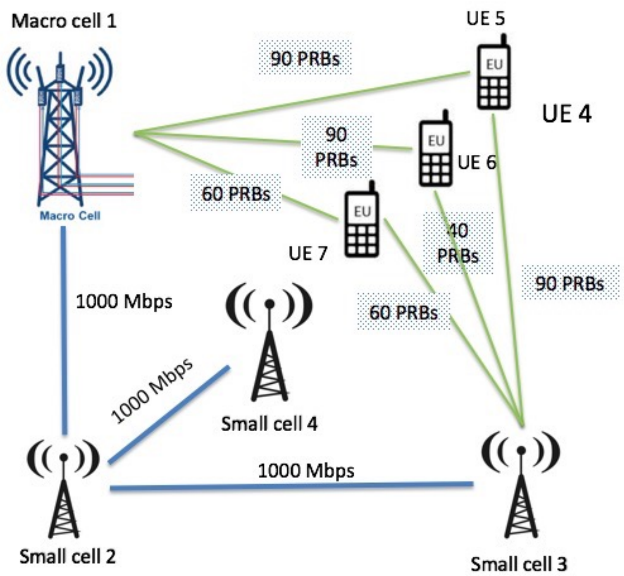
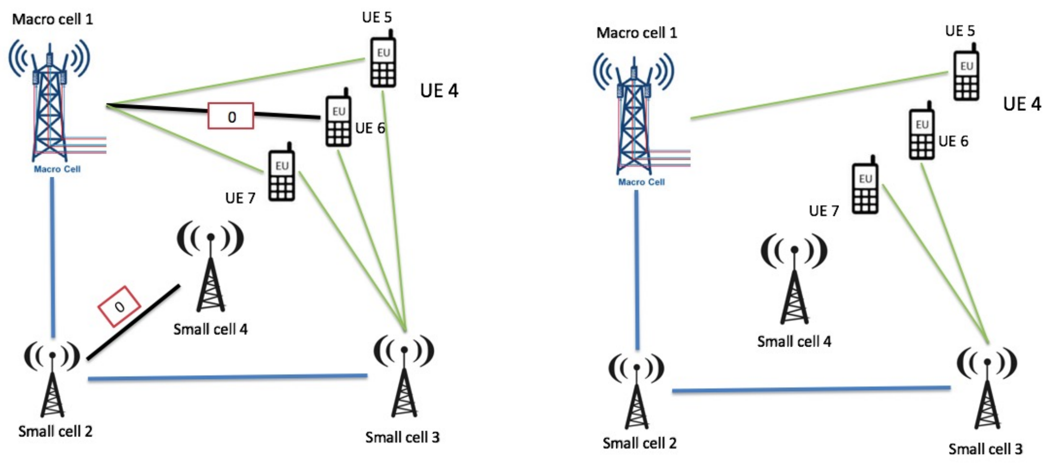


Figure 5.13: Validation scenario



(a) On-off decision (b) Solution

Figure 5.14: Scenario results

This section discusses about the whole processes of heuristic algorithm illustrated in section 5.2. The details of parameters are shown with some pictures.

Edges (size 9)		User (size 3)		
fromnode	tonode	source	sink	Value
1	2	1	5	0.528888888888889
1	2	1	6	0.98
1	2	1	7	0
2	3	1	5	0.538888888888889
2	3	1	6	0.99
2	3	1	7	0
2	4	1	5	0
2	4	1	6	0
2	4	1	7	0
1	5	1	5	0.451111111111111
1	5	1	6	0.01
1	5	1	7	0.01
1	6	1	5	0.01
1	6	1	6	0
1	6	1	7	0
1	7	1	5	0.01
1	7	1	6	0.01
1	7	1	7	0.99
3	5	1	5	0.548888888888889
3	5	1	6	0
3	5	1	7	0
3	6	1	5	0
3	6	1	6	1
3	6	1	7	0
3	7	1	5	0
3	7	1	6	0
3	7	1	7	0.01

Figure 5.15: Table of COI under relaxed model

A new 5G network is proposed for scenario network validation as shown in Fig 5.13. The network has 1 macro cell, 3 small cells and 3 UEs. The macro cell connects with 3 UEs and their PRB demands are 90, 90 and 60 correspondingly. The small cell 3 connects to the same UE as the macro cell but their PRB demands are 90,60 and 60. For BH links, the small cell 2 fully connects to the rest of cells with bite rate of $1000Mbps$.

To do the heuristic algorithm as shown in Fig 5.9, the first step is to execute the relaxed optimization model in CPLEX to obtain COIs etc. The table of COI is shown in the Fig 5.15.

Additionally the $mThreshold$ and $dThreshold$ are set as 0.001 and 0.0001 before running CPLEX. The picture displays a two-dimensional array. The array is consisted of $Edge$ and $User$. The $Edge$ is a collection of BH links and AL links. Those links are identified by $fromnode$ and $tonode$. The $User$ is a collection of UEs formed by $source$ and $sink$. The $source$ is fixed to be 1 because of only one macro cell. In the table, all COIs of the BH link between small cell 2 and small cell 4, are 0. According to the algorithm of backhaul decison, then this BH link would be discarded. It is emphasized by a red circle. And COI of an access link from macro cell 1 to UE 6 is 0, so it will be discarded too. The only access link, whose COI is 1, is the AL link between small cell 3 to UE 6. So UE 6 has pretty high probability to connect to small cell 3.

