Thesis submitted to the University of Sheffield for the degree of
Doctor of Philosophy

Energy-Efficient Base Station Activating/Sleeping Strategies for Two-tier Heterogeneous Networks

by

Zaid Mujaiyid Putra Bin Ahmad Baidowi

Department of Electronic and Electrical Engineering
The University of Sheffield
United Kingdom

February 2021

I want to dedicate this thesis to my beloved late father, my precious mother, my dearest wife, and my pretty and handsome children for their constant support, sacrifice, encouragement, patience and prayer especially during these challenging times of completing this thesis.

Abstract

In wireless communications, maximising the energy efficiency of a heterogeneous cellular network has attracted a lot of attention from researchers as it is required to guarantee the quality of service (QoS). We note that the probabilities of activating base stations (BSs) in conjunction with BS sleeping strategies, partial spectrum reuse (PSR), and bias factors in adjusting the power consumption of BSs have not been extensively studied in maximising the network energy efficiency. Besides, mobile users' mobility may lead to an unbalanced distribution of traffic load among BSs, which will affect the energy efficiency of the network. To address the above research gap, the main objective of this thesis is to propose solutions to maximising the energy efficiency of a two-tier network while considering BS activation probabilities, BS sleeping strategies, PSR, BS bias factors, and user mobility. The first contribution is to maximise the network energy efficiency through joint optimisation of the activation probability of small cell base station (small BS), the activation probability of macrocell base station (macro BS) and the PSR factor. The simulation results show that a higher activation probability of small BSs and a higher PSR factor leads to the network's higher energy efficiency, where the inter-tier interference is mitigated by applying PSR. The second contribution is to maximise the network energy efficiency by jointly optimising the spatial density of active BSs and the user-cell association indicators. Hence, a Switching Off Decision and User Association (SODUA) algorithm is proposed for a Control-Data Separation Architecture (CDSA) where it allows the macro BS to control the small BSs to be switched on or off. The simulation results show that for a given service area, there is an optimal number of active small BSs maximising the network energy efficiency, but the energy efficiency cannot be further improved by switching off more small BSs than a certain number. The third contribution considers four modes of small BSs: On, Standby, Sleep, and Off, where a different bias factor is associated with each mode, CDSA is considered for the macro BS to determine the mode of each small BS, and the macro BS is always in the On mode and is associated with the corresponding bias factor without having the four modes since it is always in active mode to control the network. A Genetic Algorithm based Power Mode Variant Selection (PMVS) algorithm is proposed to maximise the network energy efficiency by jointly optimising the bias factors of all BSs. The simulation results reveal that the proposed Genetic Algorithm based PMVS algorithm improves the two-tier network's energy efficiency as compared with the SODUA algorithm.

Acknowledgements

I would like to express my endless gratitude to those who helped me while pursuing my study at this prestigious university. Their commitment and support made this thesis completed.

First and foremost, I would like to express my sincere appreciation to my supervisor, Professor Xiaoli Chu, for the continuous guidance, encouragement and immense knowledge throughout my study, especially during my darkest days.

I would also like to extend a million thanks to Universiti Teknologi MARA and the Ministry of Education Malaysia for the scholarship. Without their unwavering support, I would not stand a chance to pursue my study at this university.

Finally, to those who helped me directly or indirectly, my friends and colleagues in the laboratory for the stimulating discussions, who morally support me whenever I feel demotivated, I am forever grateful to all of you.

Table of Contents

List of Figures

List of Tables

Acronyms

BSs	Base Stations
QoS	Quality of Service
PSR	Partial Spectrum Reuse
CDSA	Control-Data Separation Architecture
SINR	Signal-to-noise-plus-interference Ratio
SIR	Signal-to-interference Ratio
PPP	Poisson Point Process
PMVS	Power Mode Variant Selection
USR	Universal Spectrum Reuse
RSS	Received Signal Strength
LSA	License-shared Access
LAA	License-assisted Access
LTE	Long Term Evolution
3G	Third Generation
WiFi	Wireless Fidelity
MNOs	Mobile Network Operators
CRE	Cell Range Expansion
RSRP	Received Signal Received Power
SODUA	Switching Off Decision and User Association
MU	macro BS's mobile user
SU	small BS's mobile user
MIRP	maximum instantaneous received power
MARP	maximum average received power
RSRP	received signal received power
CP	control plane
DP	data plane
CBSs	control BSs
DBSs	data BSs
RAN	radio access network
C-RAN	cloud-radio access network

F-RAN	fog-radio access network
DC	Direct Current
MIMO	Multiple-Input Multiple-Output

Chapter 1

Introduction

This chapter presents an overview of the research topic that begins with Section 1.1 where the background and the motivation of the research are highlighted. Section 1.2 describes the problem statement in detail that produces the main research objectives, which are then explained in Section 1.3. Next, Section 1.4 describes the thesis contributions and the strategies used in each objective. Besides, this section lists the works that is planned to submit, were presented and published in several events. Finally, to help the readers to get a better understanding, the thesis organisation is described in Section 1.5.

1.1 Research Background and Motivation

It is a fact that the number of wireless cellular communications users is proliferating worldwide [1]. The deployment of small cell Base Stations (BSs) in macrocell networks helps the power consumption of the macro BSs to be effectively used and managed especially during communications between BSs and mobile users [2]. It is due to the small BSs consume less power and less cost of deployment [3] compared to the macro BS. Deploying small BSs in a macro cell network also helps in extending coverage of the macrocell network. In other words, the small BSs can help to boost signals propagation over the communication channel within macrocells' coverage. As a result, the macrocell network has better and wider coverage as one of the characteristics of the small BS to improve the capacity of the macrocell networks [4]. However, uncoordinated deployment and improper planning of small BSs in macrocell networks cause heavy traffic in the network [4], intracell interference [5], energy inefficiency [6], and high operational cost [1]. Therefore, the existence of the small BSs in macrocell networks needs attention for improvements such as interference management and spectrum sharing to defeat various challenges as suggested by the authors in [7]. Hence, one of the strategies that is considered in this thesis is spectrum sharing. This will be discussed further in Chapter 2.

To ease the reader to understand the function of small BSs, the explanation as follows. In this thesis, only a single cell association is considered where a mobile user can only be associated with a macro BS at one time even though there are many other macro BSs in the network. Therefore, when a mobile user moves from one place to another, there is no guarantee that the mobile user receives the same Quality of Service (QoS) from the same macro BS due to loss of signal during signal transmission. This leads to the deployment of small BSs that helps in extending the macro BS's coverage area. The combination of the BSs that have various ranges of transmit power is called a heterogeneous network.

A heterogeneous network is composed of macrocells and small cells. A macrocell is a macro BS's coverage, while a small cell is a small BS's coverage. A macrocell is the largest cell that can cover a large area about 30 km in radius. However, a small cell covers a smaller area as compared to the macrocell depending on the category. There are several categories of a small cell such as microcell, picocell and femtocell. The largest small cell is microcell [8] which is, usually deployed in street environment [9]. The medium [10] category of small cell BS is picocell that is, usually, deployed by service providers in a building to cover high-density user area or also known as hotspot area [11]. The smallest category is femtocell where it is designed to be used at home with easy installation [3]. The most interesting about this femtocell is that the power consumption is the lowest [10] as compared to the other two categories. The category of cells can be summarised in Table 1.1.

From a mobile user's perspective, the connection to applications or services offered by the BSs currently serving the mobile user must be continuous. Any interruptions to an application or a service, such as delays or sudden termination of the service, must be managed wisely to minimise the impact. Therefore, studies on service continuity [12, 13]

Table 1.1: The category of cells

Type of BS	**Category**	**Deployment Location**	**Description**
Femto	Small cell (smallest cell)	Personal and individual BS	Low powered. A few meters (in diameter). User installed. Indoor (Home office).
Pico	Small cell (medium cell)	Operator in high user density area (e.g. hotspot)	Support up to 100 users. Coverage less than 250 yards (228 meter). Indoor within a building (eg an office floor or retail space).
Micro	Small cell (largest cell)	Street environment	Coverage less than 1.5 km (in diameter). Uses power control to limit the radius. Can be temporarily installed to cater high traffic during an event. Can be permanently installed to cater mobile cellular users.
Macro	Macro cell	Fixed by the telecommunication company	A tower that is used to cover about 30 km.

have been extensively carried out. The solution for the service continuity is that to deploy small BSs because they can help in extending macro BSs' coverage [14]. Consequently, mobile users can be covered and get connected everywhere. This situation helps to extend macro BSs and improve energy efficiency [15].

Energy efficiency has been widely studied in the wireless communications area. Various techniques were applied previously to improve the whole network's energy efficiency, either in a homogeneous network or a heterogeneous network [6, 16]. For instance, allocating both transmit power to small BSs and bandwidth for backhauling [14], using the unlicensed band in License-assisted Access (LAA) [17], and optimising both discrete power and resource block allocation [18].

However, energy efficiency in a heterogeneous network has not been sufficiently studied, especially to improve energy efficiency that considers probabilities of activating BSs with BS sleeping strategies in Partial Spectrum Reuse (PSR) [19]. The power consumption can be reduced by sending BSs into sleep mode. Besides, applying a probability of activating BS can help us calculate estimated power consumption and finally, calculate the energy efficiency of the whole network. Moreover, by applying PSR, it will help to mitigate inter-tier interference that leads to a higher energy efficiency.