Edges (size 7)		User (size 3)		
fromnode	tonode	source	sink	Value
1	2	1	5	0
1	2	1	6	1
1	2	1	7	1
2	3	1	5	0
2	3	1	6	1
2	3	1	7	1
1	5	1	5	1
1	5	1	6	0
1	5	1	7	0
1	7	1	5	0
1	7	1	6	0
1	7	1	7	0
3	5	1	5	0
3	5	1	6	0
3	5	1	7	0
3	6	1	5	0
3	6	1	6	1
3	6	1	7	0
3	7	1	5	0
3	7	1	6	0
3	7	1	7	1

Figure 5.16: Table of COI under original model

The next step is to make on-off decision for each cell. According to the heuristic algorithm implementation, the on-off decisions made by the algorithm is shown in Fig 5.14 (a). It is noted that AL link between macro cell 1 and UE 6, is labelled with 0. And the BH link from small cell 2 to small cell 4 is also labelled with 0, which means the sum of their COIs is 0. As a conclusion, these two links are removed from the data file in CPLEX studio. Although some links with pretty high COI (like 0.99), it is not very sure to activate them at this step. The rest of links would be kept in a new data file for re-executing the model later.

After making the on-off decisions by the heuristic algorithm, a new data file would be exported. Then the next step is to re-execute the new data file with the unrelaxed model to obtain the final solution of energy consumption optimization. A new table of COI would be created by CPLEX again as shown in Fig 5.16. For UE 5, AL link from macro cell 1 to UE 5 is on. And the UE 5 does not need any BH link as it is connected to macro cell directly. For UE 6 and UE 7, they both connect to small cell 3. And two BH links from macro cell 1 to small cell 3 are used also.

The final solution of this scenario is shown in Fig 5.14 (b). The small cell 4 is totally shut down because it has not connection for any cell or UE. All UEs are connected to designed cells for Internet services. This scenario analysis fully validates the process of the heuristic algorithm and the performance of this heuristic algorithm will be discussed in next chapter.

CHAPTER 6. NUMERIC RESULT

To evaluate the performance of heuristic algorithm of energy consumption optimization in 5G network, some experiments are investigated to obtain essential data like running time (in second) and efficiency (in bits/joule). This chapter expresses the properties of used 5G networks and performance differences between optimal algorithm and heuristic algorithm.

6.1. Scenario 5G network

Table 6.1: Input parameters for six use cases

Name	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
NumUEs	10	20	30	40	50	60
BHEdges	36	36	36	36	36	36
ANEdges	84	168	251	335	420	505
Demand[Mbps]	3000	6000	9000	12000	15000	18000

The experiment is divided into 6 different use cases; for each use case, twenty different random realizations are provided, where possible connections for the UEs and the BH links vary. However, the parameters shown in Table 6.1 do not change throughout the twenty random realization. Also, the results presented in this chapter represent the statistics taken over the twenty random realization (i.e., average and standard deviation of given parameters such the energy efficiency or the execution time). And each group has 20 different networks. Networks in each group have the same amount of user equipment. The details are shown in Table 6.1. Those networks in the same group have different structures, but some characteristics remain the same. Each network has 1 macro cells and 16 small cells. The number of user equipment, access links and demands are different. The number of links increase as the number of user equipment increases. The original parameters for the input files have been provided through external simulations.

The purpose of those scenario networks is to investigate performance of the models when at different scales of user equipment to simulate the reality that 5G network usually need to support more and more UEs. The total demand is increasing when the number of UEs rises. Precisely, use equipment has different demands in each network, but the average demand of each UE keep constant and the average demand is 300Mbps per user.

More properties about the networks are shown in Table 6.2. The Table 6.2 is quoted from [20]. In our experiment, two data in Table 6.2 are changed as our models are different from the the models expressed in [20]. In our heuristic algorithm, the relaxed model and original model are executed to gain energy consumption optimization result. A new data file is created by relaxed model. In the new file, many BH links and access links of the network are discarded by relaxed model. So $p_0(w)$s of access link and BH link of small cells are 0 instead of 6.8 and 3.9 in our experiment. But $p_0(w)$s of access link of macro cell is 130 as there is only one macro cell in our networks and it will be used for Internet services.

Table 6.2: Properties of scenario networks

Parameter	**AL: eNB**	**AL:SC**	**BH link**
Frequency f(GHz)	2		73
Available BW (MHz)	200(100 PRBs)		500
N$_T RX$	8 (MIMO 8x8)		variable
p_0(W)	130	0	0
p_{max}(W)	39.8107	1	1.9953
Δ_p	4.7	4.0	variable
Path Loss	69.55+26.16 log$f$ - 13.82 log$h$ - C_H + (44.9 - 6.55 log_h)log($d_{iu(km)}$)		Eq. 6-11 in [2]
C_H	0.8+(1.1log$f$ - 0.7)h_{UE} - 1.56 log$f$	0	-
$h(m)$	25	2.5	-
	$h_{UE} = 1.5$		-
$NF(dB)$	9		6
G_{TX}, G_{RX} (dBi)	17	5	43

6.2. Performance comparison

The performance analysed is about two evaluation factors. One factor is energy efficiency (E_e), which is measured by $bit/joule$. Another one is Average time (T_{avg}), which is measured by second. The formulas are shown in Eq 6.1 and Eq 6.2.