The existence of small cells in a heterogeneous network helps in minimising power consumption because the small BSs are low-powered radio communications' equipment. Nevertheless, due to mobile users' mobility, some of the small BSs are lightly loaded and still consume some amount of energy. In fact, the small BSs cannot be turned off to avoid coverage holes and to guarantee network coverage at all times at all locations in the network. To solve this problem, a separation architecture or known as a Control-Data Separation Architecture (CDSA) was proposed where the small BSs could be switched off when necessary by the macro BS [20]. In this thesis, the terms separation architecture and CDSA are used interchangeably. Hence, the separation architecture helps in controlling the network activities especially sending small BSs either to sleeping mode, off mode, or just leave them on. The separation architecture splits the tasks between the macro BS and the small BSs logically, where a macro BS controls the signalling tasks. In contrast, the small BSs serve the data transmission. The task segregation between the two types of BS helps to release their burden with other unrelated tasks.

Nonetheless, there is something that can be contributed to maximising energy efficiency in separation architecture. For instance, finding an optimal density of active small BSs with switching off strategy can help in improving energy efficiency. In fact, by having an optimal density of active small BSs, a density of small BSs active or a number of small BSs active to be added into the network can be limited. This is to ensure that the network is not overloaded with unnecessary small BSs.

Typically, mobile users tend to associate with macro BSs due to the high transmit power signal of a macro BS as compared to the small BSs [21, 22]. By employing a bias factor at the small BSs, the received signal at the mobile users could be increased, which would help the small BSs be selected for the user-cell association. However, according to [23], a bias factor can be used for power saving by adjusting the bias factor at the power amplifier. In the previous works, a bias factor was used to adjust certain values such as to increase an average throughput [24], to maximise a number of mobile users [25], and to reduce a number of amplifier measurements [26]. Therefore, a bias factor used for adjusting the power consumption of a BS can be used to maximise the energy efficiency of a heterogeneous network. To the best of our knowledge, less work was carried out recently in adjusting power consumption by having the bias factor for maximising energy efficiency in a separation architecture with BS sleeping strategy.

1.2 Problem Statement

From the previous section, it is clearly mentioned that implementing PSR with sleeping BS strategies could help in minimising the power consumption of the whole network. Nonetheless, less work was carried out to measure the energy efficiency performance of the whole network. Besides that, implementing a BS sleeping strategy in a separation architecture would improve the whole network's energy efficiency. However, the current studies suffer from several weaknesses in providing a higher energy efficiency that considers certain constraints highlighted later in this section. Therefore, this section accentuates the problems to be investigated based on the above motivation section.

BS sleeping strategy is the most popular strategy that is used with various techniques and algorithms among researchers in this area. One of the recent studies applied sleeping strategies to minimise the BSs' power consumption in a heterogenous network [27]. In contrast, another study applied two types of sleeping strategies (random and strategic) on macro BSs only to maximise the energy efficiency in a homogeneous network which was also known as a one-tier network [6]. However, the authors deployed femtocells in the macrocell network coverage area, not for the purpose of maximising the energy efficiency but providing better coverage. To the best of our knowledge, less work has been carried out in maximising the energy efficiency of a two-tier network that considering probabilities of activating BSs with BS sleeping strategies in PSR environment. Therefore, this thesis investigates how energy efficiency of a two-tier network can be improved.

PSR is one of the inter-tier interference mitigation strategies that has not been sufficiently studied especially for maximising energy efficiency. A study that carried out by [28] determined which type of BSs was preferable to be deployed either to add more micro BSs or to switch off more macro BSs in order to maintain the energy cost of the whole network. These options were based on the micro BS energy cost minimisation calculation. If it were below the predetermined threshold value, the first option would be selected. Otherwise, the second option would be chosen. This study's drawback was that the micro BSs density would need to have remained constant if the second option was selected. It means that no more micro BSs could be added. Supposedly, in mobile communications dealing with mobile users with additional small BSs especially femtocell, a study that considers ad-hoc femtocell is necessary. The study did not consider BS sleeping mode if there were more small BSs deployed out of sudden.

This has been further studied by [27] where PSR with BS sleeping strategy was proposed to solve the problem of minimising total energy cost. An active probability ratio was used together with the optimal PSR factor in solving the problem. This work also considered closed-access strategy and interference-limited environment to achieve minimum energy consumption. Similarly, the work in [29] applied PSR that focused on total energy cost, too, where the whole delay experienced by the users and the total energy cost was minimised. In that case, the delay happened when the mobile users did not get any transmission signal and thus, retransmission was needed. In short, the abovementioned studies did not consider maximising energy efficiency except minimising energy cost.

Due to mobile users's mobility, many small BSs are lightly loaded which means a small BS serves a few mobile users. Nevertheless, small BSs still consume some amount of power. Therefore, in the previous works, the BS sleeping strategy was proposed, to minimise the power consumption by sending certain BSs to sleep mode based on some criteria. This strategy led to coverage holes where the coverage of the network was not guaranteed. Consequently, some users could not be associated with any small BSs due to the coverage holes. Thus, a separation architecture, or CDSA consists of a macro BS and several small BSs were proposed to solve the problem. In this architecture, the macro BS controls the whole network activities including controlling the small BSs that under its coverage [20]. This also helps to split between control signalling and data transmission where the macro

BS controls the whole network activities including the small BSs. Nevertheless, the small BSs provide flexible data transmission due to uncertainty of traffic load, the distance to the small BSs and the Signal-to-noise-plus-interference Ratio (SINR). Consequently, by applying CDSA, the small BSs can be switched off when necessary without affecting the coverage holes because the macro BS will take over the data transmission jobs when there is no active small BS in that particular area. This helps to save energy and lead toward maximum energy efficiency.

Normally, CDSA is applied together with BS sleeping strategy where a macro BS controls the small BSs and instructs the small BSs to go into sleep mode [30]. Thus, this would help the power consumption of the network to be reduced. In the previous works, the macro BSs sent the small BSs to sleep mode [31,32] if the number of mobile users was less than the predetermined threshold value. According to [33], sleeping mode consumes 10% of the power consumption but switching off mode, consumes none. Therefore, a study that applies a CDSA and considers switching off strategy is necessary to be carried out to investigate the whole network energy efficiency performance.

However, the downside of switching off BSs is, the wake-up time is longer than the sleeping BSs when needed [34]. Hence, it is indeed better to consider various sleeping modes of a BS that would let only necessary small BSs to be sent to off mode.

1.3 Research Objectives

i. To optimise the energy efficiency of a two-tier network by considering activation probabilities and PSR factor.

ii. To propose an algorithm that maximises the energy efficiency of a two-tier network in CDSA.

iii. To solve the optimisation problem by using the proposed algorithm with bias factors employed on each BS mode.

1.4 Thesis Contributions and Publications

Based on the problem statements presented above, and the literature review that will be ventured later, this thesis elucidates three objectives with its highlighted contributions. The three objectives of the thesis are explained separately in each chapter.

1.4.1 Base Station Activation Probabilities and Partial Spectrum Reuse Factor

In the first objective, a joint optimisation of BS activation probabilities and PSR factor is proposed to maximise a two-tier heterogeneous network's energy efficiency. The contributions of this work are listed as follows.

i. Proposing a joint optimisation of BSs activation probabilities and PSR factor in order to maximise the energy efficiency of a two-tier network,

ii. Formulating the optimisation problem where the objective is to maximise the energy efficiency by optimising the activation probability of a macro BS, the activation probability of a small BS, and the PSR factor. The optimisation problem is subject to constraints such as activation probabilities, data rates of both tiers and PSR factor, and

iii. Solving the problem by finding first the best target Signal-to-interference Ratio (SIR) where our proposed scheme works best. The best target SIR is defined as the SIR that leads the network to achieve the highest energy efficiency given various value of BS activation probabilities. By assuming the target SIR to be the same for both tiers, it will be used in obtaining the highest coverage probabilities given by various combination of the BSs activation probabilities and the PSR. This is to ensure that the best energy efficiency is achieved given the best target SIR. The optimisation problem is solved by using Genetic Algorithm where the highest value is obtained.

The main strategies applied to maximise energy efficiency of a heterogeneous network are spectrum sharing and sleeping BSs. Therefore, applying spectrum sharing will minimise the interference and finally maximise the energy efficiency. There are two types of spectrum sharing that researchers focus on which are: Universal Spectrum Reuse (USR) [35,36] and PSR [29]. The USR allows both macro BSs and small BSs to access the whole spectrum whilst the PSR allows only one of the tiers (normally small BSs) to access a portion of the other spectrum (normally macro BSs). Applying USR in a heterogenous network is not the best option because it causes severe inter-cell interference and limits the QoS performance of macrocell networks [19]. Apart from spectrum sharing, other interference mitigation strategies such as sensing resource blocks and seeking the optimal sensing period [4] as well as coordinated scheduling [37] were applied in many studies. However, only spectrum sharing is focused on this thesis, specifically, the PSR.

The PSR factor is applied to achieve a higher energy efficiency due to less work carried out as an alternative to interference mitigation strategy. A lower PSR factor value will be discovered for a lower inter-tier interference that results in less spectrum usage. Not only the interference mitigation, but the network energy consumption can also be reduced [27]. The optimal PSR will benefit both users in macrocell networks and small cell networks as proved by a study done by [28].

If the PSR factor is higher, more macro BSs will be activated but more small BSs will be sent to sleep mode [27]. A lower PSR factor indicates more small BSs will be activated and vice versa. The concept of universal or spectrum reuse allows each BS to occupy the whole system spectrum. This would cause severe inter-cell interference [28].

BS sleeping strategy was applied in previous works not only to optimise the total network energy cost with PSR [28] but also to improve the energy efficiency of a heterogeneous network. Moreover, BS sleeping strategy was also used with USR in both homogeneous network and heterogeneous network to optimise the total network energy cost [38]. Similarly, this thesis applies BS sleeping strategy and spectrum reuse to optimise the energy efficiency of a heterogeneous network. The optimal probability of activating a macro BS and a small BS are investigated to maximise the energy efficiency by using Genetic Algorithm.

1.4.2 Switching Off Decision and User Association Algorithm for Optimal Base Station Density

In the second objective, a Switching Off Decision and User Association (SODUA) algorithm is proposed to maximise the energy efficiency of a two-tier heterogeneous network's energy efficiency. The contributions of this work are listed as follows.

i. Modelling the spatial distribution of the small BSs and the mobile users as two independent Poisson Point Process (PPP). While, a single macro BS is located at the center of the network to control the small BSs' activities in the CDSA. The expressions for the SIR, user-cell associations, power consumption and energy efficiency of a two-tier network are formulated,

ii. Formulating the energy efficiency maximisation problem and solving it by using the proposed algorithm. The proposed algorithm considers the traffic load of each small BS and switching off strategy that could improve the two-tier network, and

iii. Proving the combination of various SIR, the random small BSs' transmit power, and the small BSs switching off in CDSA can give a significant result toward the energy efficiency of a two-tier network.

The main strategies used to maximise a two-tier heterogeneous network's energy efficiency are switching off BSs, CDSA and the proposed SODUA algorithm. However, for this objective, the main target is to find an optimal BS density.

Based on literature, most of the previous works obtained optimal BS densities by optimising their network energy efficiency like works done by [27, 38–40]. The works optimised their network energy efficiency subject to the coverage probabilities larger than their threshold values. On the contrary, the works in [28, 41] considered outage probability instead of coverage probability as their constraints. Nevertheless, the work in [42] found the optimal BS density by only considering a BS density value.

Normally, when a study applies a BS sleeping strategy or a BS switching off strategy, a BS density [43] is one of the factors that will be considered in making sure that a network achieves a higher energy efficiency. In short, an optimal BS density is used to help in maximising the energy efficiency of the whole network. Many works have been carried out to find an optimal BS density by optimising the coverage probability, the energy efficiency, and the total network energy cost [38, 40, 43]. For example, the work that was carried out by [38] obtained an optimal BS density through a binary search algorithm. Then, the optimal BS density value was used to minimise the network energy cost.

In contrast to [38], the work that carried out by [44] formulated an area power consumption minimisation framework to obtain the optimal values of the deployment factor which consist of BSs density and transmit power. Specifically, an optimal BS density was obtained through an analytical model. The authors considered minimising a total energy expenditure problem where the optimal combination of BS densities was computed. An optimisation problem was formulated to find an optimal BS density. However, the problem was hard to solve thus it was just solved numerically [36]. Similarly, several works were carried out to find an optimal BS density by formulating an optimisation problem [40] by applying various methods.

As mentioned, a separation architecture or also known as CDSA was introduced to guarantee the coverage of the network [45, 46]. As the main controller, the macro BS can determine the small BSs' modes based on certain criteria that will be discussed later.

In comparison, the second objective switches off only the selected BSs whilst the work done by [47] activated only selected BSs that were near to the uncovered network corner, or known as edges. The reason was if the BSs were simply selected to be switched off because they resided in uncovered area, the unnecessary BSs would as well be selected. For example, the BSs without users that were not selected to be switched off in the area would just waste the power consumption. Therefore, it would be better if the algorithm could be improved by selecting the BSs where at least a user resided in the uncovered area.

1.4.3 A Genetic Algorithm Based Power Mode Variant Selection Algorithm

In the third objective, a Genetic Algorithm Based Power Mode Variant Selection (PMVS) algorithm is proposed to maximise a two-tier network's energy efficiency in a CDSA. The main contributions of this work are summarised as follows.

i. Proposing a system model that allows each small BS to flexibly switch modes, according to its rank (the details will be further discussed in Chapter 5),

ii. Deriving the expressions for the downlink SIR, a user-cell association indicator, power consumptions of each BS, and energy efficiency of a two-tier network. Based on the model and the derivation, the optimisation problem is formulated, and

iii. Solving the optimisation problem by applying a Genetic Algorithm based PMVS algorithm. As a result, the optimum values of the bias factors are found for each BS's mode. In general, the proposed algorithm decides the appropriate mode for each small BS by using ranking method. Besides that, the proposed algorithm calculates energy efficiency where the bias factors modify the power consumption of each BS's mode subject to several constraints.

The proposed algorithm, that selects an appropriate power mode and finds the optimal bias factor value for each BS's mode, is proposed to maximise the energy efficiency of a two-tier network in a CDSA. At this point, the proposed algorithm modifies the SODUA algorithm that is proposed in the second objective to achieve a higher energy efficiency of a heterogeneous network. Besides CDSA, Genetic Algorithm is used in this work as an optimisation method.

In short, the Genetic Algorithm is a type of heuristic search of an evolutionary algorithm where the best solution of an optimisation can be obtained by combining different possible solutions [48]. The algorithm has been used in various works including in minimising a network's energy consumption [48, 49]. However, less works studied on maximising energy efficiency of a two-tier network.

In this third objective, a bias factor is applied on each small BS mode as well as macro BS to maximise energy efficiency. Here, a bias factor on each power consumption's mode is used to adjust the total power consumption in order to optimise the energy efficiency. The bias factors will be determined by the Genetic Algorithm to obtain a higher energy efficiency. The power consumption of each mode varies depending on the number of small BSs of each mode. The Genetic Algorithm will be used to determine the bias values that satisfy the objective problem with several constraints.

In the previous work of [24], each mobile user sought the appropriate bias value, and aimed to increase the average throughput. Besides that, the Cell Range Expansion (CRE) was introduced to reduce the interference of a macro BS by adding a bias value to the received signal received power (RSRP) of a small BS to induce adjacent users in order to select a small BS. Normally, most of the users tend to associate with a macro BS because the transmission power of a macro BS is higher than the small BSs. By employing a bias value, the BSs could extend its coverage area. Therefore, more users are pushed from highly loaded macro BSs to lightly loaded small BSs.

On top of that, sleeping or switching off strategy is one of the popular strategies for maximising energy efficiency of a network. Some studies applied sleeping mode in sleeping strategy whilst the others applied switching off mode in switching off strategy. According to [33], sleeping mode consumes 10% of the power consumption but switching off mode consumes none. In this work, four different power modes: On, Standby, Sleep and Off, was considered as studied by [34] to ensure the energy is used efficiently. On top of that, the repulsive strategy [50] is applied in determining whether or not the small BSs can be put in one of the power modes for the small BSs that are in a specific area.

Apart from that, a bias factor on each power consumption's mode of the small BSs will be introduced as an adjustment factor in order to maximise the energy efficiency of a two-tier network. The bias factors of all modes will be determined by the Genetic Algorithm in order to obtain a higher energy efficiency. The power consumption of each mode varies depending on the number of small BSs of each mode. Besides, an adjustment of a macro BS will be considered as well, but at a minimum level due to the heavy tasks done by the macro BS.

As at this thesis is written, we plan to submit and have submitted, presented,and published several papers as listed below.

i. Zaid Mujaiyid Putra Bin Ahmad Baidowi, Xiaoli Chu," Maximising energy efficiency by bias factors at base stations in a two-tier network with control-data separation architecture." (Have been accepted in 2021 2nd Information Communication Technologies Conference (ICTC2021) but withdrawn due to funding).

ii. Zaid Mujaiyid Putra Bin Ahmad Baidowi, Xiaoli Chu, "An optimal energy efficiency of a two-tier network in control-data separation architecture," Journal of Communications, vol. 15, no. 7, pp. 545-550, July 2020.

iii. Zaid Mujaiyid Putra Bin Ahmad Baidowi, Xiaoli Chu,"Energy-efficient joint optimization of activation probabilities and partial spectrum reuse factor in hetnets," in 2019 IEEE 9th International Conference on System Engineering and Technology (ICSET 2019), Shah Alam, Malaysia, Oct. 7, 2019, pp. 303-308.

iv. Zaid Mujaiyid Putra Bin Ahmad Baidowi, Xiaoli Chu (2019). Optimizing Density of Macro Base Stations for Maximizing Energy Efficiency. Poster session presented at the Engineering Research Symposium (ERS2019). Engineering Researcher Society, PGRForum and Think Ahead, The University of Sheffield, United Kingdom.

v. Zaid Mujaiyid Putra Bin Ahmad Baidowi, Xiaoli Chu (2018). Optimizing energy efficiency in two-operator heterogeneous networks. e-Poster session presented and published at the Euroscicon Conference on 3D Printing and Wireless Technology. Am J Compt Sci Inform Technol 2018 Volume: 6 DOI: 10.21767/2349-3917-C2-006.

The next section introduces each subsequent chapter to the readers for the better understanding of this thesis.

1.5 Thesis Organisation

This report consists of six (6) chapters where the remainder chapters are described as follows. Chapter 2 covers fundamental concepts that related to the research and literature review as this report is written. Chapter 3, 4 and 5 explain the first, second and third objectives where the proposed system model development, the problem formulation, the solutions and the results are presented. Finally, Chapter 6 concludes the research and discusses the recommendation for future works. The following paragraphs introduce Chapter 2 until Chapter 6.