In Eq 6.1 and Eq 6.2, $UserDemand_i$ is the user demand (in $Mbps$) of ith realization in the group, $Energy_i$ is energy consumption (in $watt$) of ith network, T_i is execution time of CPLEX studio. K is 20 because each group of experiments has 20 realizations.

$$E_e = \frac{\sum_{i\in k} UserDemand_i}{\sum_{i\in k} Energy_i} \qquad k \in [1:20] \tag{6.1}$$

$$T_{avg} = \frac{\sum_{i\in k} T_i}{K} \qquad k \in [1:20], \quad K = 20 \tag{6.2}$$

Standard deviation is used to quantify the amount of variation or dispersion of a set of data values. A low standard deviation indicates that the data points tend to be close to the mean (also called the expected value) of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values. Standard deviation of energy efficiency is calculated as $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_e^i - E_e^{avg})^2}$, where E_e^i is ith network's E_e and E_e^{avg} is that group's average E_e. Standard deviation of time, which is calculated as $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_i - T_{avg})^2}$, where T_i is ith network's running time and T_{avg} is that group's average running time.

As shown in Fig 6.1, X-axis labels the number of UEs that each group of network has. The numbers of UE is ranged from 10 to 60. Left side of Y-axis labels the E_e and standard

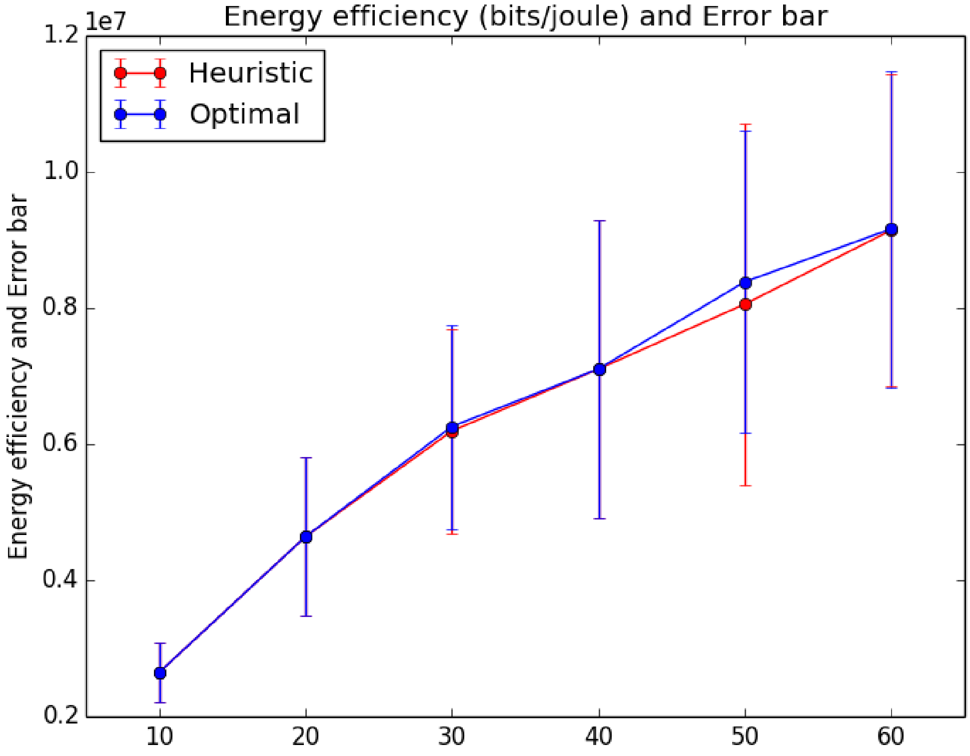


Figure 6.1: Energy efficiency

deviation. A solid red line is energy efficiency of heuristic algorithm and the red line closely next to it is energy efficiency of optimal algorithm.

In Fig 6.2, the left side of Y-axis labels the T_{avg} and standard deviation. The blue line is running time of optimal algorithm and red line is time consumption of heuristic algorithm.

Four conclusions are made based on those two figures:

(1) Comparing energy efficiency of heuristic algorithm and that of optimal algorithm, generally, the energy efficiency is more or less at the same level. In the case of 50 users, energy efficiency of heuristic algorithm is lower than that of optimal algorithm, but the difference is less than 4%. The reason behind this is that the eleventh network in this group costs almost 190% energy consumption higher than that of optimal algorithm. In the rest cases, energy consumption deviation between optimal solution and heuristic solution is less than 0.05%.

(2) As to time efficiency, in the case of 10 users, heuristic algorithm costs more time than optimal model. But with the increasing the number of user equipment, optimal algorithm costs more time than heuristic algorithm. In the case of 60 users, time efficiency of heuristic algorithm is 2.45 times faster than optimal algorithm.