Chapter 2 covers fundamental concepts related to the research and literature review as this report is written. Before presenting the literature reviews, it is essential to describe the fundamental concepts related to our research topics to enlighten the readers about the research topics. The topics discussed in this chapter are the difference between homogeneous and heterogeneous network, the Voronoi tessellation that makes the distance of the BSs to the mobile users are inequal, the SINR as a measurement of the signal strength over the interference and noise, the coverage probabilities of BSs, the sleeping strategies used in this thesis, and finally the energy efficiency as the performance measurement of the whole network. However, during the literature review, the previous works as references will be discussed extensively and critically. For instance, the closed-access and open-access used as the network configuration, the highlight of user-cell association indicates the serving BSs for the mobile users, the spectrum sharing used as an interference mitigation technique, the strategies used in maximising the energy efficiency, the traffic offloading to allow the small BSs to be sent to sleep mode, the CDSA, the BSs sleeping and switching off strategies, and the bias factor used for adjusting the power consumptions.

Chapter 3 further explains the first objective, where a joint optimisation of BS activation probabilities and PSR factor is proposed to maximise a two-tier heterogeneous network's energy efficiency. The strategies applied in this work are BSs sleeping strategy and Partial Spectrum Reuse (PSR). The BSs sleeping strategy is used to reduce the power consumption while the PSR is used to reduce the inter-tier interference. To the best of our knowledge, less work was carried out to maximise the energy efficiency especially applying PSR factor in a two-tier network. Therefore, in this first objective, the PSR factor is applied together with BSs sleeping strategy in a two-tier network.

Chapter 4 is different from Chapter 3. In Chapter 3, the energy efficiency of a two-tier network, that consists of a set of macro BSs and a set of small BSs, is maximised. The macro BSs and small BSs are scattered over a network in a closed-access configuration where only mobile users that belongs to each tier can be connected to the BS that belongs to the same tier. However, this chapter's model considers only one macro BS and several small BSs that scattered over a network in an open-access configuration. Besides, Chapter 3 did not consider CDSA but it only considered the activation probability of a small BS and activation probability of a macro BS as well as PSR factor. Nevertheless, in this chapter, the proposed algorithm maximises the energy efficiency by jointly optimising the decision making of switching off the active small BSs and the user-cell association. The difference between this chapter to the previous is that a CDSA is applied, where a macro BS controls all the small BSs under its coverage. Furthermore, in this second objective, a SODUA algorithm is proposed to maximise a two-tier heterogeneous network's energy efficiency. The main strategies to maximise a two-tier heterogeneous network's energy efficiency are switching off BSs, CDSA and the proposed SODUA algorithm. The switching off BSs is applied only to the small BSs to reduce the network's power consumption where the mobile users associated to the BSs will be offloaded to the other active small BSs. At the same time, the CDSA is used as the network architecture to guarantee the network coverage when the small BSs are switched off. Besides, the architecture allows a macro BS to control the small BSs especially in determining which small BSs to be switched off. Based on that, a SODUA algorithm is proposed to maximise the network's energy efficiency.

Chapter 5 unfolds the third objective where a Genetic Algorithm Based Power Mode Variant Selection (PMVS) algorithm is proposed. The main strategies to maximise a two-tier heterogeneous network's energy efficiency applied are four different power modes of a BS, a bias factor, and CDSA. To apply only switching off BSs is not practical because it will contribute to other drawbacks such as time delay in BS's waking up. Hence, the four different power modes of a BS consist of On, Standby, Sleep and Off modes, are applied. The bias factor of each mode of a BS is applied to adjust the BSs' power consumption. An optimal bias factor of each mode is investigated to maximise the network's energy efficiency.

Chapter 6 concludes the work done in Chapter 3, 4 and 5. Ultimately, the recommendation for future work is highlighted here to improve the work that has been carried out.

In a nutshell, the main strategies used in this thesis are sleeping BSs, switching off BSs, and sharing spectrum. Switching off and sleeping strategies are different in terms of the power consumptions and the categories exist in sleeping mode. Thus, they are deployed in this thesis separately. The random sleeping strategy is applied in the first objective, whereas the repulsive strategy is applied in the second and the third objective. Nevertheless, in the second objective, switching off BSs is applied while sleeping BSs is implemented in the third one. The repulsive strategy allows the selected small BSs in the sleeping area to be sent to the one of the sleeping categories while the selected small BSs, in the switching off area, are sent to off mode. While the second objective considers only switching off BSs, the third objective considers four different modes that comprise of On, Standby, Sleep and Off [34]. The reason of having these four modes are: not all BSs need to be switched off, and by applying switching off mode, the wake-up process will be a bit longer as described by [34] and this can be summarised in Table 1.2. As mentioned, this thesis applies both sleeping mode and switching off mode separately in the objective. Therefore, for the second objective, only BSs that are in switching off area can be switched off whereas in the third objective, only BSs that are in the sleeping area are sent to the other three sleeping categories. The rests remain Awake, that is, in On mode.

Table 1.2: Waking up time

Category	**Mode**	**Wake up Time (in second)**
Awake	On	0
Sleeping	Standby	0.5
Sleeping	Sleep	10
Sleeping	Off	30

Chapter 2

Fundamental Concepts and Literature Review

Before reviewing the literature related to the topics in this research, it is better to understand the Fundamental Concepts described in Section 2.1. Then, the extensive literature reviews written in Section 2.2.

2.1 Fundamental Concepts

Before presenting the literature reviews, it is important to describe the fundamental concepts that are related to our research topics, to enlighten the readers about the research topics. Furthermore, the general formulas for calculating energy efficiency are explained in this section.

2.1.1 Homogeneous and Heterogeneous Networks

A homogeneous is a conventional network where the network consists only similar power transmission range for all BSs reside in the network as the only macro BSs as shown in Figure 2.1. A heterogeneous network is a network with multiple transmit power range for all BSs in the network. It can be two or more for range of transmit power. This is best illustrated in Figure 2.2. The heterogeneous network consists of various types of BSs with different transmit power ranges shown a significant impact to the performance of the network's energy efficiency. Small BSs, that reside in a heterogeneous network's coverage proven that the total power consumption of the heterogeneous network could be reduced due to their low-powered radio communication's equipment [51]. Intuitively, the use of low-powered equipment in the heterogeneous network helps in reducing the power consumption of the network as compared to a homogeneous network. It can be said that the energy is efficiently used and managed.

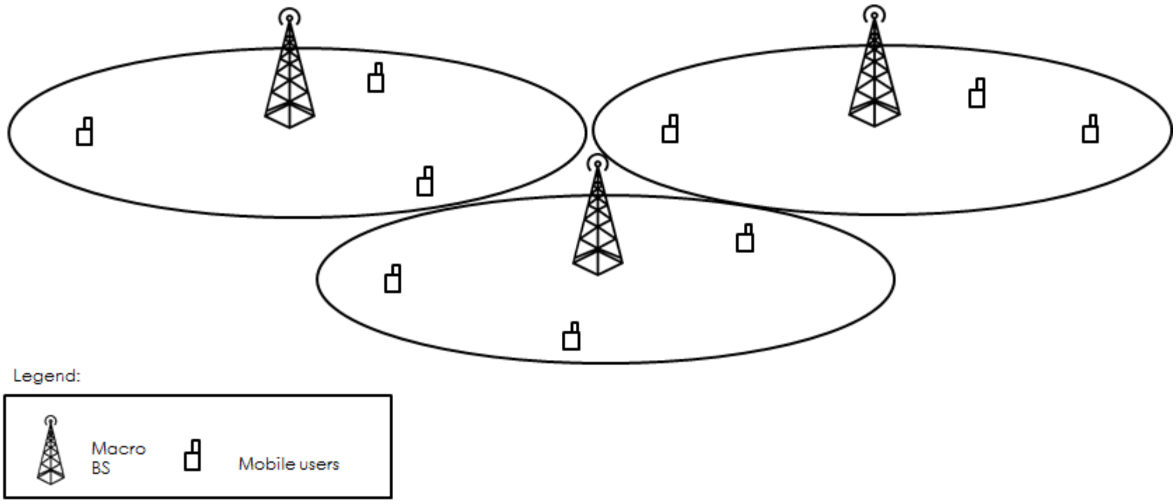

Figure 2.1: Homogeneous network with similar type of base stations

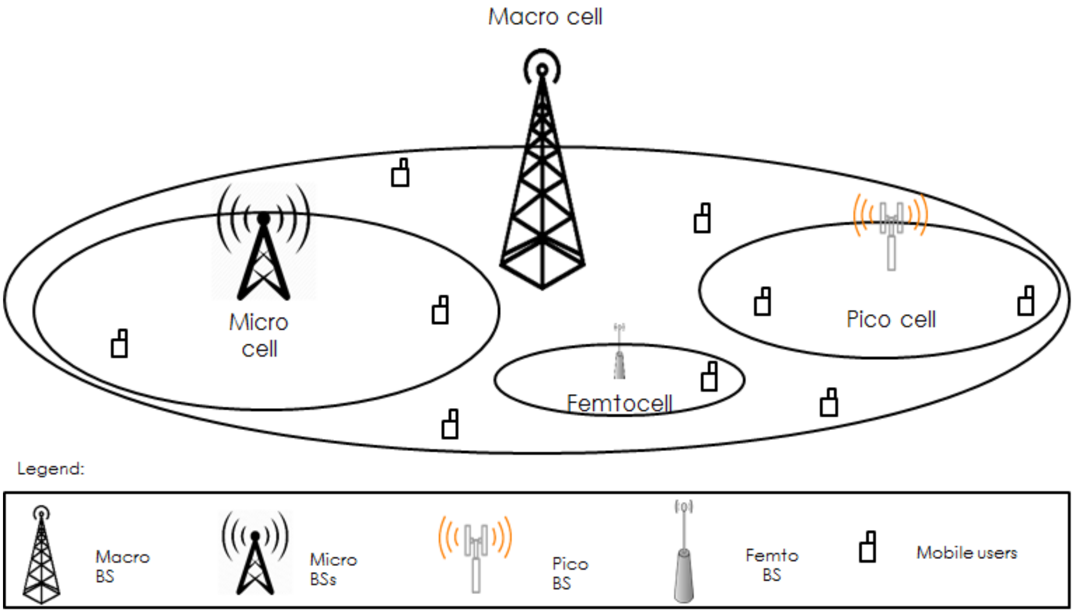

Figure 2.2: Heterogeneous network with different types of base stations

2.1.2 Voronoi Tessellation

A Voronoi tessellation is a division of a region that relates to a region where a user that is near to a BS is associated with that particular BS as compared to the other BSs. Voronoi tessellation is normally used in distributing users and BSs on a plane, when the BSs are not equal in distance [52, 53]. It can also be used when different transmit power over tiers are used [54]. The rest of the BSs, that are not associated with a typical mobile user, are considered as interferers. This is used when calculating a signal received at a mobile user from the nearest BS. The BS that is communicating with the mobile user is called a serving BS. The location of a mobile user is important in determining whether or not the user can get the coverage from the BS. The BS that is partitioned by using Voronoi tessellation is illustrated in Figure 2.3 where the dots on the diagram are the location of the BSs. The regions are divided based on the nearest location that a BS can serve when a mobile user moves from one region to another.

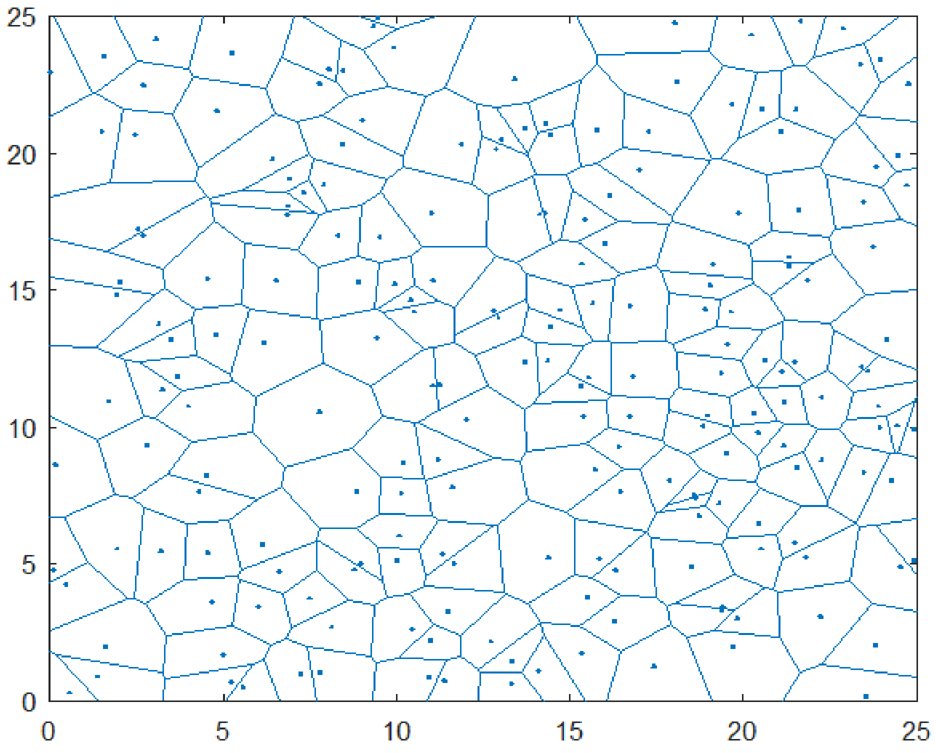

Figure 2.3: Voronoi tessellation

In this thesis, Voronoi tessellation is applied to simulate inequality of the distance from a BS to a user for user-cell association purposes.

2.1.3 Signal-to-interference-plus-noise Ratio

Signal-to-interference-plus-noise ratio or SINR is a basic concept in defining the received signal at a mobile user. The transmit signal is attenuated due to fading, path loss and shadowing as it is propagating from a BS known as a transmitter to a mobile user that is a receiver.

Basically, the SINR can be measured as the ratio of power, P, to interference, I, plus noise, N, as follows

$$\mathrm{SINR} = \frac{P}{I+N} \tag{2.1}$$

When the transmit power experiences attenuated signal in the channel model, the SINR can be written as follows

$$\mathrm{SINR} = \frac{Phd^{-\alpha}}{I+N} \tag{2.2}$$

Referring to Equation (2.2), the numerator consists of the received power at the receiver while the denominator consists of interference and noise factors that contribute to the SINR. The received power consists of transmit power which is coming from the transmitter, P, and it is modified by fading, h, and path loss over the distance $d^{-\alpha}$.

The transmit power of the BS is within the minimum and the maximum allowable transmit power depending on the category of the BSs. For instance, a macro BS's maximum transmit power is 20 Watt. However, for small BSs, it depends on its categories such as micro's maximum transmit power is 6.3 Watt, pico's is 0.13 Watt, and femto's is 0.05 Watt [55].

The fading is usually modelled as Rayleigh distribution because it is suitable with our environment where the interference signal powers are scattered. This is because the signals traverse the air through many objects before arriving the receiver or the signal can be said as coming from multipath. The Rayleigh fading can be modelled using exponential distribution as the interference power is exponentially distributed [53]. The channel effect such as fading is random, thus communication between the BS and the mobile users experience only Rayleigh fading with mean 1, while the transmit power is $1/\mu$.

For example, Rayleigh fading has been widely used in modelling fading distribution where the signals are scattered all over the environment with no dominant components scatter the signals. It was implemented in a homogeneous network where it is much suitable for macro cells in an outdoor dense urban area with non-line-of-sight (NLOS) environment where obstacle are in presence [56]. However, it was also used to model fading distribution in heterogeneous network [57] with background noise in presence [58].

Fading is also known as small-scale fading because the fluctuation of the signal happens rapidly within a small area. The example of the situation that causes the fluctuation is the movement of a mobile user from one location to another. This type of fading is, normally, modelled as Rayleigh fading. It is also known as a small-scale effect due to fast changes in respect to time. It happens because power signals propagate from the transmitter to the receiver by using multipath. Finally, all the signals arrive at the receiver in a slightly different time.

Mathematically, the fading, h, is Rayleigh distributed if $h = \sqrt{X^2 + Y^2}$, where X and Y are two independent variables that follow normal distribution, that can be written as $X \sim N(0, \sigma^2)$ and $Y \sim N(0, \sigma^2)$. The σ is the variance and mean is 0 since there is no dominant component to the scatter.

The total received power at a mobile user usually is less than the total transmit power due to many factors along the way from a transmitter to a receiver. Thus, the transmit power is decreased as it travels to the receiver. The transmit power also decreases over the distance the signal power travels. The decreasing power can be measured by path loss exponent which is a type of distance-dependent. The path loss, P_L, can be measured as the ratio of the transmit power, P_t, to the received power, P_r, and written in linear equation as

$$P_L = \frac{P_t}{P_r} \tag{2.3}$$

Besides, it can also be measured in decibel unit as

$$P_L(dB) = 10\log_{10}\frac{P_t}{P_r}(dB) \tag{2.4}$$

On top of that, path loss can also be calculated based on the distance, d, to the power of path loss exponents, α, as follows

$$P_L = d^{-\alpha} \tag{2.5}$$

The negative power indicates that the value is decreasing over the distance. The path loss exponent varies depending on the environment it propagates [59]. Basically, the indoor environment experiences a higher path loss exponent as compared to the outdoor environment due to strong obstacles such as wall, floor, and curtain. The path loss exponent can be classified as shown in Table 2.1 [60].

Table 2.1: Path loss exponent

Environment	**Path loss exponent**
Free space	2
Urban area	2.7 - 3.5
Suburban area	3 - 5
Indoor line-of-sight	1.6 - 1.8
Obstructed in building	4 - 6
Obstructed in factories	2 - 3

Another modifying factor to the transmit power is shadowing. It happens when the power signal is blocked by any obstacles such as buildings during the propagation. It is also known as large-scale fading because the changes to the transmit signal are large in a small area. For example, signal changes due to blockage of the building, mountains, or hills. The shadowing is typically modelled as log-normal distribution. However, shadowing is not our focus in this thesis because only small-scale fading is considered. Hence, shadowing can be put aside in this thesis.

The interference is the other signals that are coming from another BSs to a typical mobile user. A noise is a basic noise model to reflect the random process of thermal noise that naturally exists. However, some studies considered as an interference-limited case where the SINR is reduced to SIR, that is without noise power. It happens when the interference is dominated over noise power, N [61]. Therefore, the expression is written as follows

$$\text{SINR} = \frac{Phd^{-\alpha}}{I} \tag{2.6}$$

where the numerator consists of P, the transmit power of a transmitter that is subject to minimum and maximum allowable power depending on the type of BS, h, the Rayleigh fading, d, the distance from the BS to a typical mobile user, and α, the path loss exponent depending on which category. If the interference-limited case is considered, the denominator consists of only I, the interference that coming from another BSs.

2.1.4 Coverage Probability

A coverage probability was developed for SINR using stochastic geometry framework by [53]. This is, then, used widely by other researchers to carry out more research. At first, the coverage probability model was implemented in only homogeneous network but it was implemented also in a heterogeneous network [62]. The model was introduced to solve problems for mobile users where the locations are randomly located unlike the prior studies wherein focused on grid model and based on fixed deployment of BSs. The SINR's coverage probability expression derived was tractable and easy to solve as compared to the previous expressions' coverage probability.