(3) The explanation for the case of 10 users is that, in heuristic algorithm, it needs to generate a new data file, the execution for generating new file costs more time and it affects the time efficiency as total time costed is very little. But when it comes to big scale of networks, the costs of generating a new data file can be ignored as it makes little

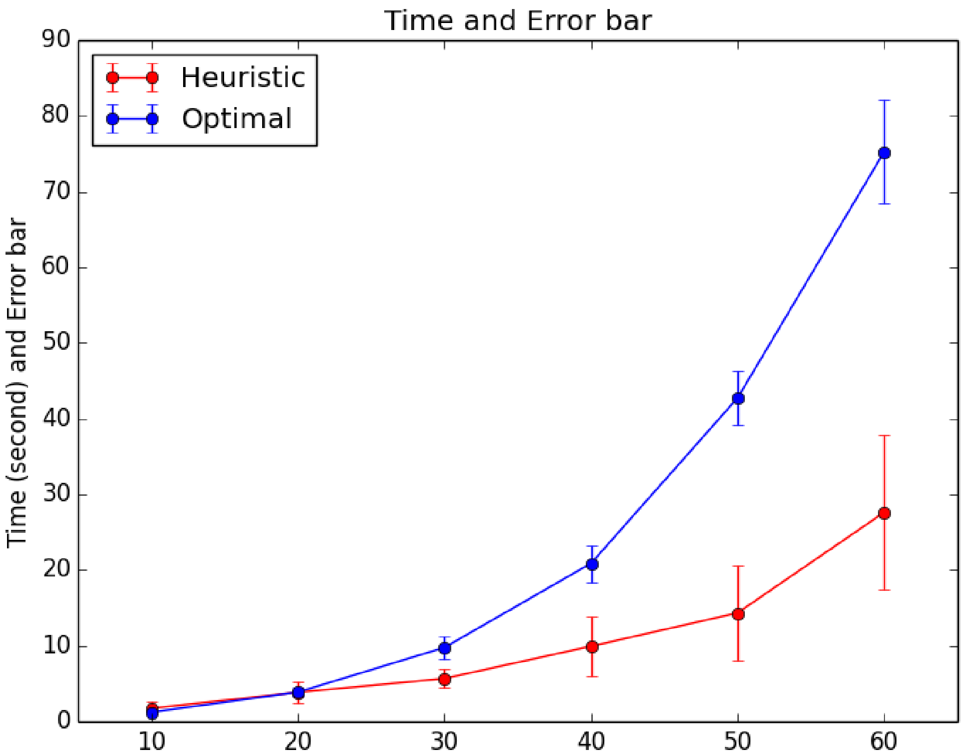


Figure 6.2: Time

influence to time efficiency.

(4) As to standard deviation of energy efficiency, both algorithms are at the same level except the case of 50 users, where the standard deviation of heuristic algorithm is 19.2% higher than that of original algorithm. This is a consequence of the 11th network, which has much higher energy consumption under heuristic algorithm. As to standard deviation of time, generally values of heuristic algorithm are higher than that of optimal algorithm. Only in the case of 30 users, heuristic value is lower than that of optimal solution. Overall, data of optimal algorithm are closer to mean value compared with heuristic algorithm's.

Deviation analysis of energy efficiency and time for both algorithms is shown in Fig 6.3. The green line is efficiency deviation, which is calculated as: $E_e^{D_i} = E_e^{O_i} - E_e^{H_i}$, where $E_e^{D_i}$ is deviation, $E_e^{H_i}$ is ith group's energy efficiency of heuristic algorithm, $E_e^{O_i}$ is ith group's energy efficiency of optimal algorithm, and $i \in \{10, 20, 30, 40, 50, 60\}$. And red line is time deviation, which is calculated as: $T_{avg}^{D_i} = T_{avg}^{O_i} - T_{avg}^{H_i}$,where $T_{avg}^{D_i}$ is time deviation, $T_{avg}^{O_i}$ is ith group's running time of heuristic algorithm and $T_{avg}^{O_i}$ is ith group's running time of optimal algorithm. It is more clear that time saving is increasing when the number of user equipment increases and the tendency is getting faster. In the case of 10 users, 20 users, 40 users and 60 users, their energy consumption is very close to optimal value.

A statistical data of small cell usage is shown in Fig 6.4. Each 5G network in experiments has 16 small cells, which is shown as a black link in the upper part of the figure. The red link is small cell usage of original algorithm and the blue link is for heuristic algorithm. In the case of 50 users, the optimal solution uses one more small cell than the heuristic

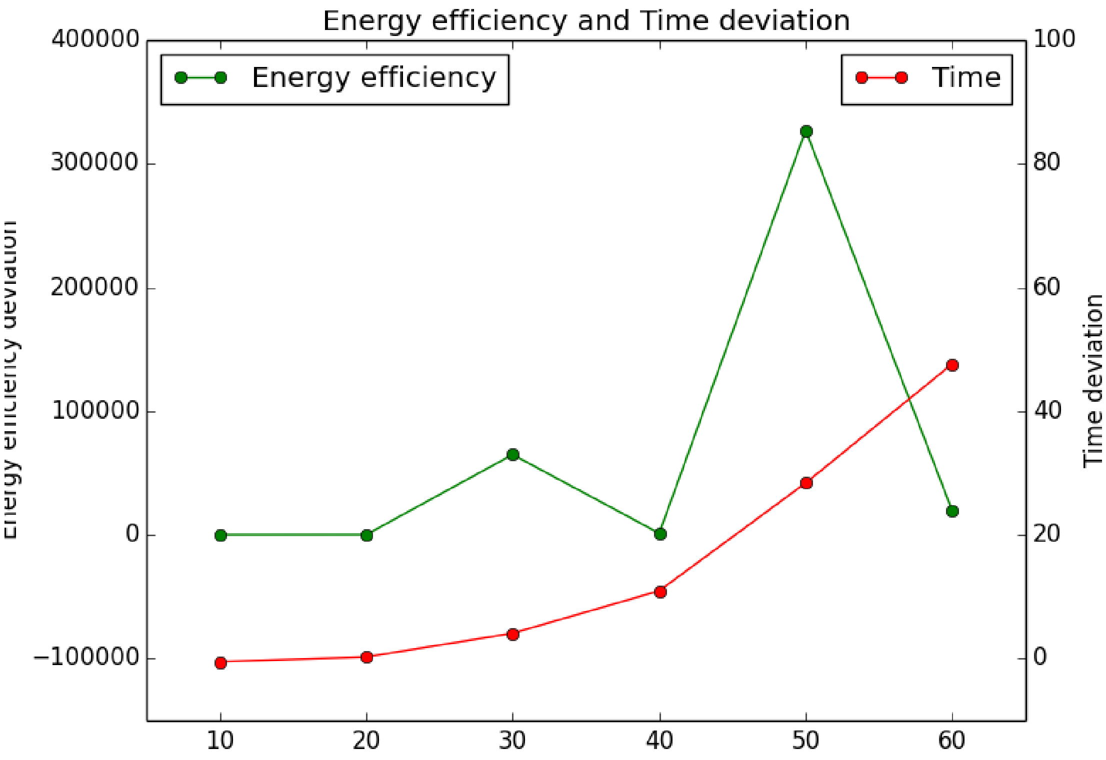


Figure 6.3: Deviation

solution, but the others' value are more or less at the same level. It means that the number of UEs makes huge influence on small cell usage. And more small cells would be used when the number of UEs increases. The heuristic algorithm makes little difference in small cell usage compared with original algorithm.

BH link usage is analysed in Fig 6.5. For all the networks, each of them has 36 BH links, which is shown as a dotted black link on the upper part of the figure. The green line with small circle is the number of BH links, which are from the new data file generated by relaxed model. Blue and red lines are BH link usage for heuristic algorithm and optimal algorithm. The cyan line with stars is elimination rate, which is calculated as:

$$Eli_{BHrate} = \frac{N_{BHtotal} - N_{BHrelaxed}}{N_{BHtotal}} \quad x \quad 100\% \tag{6.3}$$

where $N_{BHtotal}$ is the number of BH links in the original data file, $N_{BHrelaxed}$ is the number of BH links in the new data file generated by relaxed model. It shows that BH link usage for the two algorithm are approximately at the same level. In the heuristic algorithm, 75% of BH links could be eliminated by the relaxed model in the case of 10 users, but only 7% BH links are eliminated in the case of 60 users. So the relaxed mode can eliminate unnecessary BH links at different level according to the density of UEs. The elimination rate would be lower in high density network.

AL link usage results are shown in Fig 6.6. The total number of AL links is shown as a dotted black line with stars. The green line is the number of AL links in the new data file

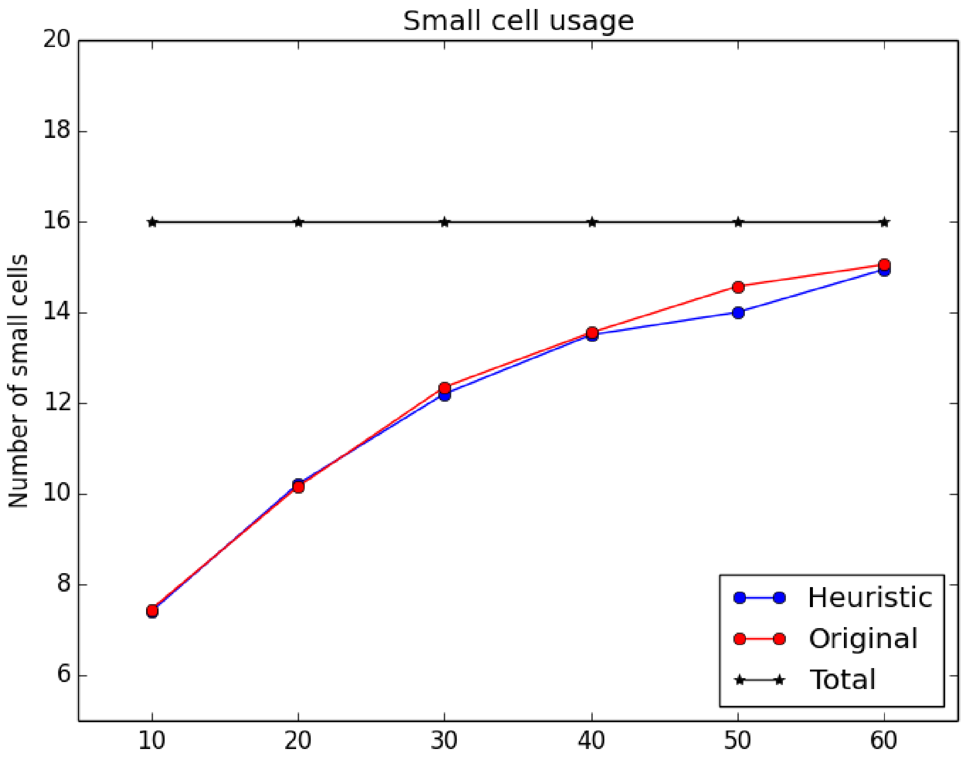


Figure 6.4: Small cell usage

generated by the relaxed model. The blue line shows the number of AL links used for the final solution, which equals to the number of user equipment in the network. The red line with stars is AL link elimination rate, which is calculated as:

$$Eli_{ANrate} = \frac{N_{ANtotal} - N_{ANrelaxed}}{N_{ANtotal}} \quad x \quad 100\% \tag{6.4}$$

where $N_{ANtotal}$ is total amount of AL links in original data file, $N_{ANrelaxed}$ is the number of AL links in the new data file. Comparing with BH link usage, it is very impressive that the relaxed model can eliminate much more AL links regardless of density differences of the networks. The elimination rate is decreasing while the number of user equipment increases. But in all the cases, the relaxed model can still eliminate higher than 60% of the total AL links in heuristic algorithm. It makes huge contributions for time efficiency.