To date, the coverage probability was studied extensively by researchers in the wireless communication area. Coverage probability is one of the vital performance metrics to measure the probability of a typical mobile user to be able to achieve a certain threshold value of SINR [63]. Here, the BSs are deployed according to a homogeneous PPP where the points (i.e. BSs) are scattered all over the network.

2.1.5 Small BS Sleeping Area

To determine whether or not the small BSs can be assigned to one of the modes, this thesis applies repulsive strategy as in [50] where the small BSs that are in a specific service area could be assigned in sleeping strategy when necessary. This can be illustrated in Figure 2.4 and the Average Sleeping Ratio's formula is written as follows

$$\text{Average Sleeping Ratio} = \frac{\text{The area of allowable maximum coverage}}{\text{The actual area of the coverage}} = \frac{\pi r_s^2}{\frac{3\sqrt{3}}{2}D^2} \quad (2.7)$$

where r_s is the radius from the serving BS, that is a macro BS, to the allowable maximum coverage area, D is the radius from the serving BS to the end of the actual coverage area. In this case, the hexagonal area is applied [50].

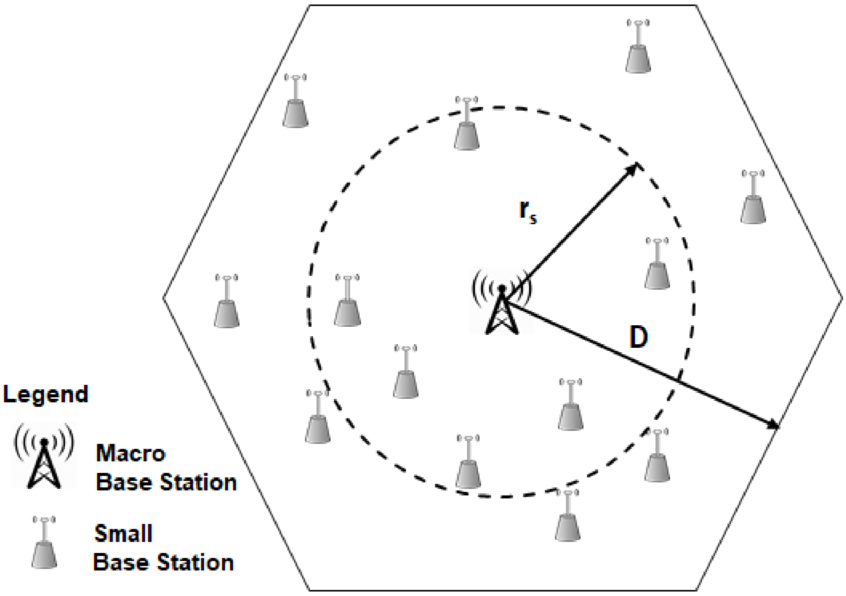

Figure 2.4: Small BS sleeping area

2.1.6 Energy Efficiency

Energy can be defined as a total amount of work done that is measured in Joule. Power, on the other hand, is defined as how many data rate is transferred at what energy or how fast it can be done. The unit of power is Watt and a Watt is equal to one Joule divided by one second. It can be expressed as follows

$$\text{Power in Watt} = \frac{\text{Joule}}{\text{second}} \tag{2.8}$$

Energy efficiency is measured by a throughput of a system per unit power consumption [64]. The throughput is the amount of data rate transferred from the BSs to the mobile users in a specific service area (if considering an area). The power consumption is the amount of power in Watt used by each BS in a network. Therefore, an energy efficiency can be described as how many data per second can be transferred from a transmitter to a receiver over a total of power consumption. This can be shown as follows

$$\text{Energy Efficiency, EE} = \frac{\text{Total number of data transferred (in bits / s)}}{\text{Total power consumption (in Watt)}} \tag{2.9}$$

Therefore, the throughput of a network can be calculated based on two definitions either using achievable data rate [18] or using average spectral efficiency [65] as the numerator. As a result, the energy efficiency can be calculated based on one of the two definitions over the total of power consumption. The achievable data rate is measured in bits/seconds while the average spectral efficiency is measured in bits/seconds in a unit area by considering density of BSs. The two formulas can be written as follows

i Achievable Data Rate as the network throughput

$$\text{Energy Efficiency, EE} = \frac{\text{Achievable Data Rate}}{\text{Total Power Consumption}}$$

ii Average Spectral Efficiency as the network throughput

$$\text{Energy Efficiency, EE} = \frac{\text{Average Spectral Efficiency}}{\text{Total Power Consumption}}$$

The energy efficiency that is based on achievable data rate is the performance metric for network capacity, and it is defined as a network throughput in terms of total data rate (in bits/s) without considering BS density. Nevertheless, the energy efficiency that is based on average spectral efficiency is the performance metric for network capacity, too, but it is defined as the network throughput that considers BS density (in unit area, e.g. m^2).

According to [6], a network throughput can be obtained through all connections from the given BSs to the mobile users where it is taken over all the connections in a certain area of a network such that

$$\mathbb{P}(\mathrm{SIR} > T)\log_2(1+\mathrm{SIR})$$

and this is called average rate where, $\mathbb{P}(\mathrm{SIR} > T)$ is the coverage probability, $\log_2(1+\mathrm{SIR})$ is the achievable data rate and T is the threshold value.

Therefore, for each tier, the average rate is defined as $\lambda\mathbb{P}(\mathrm{SIR} > T)\log_2(1+\mathrm{SIR})$ by having a BS density, λ. Consequently, the average rate of a two-tier network can be written as follows

$$\mathrm{ASE}_{\mathrm{hetnet}} = \lambda_m\mathbb{P}_m(\mathrm{SIR}_m > T)\log_2(1+\mathrm{SIR}_m)+\lambda_s\mathbb{P}_s(\mathrm{SIR}_s > T)\log_2(1+\mathrm{SIR}_s) \quad (2.10)$$

where λ_m and λ_s are the BS density of the macro BSs, and the small BSs, $\mathbb{P}_m(.)$ and $\mathbb{P}_s(.)$ are the coverage probability of the macro and the small BSs, SIR_m and SIR_s are the SIR of the macro and the small BSs.

2.2 Literature Review

2.2.1 Closed-access and Open-access

Network access can be configured in two ways: closed-access and open-access [54]. In an open-access scenario, the mobile users can be connected to any nearest BSs regardless of their tiers [43]. For example, a mobile user can be connected to either a macro BS or a small BS based on the association strategy used such as nearest BS or the BS that offers the highest SINR. This can be illustrated in Figure 2.5. By applying an open-access configuration, the network operators can expand their network capabilities at a lower cost deployment [66]. In contrast to when closed-access is deployed, a mobile user can only be connected to BS of the same tier. For example, a mobile user that is connected to a macro BS is called macro BS's mobile user (MU) while a mobile user that is connected to a small BS's is called small BS's mobile user (SU). This can be illustrated in Figure 2.6 for closed-access involving small BSs only and Figure 2.7 for closed access involving macro BSs only. Even though the open-access offers cheaper and flexible network configuration, the closed-access ensures that no inter-tier interference occurs because the interference is coming from only the same tier with no interference from other tiers.

2.2.2 User-cell Association

A user-cell association tells us about how a mobile user is connected to a BS. Various user-cell association strategies were proposed in the earlier works. For example, a user-cell association strategy that was based on the fading-average propagation loss process where a mobile user was associated with a BS that offered the strongest signal [67]. Besides that, maximum instantaneous received power (MIRP) and maximum average received power (MARP) were used to determine a user-cell association strategy that was proposed by [40]. Here, the CRE bias value was used to ensure that the mobile users were connected to a small BS instead of a macro BS. Similarly, a work done by [68, 69] used CRE bias as well to ensure that a mobile user, that was being associated with a small BS, would not be offloaded to a macro BS for a user-cell association. However, this user-cell association was