6.3. Networks with more user equipment

This section shows some special results for the cases that the number of user equipment goes to equal or higher than 80. Experiment in this section has three groups and each group has 20 networks.

Table 6.3 shows the energy consumption and time for both algorithms. In the case of 80 users, energy efficiency of optimal algorithm is slightly higher than heuristic algorithm,

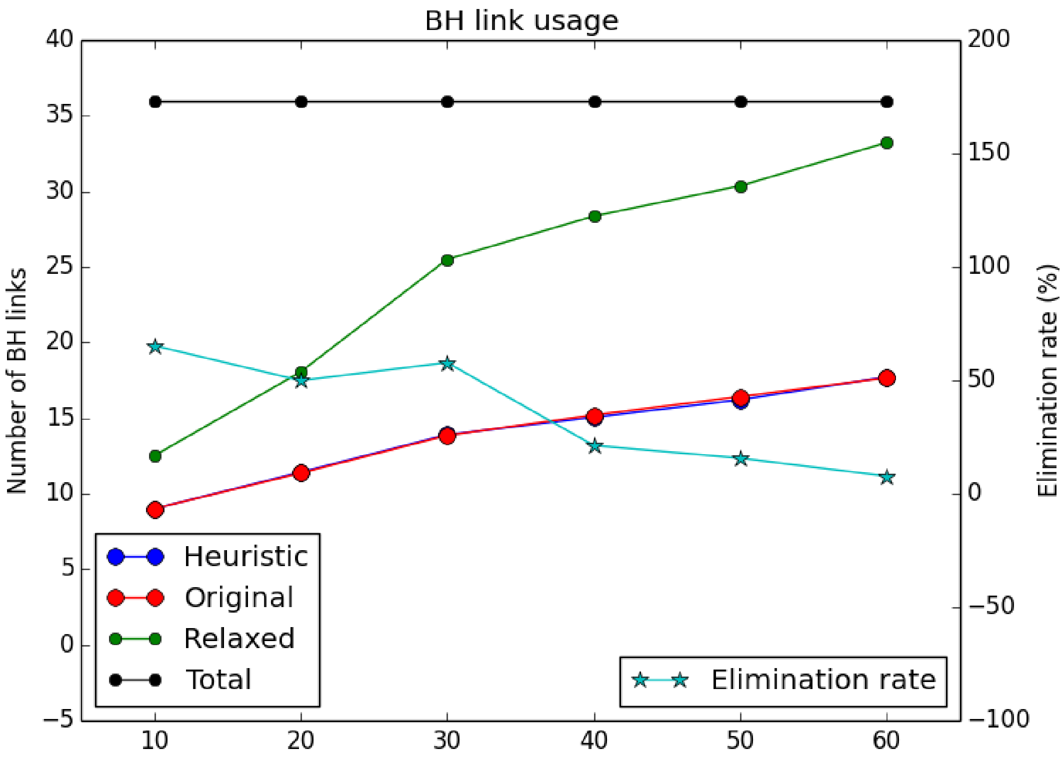


Figure 6.5: BH link usage

but it costs 743% times more on time. In the case of 100 users and 120 users, heuristic algorithm can easily figure out solutions for both of them, and the time consumption is less than 2 minutes. But the original algorithm can not generate any solution because of out-of-memory problems. CPLEX can not run optimal algorithm with huge networks.

Table 6.3: Energy efficiency and Time

Name	Heuristic		Original	
	Enegy (bit/joule)	Time (s)	Enegy (bit/joule)	Time (s)
80	7113957	30	7114334	223
100	8188341	56	-	-
120	9060879	118	-	-

Table 6.4 shows BH link and AL link usage. The elimination rate of BH link is still very low and elimination rate of AL link is high. Those are consistent with the conclusions in section 6.2. This section illustrates the special occasions, and it evident that the performance of heuristic algorithm outperform optimal algorithm as it can be used in large-scale networks, where optimal algorithm fails owing to out-of-memory problems.

In conclusion, our heuristic algorithm can make an energy consumption optimization solution whose energy efficiency is approximately close to the optimal algorithm. But our heuristic algorithm can make it many times faster than optimal algorithm from the view of time efficiency. Probably the main reason is that the relaxed mode can eliminate more than

Table 6.4: BH and AL usage

Name	BH link				AL link			
	Total	Relaxed	Used	Elimination rate	Total	Relaxed	Used	Elimination rate
80	36	35	16	2.8%	765	249	80	67.45%
100	36	33	17	5.56%	970	314	100	67.63%
120	36	35	18	2.8%	1155	378	120	67.53%

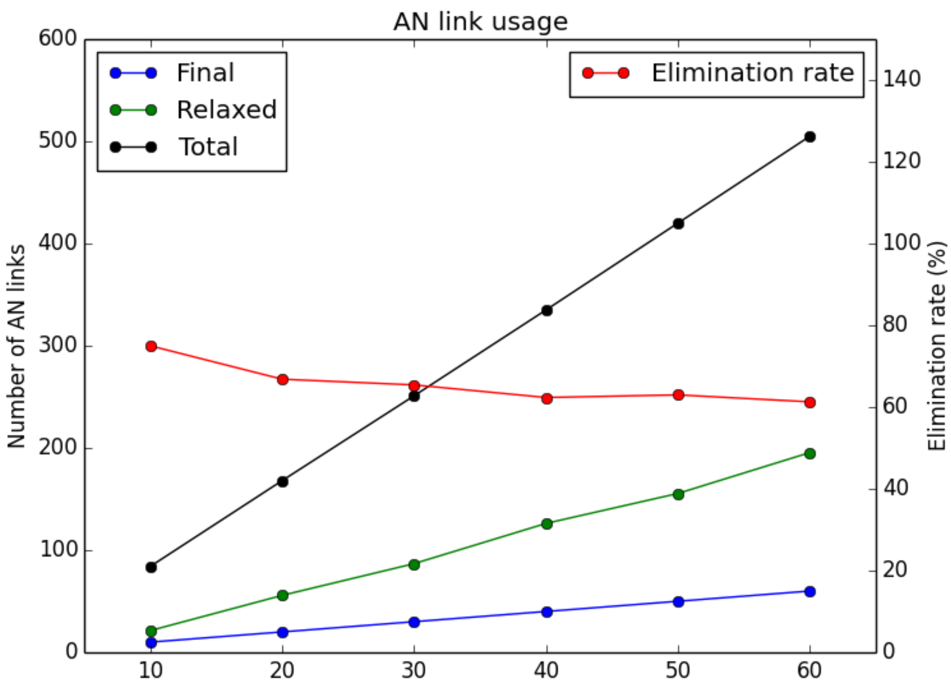


Figure 6.6: AL link usage

60% of AL links out of network. The advantage of time efficiency could bring our algorithm into industrial application.

CONCLUSIONS

Above chapters discussed the energy consumption model, heuristic algorithm and their performance. Now a brief review and conclusion about the work been done before is expressed in this chapter.

Reviews of the project

Based on a given MILP that solves the energy consumption optimization problem in a 5G network [2] [20], this research proposes a heuristic algorithm based on integer relaxation that accelerates the resolution of the MILP. The MILP in [2] needed to be updated according to PRBs rules as in [20]. Also, the scenario had to be adapted to bigger scenarios where more than one node may offer fixed connection to the internet. Then the $virtualnode$ concept is proposed to allow several cells (both macro and/or small cells) to connect to that virtual node through virtual links.

After the model is set up, a heuristic method is proposed to improve the model by reducing its running time. This method has 2 parts. The first part is to relax the model, so some important variables can be floating number instead of integer. This is achieved by modifying route constraints. The second part is to do flow control. In the end, some experiments are finished to evaluated the performance of the heuristic algorithm. The results show that the two models have approximately the same energy consumption but the heuristic model has variable time efficiency, which depends on the scale of network. Furthermore, the MILP cannot solve large scenario, while the heuristic algorithm does. Also, it is true that heuristic takes more time with large scenarios. In the end, our goals and objectives have been fully reached.

Problems occurred

The first problem is model relaxation. At the beginning, variable x is simply changed to floating number but not a constraint is changed. Then it did not work for our purpose that is to make COIs to be floating numbers between 0 and 1. Then the relationship between the constraints and COI is analysed. It approved that constraints are very essential for this purpose. Finally, all the constraints related are modified successfully.

The second problem is flow control. The flow control of CPLEX is IBM ILOG Script for OPL, which is an embedded JavaScript^{TM} implementation that provides the ”non-modeling” expressiveness of OPL. As such, it is compliant with the standard ECMA-262 [24]. Following the script, it is simple to launch models with targeted data, but it is not easy to modify the data file for next run, which is running optimal model with new data file. Updating the existing data file for re-executing the CPLEX with heuristic model was under consideration, but the obstacles were the lack of functions for deleting data in the original data file. So a feasible approach is to create a new data file and write the new data into this new file. And this method works very well in CPLEX studio.

The third problem is to decide the thresholds as generally the thresholds would be changed in different networks. Fortunately, after many tests, 0.01 and 0.001 are suitable values for almost all the tested scenarios.

The last problem is still under investigation as it has not been solved up to now. When the experiments were processing, heuristic method can not figure out solutions for some networks. 2 failures occurred in group 5 and 1 failure in group 6. Probably, the potential solution is to find new thresholds as the key BH links and AL links are removed after heuristic model in those failures. So the new threshold should be able to keep those essential BH links and AL links after heuristic algorithm.

Future work

As future work, the heuristic method has obtained notable improvement, but the issue that it fails some networks should be solved in the future. Another work is about energy consumption optimization. The energy savings can be improved more by other ways like switching-off both the base stations and backhaul links, which would enable to achieve further energy saving gains. The heuristic model has almost the same level of energy consumption compared with optimal model. So if the energy efficiency of original algorithm is improved, the heuristic algorithm would be improved also.