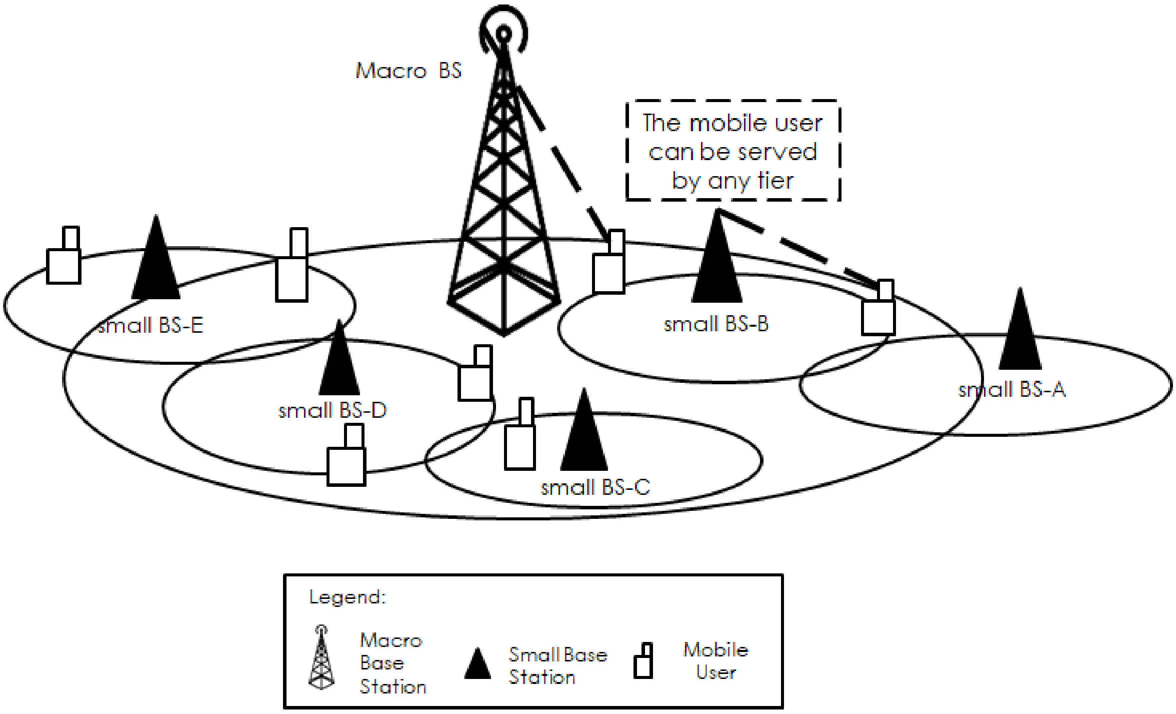

Figure 2.5: Open access

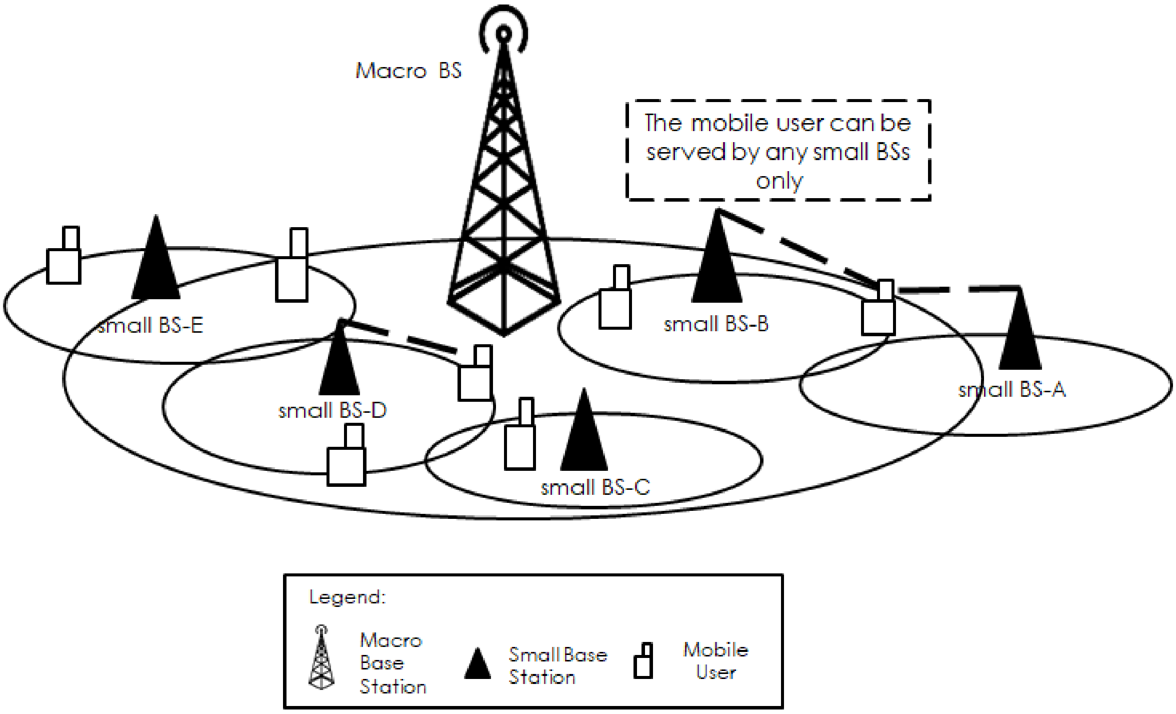

Figure 2.6: Closed access (small BS only)

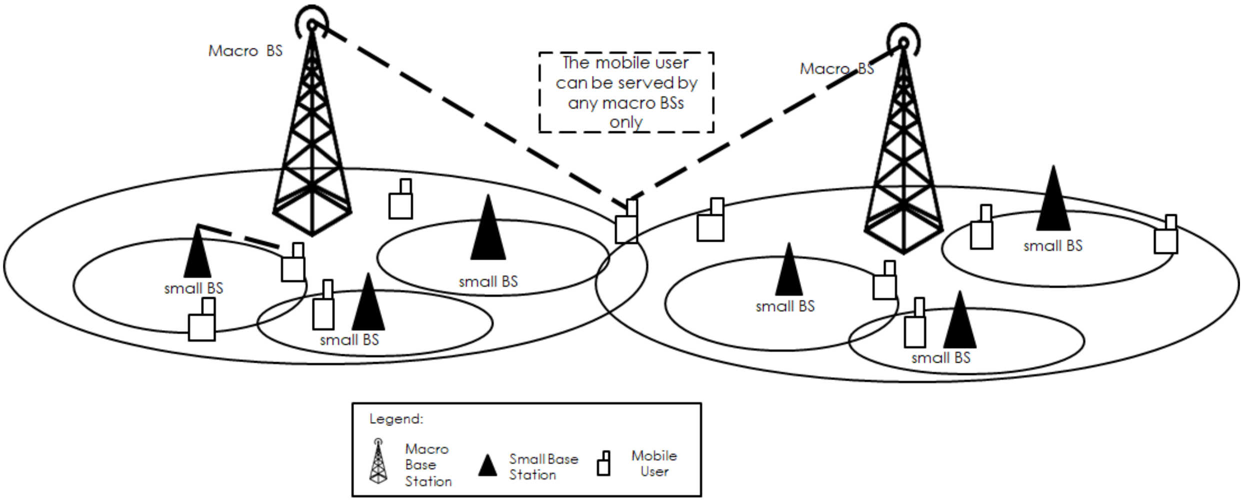

Figure 2.7: Closed access (macro BS only)

based on conventional SINR and received signal received power (RSRP) measurement. Even though many studies no longer used the conventional SINR due to its limitation such as prone to connected to macro BS, a study that was conducted by [39, 47] used the conventional SINR for cell association. However, an interference margin was added to the SINR to mitigate the interference coming from neighbouring BSs.

Nevertheless, in another study, a mobile user was associated with the nearest BS [70] instead of the MIRP, MARP, RSRP and SINR. If a mobile user is associated with a BS that is based on the conventional SINR, it might be associated with a macro BS which located far from the user as compared to the small BS that is closer. This is the downside of the conventional SINR because the transmit power of a macro BS is larger than the small BS. However, if the nearest BS approach is applied, the nearest BS to the user will be selected even though the received power is lower, regardless of the tier.

However, some studies applied closed-access where the mobile users could only be connected to the same tier [27]. For instance, if a mobile user belongs to a small BS or known as SU, the mobile user can only be connected to small BS not a macro BS. If the mobile user belongs to a macro BS, or known as MU, they can only be connected to a macro BS. This is quite similar to the concept of separation architecture where only small BSs can serve mobile users. A macro BS in contrast, does not serve any users for data transmission except controlling the signalling activities.

In a user-cell association, an indicator variable is used to show that a BS is associated with a mobile user. An indicator 1 shows that the BS is associated with the mobile user while an indicator 0 shows that the BS is not associated with the mobile user. The general association relationship between the mobile users and the small BSs can be represented by matrix $\mathbb{A} = [a_{su}]_{\mathcal{S}\times\mathcal{U}}$

$$a_{su} = \begin{cases} 0, \text{if mobile user } u \text{ is not associated with the small BS } s \\ 1, \text{if mobile user } u \text{ is associated with the small BS } s \end{cases} \tag{2.11}$$

where $\mathcal{S}$ is a set of small BSs, $\mathcal{U}$ is a set of mobile users.

2.2.3 Spectrum Sharing

Interference in wireless communications is common due to signal propagation from one to another. In a homogeneous network, there is only one type of interference which is co-tier interference or known as inter-cell interference. Whilst, in a heterogeneous network, there are two types of interference occurs. The first type is co-tier or inter-cell interference and the other is cross-tier or inter-tier interference. Co-tier interference happens among the same tier while cross-tier happens between different tiers [71]. For instance, interference coming from other small BSs to a small BS is a type of co-tier interference. However, the interference that is coming from small BSs to a macro BSs is a type of cross-tier interference.

However, the solution for cross-tier interference is to implement either spectrum splitting or spectrum sharing [72, 73]. Due to using orthogonal frequency bands in spectrum splitting, macro BSs and small BSs are totally in separate networks. Hence, no cross-tier interference occurs and this solves the issue of interference coming from other tiers. However, due to using the same spectrum by both macro BS and small BSs in spectrum sharing scheme, co-channel interference arises.

The cross-tier interference problem was also proposed to solve by applying different cells on a spectrum such as PSR scheme [29]. The scheme allows the spectrum to be shared and reused by different tiers. For example, macro BS's spectrum not only used by itself but a fraction of the spectrum is shared by small BSs as well. This will reduce the interference to the macro cell.

2.2.4 Strategies in Maximising the Energy Efficiency

Information and communication technology (ICT) industry was identified as the main factor to carbon dioxide emission due to high electric energy consumption [74]. According to [1], it was predicted to be exponentially increasing in a short period and it could lead to global warming. In order to overcome this problem, many researchers worked toward minimising power consumption of BSs and energy efficiency of a network in ICT communications [75–78]. For instance, improving energy efficiency performance in a fast-moving vehicle such as high-speed railway communication system [79], maximising the energy efficiency in a Multiple-Input Multiple-Output (MIMO) network [80], and proposing energy-efficient radio resource management to improve cell edge users throughput [81].