Sustainability considerations

Energy consumption is always the most important topic in the world. Many countries are focuses on this topic and trying many efforts to optimize energy efficiency in different ways. With the rising of 5G, as it will be widely deployed around the world in decades, energy consumption for 5G network is an urgent research topic recently. So in a long run, energy consumption in 5G network is still one of the most important topic. This research has huge sustainability as there are many aspects that can be improved to do more energy consumption optimization for more complex scenarios.

Ethical considerations

Energy consumption optimization for 5G network has been studied and investigated for many years. It brought huge economical and environmental benefits for our nations and society. This research is focuses on improving energy efficiency of 5G network and decreasing running time of the model. It improves user experience and 5G network performances, but it makes not negative affects on human beings as it interact with cells and user equipment directly. There is not ethical consideration should be worried about this research.

BIBLIOGRAPHY

[1] Control variable [online] *https://en.wikipedia.org/wiki/Control_variable* 4

[2] Enrica Zola, Andreas J. Kassler, Wooseong Kim*Joint User Association and Energy Aware Routing for Green Small Cell mmWave Backhaul Networks*. **Sustainable Green Networking and Computing in Wireless Communications and Networking Conference (WCNC), 2017 IEEE.** (IEEE) 3, 4, 7, 11, 13

[3] *Next Generation Mobile Network (NGMN) alliance 5G white paper*. **Computer Communications, 2015**(50), 5

[4] Boccardi F, Heath R W, Lozano A, et al.*Five disruptive technology directions for 5G*. **IEEE Communications Magazine, 2014, 52(2): 74-80** 5

[5] 5G: ISSUES & CHALLENGES [online] *https://www.arcep.fr/uploads/tx_gspublication/Report-5G-issues-challenges-march2017.pdf* 5

[6] Ward Van Heddeghem, Sofie Lambert, Bart Lannoo, Didier Colle, Mario Pickavet, Piet Demeester *Trends in worldwide ICT electricity consumption from 2007 to 2012*. **" February 2015**, 64–76. (ELSEVIER) ix, 6

[7] Mobile World Congress *5G Public Private Partnership 5G manifesto*. **" March 2015**, 6

[8] About the U.S. Electricity System and its Impact on the Environment [online] *https://www.epa.gov/energy/about-us-electricity-system-and-its-impact-environment* **2017** 6

[9] Fatma Ezzahra Salem†, Abdoulaye Tall, Zwi Altman and Azeddine Gati*Energy consumption optimization in 5G networks using multilevel beamforming and large scale antenna systems*. **IEEE Wireless Communications and Networking Conference (WCNC 2016)** 7

[10] Kantorovich Leonid. *Mathematics in Economics: Achievements, Difficulties, Perspectives* **Mathematical Programming, 1976, 11(1): 204-211.** 7

[11] Eeva Lähetkangas, Kari Pajukoski, Jaakko Vihriälä, Gilberto Berardinelli, Mads Lauridsen, Esa Tiirola, Preben Mogensen*Achieving low latency and energy consumption by 5G TDD mode optimization*. **ICC'14 - W8: Workshop on 5G Technologies**, (IEEE) 7

[12] Xumin Huang, Rong Yu, Jiawen Kang, Yue Gao, Sabita Maharjan, Stein Gjessing, and Yan Zhang*Software Defined Energy Harvesting Networking for 5G Green Communications*. **Sustainable Green Networking and Computing in 5G Systems: Technology, Economics, and Deployment**, IEEE Wireless Communications (Volume: 24, Issue: 4, 2017). (IEEE) 7

[13] Yi-Feng Hung and Robert C. Leachman *A Production Planning Methodology for Semiconductor Manufacturing Based on Iterative Simulation and Linear Programming Calculations* . **"May 1996**, VOL. 9. (IEEE transactions on semiconductor manufacturing) 8

[14] ADMB [online] *https://en.wikipedia.org/wiki/ADMB*. 9

[15] CPLEX [online] *https://en.wikipedia.org/wiki/CPLEX*. 4, 10, 17

[16] Heuristic (computer science) [online] *https://en.wikipedia.org/wiki/Heuristic_(computer_science)*. 10

[17] Lin S, Kernighan B W *An effective heuristic algorithm for the travelingsalesman problem[J]*. " **1973**, 21(2): 498-516(Operations research) 11

[18] Heuristic analysis [online] *https://en.wikipedia.org/wiki/Heuristic_analysis*. 11

[19] heuristic evaluation [online] *https://en.wikipedia.org/wiki/Heuristic_evaluation*. 11

[20] Agapi Mesodiakaki, Enrica Zola, Andreas Kassler*Joint User Association and Backhaul Routing for Green 5G Mesh Millimeter Wave Backhaul Networks*. **ACM MSWiM '17 , 2017 IEEE.** 3, 11, 37

[21] Linear programming relaxation [online] *https://en.wikipedia.org/wiki/Linear_programming_relaxation*. 27

[22] Geem Z W, Kim J H, Loganathan G V *A new heuristic optimization algorithm: harmony search[J]*. " **2001**, 76(2): 6068. (Simulation) 27

[23] Examples of Flow Control in OPL [online] *http://www-01.ibm.com/support/docview.wss?uid=swg27039529&aid=1*. 33

[24] IBM ILOG Script Extension Classes for OPL - General Presentation [online] *https://www.ibm.com/support/knowledgecenter/en/SS6MYV_3.3.0/ilog.odms.ide.odme.-help/html/refjsopl/html/intro.html?pos=2*. 45