One of the techniques to minimise the power consumption of BSs is coordinated beamforming [82] where the transmitted signal is directly sent to the destination rather than to all areas. Besides that, a separation architecture or known as CDSA was proposed to be applied to reduce network energy consumption [78]. In this study, a conventional macro BS that was used to serve users was replaced with two types of light-weight BSs. The first one was for a coverage BS to cover the network and the latter was used for traffic BSs. The coverage BS was for serving a specific coverage area whereas the traffic BSs were used specifically to handle user traffic. The traffic BSs could be switched on and off based on the traffic load. This would certainly help the network to minimise its power consumption.

In another study, a group of BSs of different tiers were clustered together to serve a typical mobile user, known as cooperative clusters scheme in order to maximise energy efficiency [1]. In this scheme, a typical mobile user would be served by a group of BSs, regardless of their tiers, that offered Received Signal Strength (RSS) larger than the threshold value. RSS is a measurement of power received at a mobile user that transmitted by a BS. The formulation for checking whether or not the RSS value was larger than the threshold value was formulated as follows

$$P_k \Psi_{k,s} \parallel x_{k,s} \parallel^{\alpha_k} \geq T_k \tag{2.12}$$

where, if K is the number of tier, then $k \in 1, 2, ..., K$, P_k is transmit power of tier-k of BS-s, $\Psi_{k,s}$ is fading coefficient of tier-k of BS-s, $x_{k,s}$ is location of BS, α_k is path loss exponent of tier-k, and T_k is RSS threshold value of tier-k. The work proved that the proposed cooperative clustered to be more energy-saving as compared to only macro network deployment. Similarly, the authors of [2] implemented cooperative clusters as well but the work grouped only the small BSs. Thus, a typical user would be served by either a macro BS or a cluster of small BSs which offered the larger RSS. The work expressed it as follows

$$\sum_{x_{j,s} \in C}^{x_{k,s}} P_s r_{j,s}^{-\alpha} > P_m r_m^{-\alpha} \tag{2.13}$$

where, $x_{k,s}$ is the coordinate location of the small BS-s of the tier-k, $x_{j,s}$ is the location of j-th BS that is the element of the set of cooperative small BS. The set of cooperative small BS is the small BSs that are working together to provide the RSS for serving the mobile user. Hence, $\sum_{x_{j,s} \in C}^{x_{k,s}} P_s r_{j,s}^{-\alpha}$ is the RSS of cooperation of small BSs, $P_m r_m^{-\alpha}$ is the RSS of a single macro BS, P_s and P_m are the received power of small and macro cell respectively, and $r_{j,s}^{-\alpha}$ and $r_m^{-\alpha}$ are the radius of small and macro cells respectively. Therefore, if the value of the left equation, that was the cooperative small BS, was larger than the right, that is the macro BS only, the mobile user would be associated with the group of small BSs. Otherwise, the mobile user would be associated with the macro BS.

The above-mentioned schemes were known as distributed energy-efficient power control schemes. Unlike the above-mentioned schemes, each small BS in [77] worked individually to achieve energy efficiency without having cooperation from macro BS or other small BSs. The calculation of the individual energy efficiency was expressed as follows.

$$EE_k = \frac{R_k}{P_k^c + \frac{1}{\sigma}\sum_{i=1}^{N} P_k^i} \tag{2.14}$$

where, R_k is the rate of k-th small BS, P_k^c is the circuit power consumption, σ is the inefficiency of the power amplifier with $0 < \sigma \leq 1$. Here, the small BSs made decisions in controlling their own transmit power to achieve a higher energy efficiency. In contrast, the cooperative small BSs techniques, that were mentioned previously, depending on the other small BSs. This independent technique allowed independent decision where the small BSs did not have to rely on coverage area of the macro BS.

Energy efficiency can also be maximised by applying offloading in License-shared Access (LSA) which is a type of sharing different spectrum [61, 83]. Here, the small cell networks offered offloading services to macrocell network for offloading its MU. As a reward, the small cell networks will be awarded a license due to services offered. The license could be used to access the spectrum owned by the macro BS. In this scheme, all the small cell networks in the network cooperated with the macro BS for the service. The small cell networks were divided into two categories: offloader and licensee. The offloader acted as a group who offered the offloading service while the licensee acted as a group who received the license. Nevertheless, this approach seemed unfair because the group that helped in offloading was not awarded but the other licensee, received the reward. The reward was a license, that was given by the macro BS to the licensee group, for executing data transmission in macro BS's spectrum. Intuitively, energy efficiency could be maximised since the distance from the mobile user to the small cell network was much shorter than the distance from the mobile user to the macrocell network. Therefore, if the probability of getting connected to the nearest small BS from the mobile user was higher, the more energy could be saved.

There are differences between having a license and unlicensed spectrum. Of course, the license can only be used by a company that bought the license but the unlicensed can be used by anyone. One of the benefits of having a license is there will be no interference in communication from any other operators. It is a great way to mitigate interference because the operator needs to only manage internal interference. The examples of the licensed spectrum are Long Term Evolution (LTE) and Third Generation (3G). In contrast, unlicensed spectrum, such as Wireless Fidelity (WiFi), experience a lot of interference coming from other parties. Therefore, the use of unlicensed band in wireless communication can degrade the energy efficiency of a network.

In conclusion, minimising power consumption is not necessarily maximising energy efficiency. Minimising power consumption of all BSs in the network will reduce the heat and carbon dioxide emission. For example, in reducing power consumption, some of the components such as transmit power are reduced. Consequently, reducing transmit power would reduce the coverage area too. However, maximising energy efficiency means increasing the network throughput from transmitters to receivers over the total power consumption. The higher the energy efficiency, the better the network's performance is. While the power consumption is measured in Watt, W, the energy efficiency is measured in bits per second per Watt, $b/s/W$, or bits per Joule, b/J as explained in Section 2.1.6. However, both contribute to energy saving and lead to less carbon dioxide emission.

2.2.5 Traffic Offloading

Offloading is a process of transferring jobs or tasks or activities from one party to another. For instance, if a mobile user is being served by a BS, it will be transferred to another BS to ensure the connectivity of the service. Most of the time, the users are mobile where they move from one place to another [79]. Therefore, the mobile users need to be offloaded, either to the nearest BS or to the BS that offers the best QoS, to ensure the service is continuous. Otherwise, the communication will be interrupted, delayed, or disconnected.

Hence, a lot of studies were carried out and suggested various methods for offloading activities. For example, a method, namely small cell cooperation, offloaded users from macro BSs via small cells cooperation was proposed [2]. It is clear that the small BSs were joined together as a group for offloading purpose by its name. For devices that needed high energy consumption but fewer resources and a massive amount of data, using smart devices for offloading purposes where the network was shared or offloaded with other smart devices to have a higher energy efficiency was suggested [64]. However, offloading to cloud storage, that was proposed by [13], was suitable for receiving a huge amount of data by mobile users. Besides that, this method, offloading to cloud infrastructure was studied by [12] where computational tasks were offloaded to cloud.

Offloading or handing over mobile users from one BS to another, offers several benefits and drawbacks during the implementation. Some studies said that an offloading is an approach to help reducing traffic congestion in a macro BS. When the traffic and the power consumption are reduced, the cost will too be reduced and this is known as a cost-effective approach [84]. From the macro BS's point of view, offloading from a macro BS to a small BS can help them in reducing the power consumption of a macro BS due to short distance from the mobile user to the small BS. However, from the small BSs' point of view, low access fee, that imposed to the small BS if it was chargeable [84] helped them to reduce their operational cost. While most of the studies claimed that the implementation of small BSs was cheaper than the traditional macro BSs, a study conducted by [85] highlighted that the implementation of small BSs was expensive due to licensed and limited spectrum. However, implementation in WiFi network is one of the ways to reduce cost as it operates in unlicensed spectrum.

Nevertheless, offloading is not favourable by some parties specifically mobile operator networks. The work [86–88] proposed incentive-based offloading to encourage more parties to get involved in offloading. Various types of incentives were given to the parties that involved in offloading service. For example, offering those that participated in offloading to have a reduced cost for better QoS, to share resources with the licensed spectrum, to receive a discounted price for service charge if they were willing to wait longer for downloading service.

Even though small BSs help in offloading macro BS's users, the QoS could not be guaranteed to be the same as receiving the service from macro BSs. Therefore, an offloading method of cooperation among small BSs by applying Software-Defined Network [2] and an offloading by using cell switching techniques were proposed [18] to ensure that their QoS is maintained.

In short, offloading mobile users offers benefits in a heterogeneous network environment that will be used as one of the strategies in this thesis. In fact, several studies have proven by offloading the mobile users from a macro BS a to small BS, the energy efficiency of a heterogeneous network can be maximised [74,83]. Similarly, offloading from a macro BS to a small BS or from a lightly loaded or heavily loaded small BS to another small BS, would actually benefit both the mobile users and the BSs. For instance, the mobile users keep receiving services and the BSs can reduce the burden in terms of power consumption while maintaining QoS.

2.2.6 Control-Data Separation Architecture (CDSA)

Separation architecture, or also known as CDSA, is a basic concept of separation architecture to split two signals of wireless communications such as signals that mainly for coverage purpose and signals for data transmissions purpose. It is divided into two different planes, the control plane (CP) and the data plane (DP). The architecture consists of control BSs (CBSs) in CP, basically macro BSs, and data BSs (DBSs) in DP, basically small BSs. The difference between the CP and DP is that the CP operates on the low-frequency band while the DP operates on the high-frequency band. Moreover, the CP provides great propagation capabilities to obtain high coverage but low data rate service. Whilst the DP offers a high capacity, wide spectrum resources and high data rate service.

Theoretically, when a mobile user joins a network, it will be first connected to a CBS for coverage signalling. Besides that, the idle users will also be connected to CBS. Then, CBS finds suitable DBS to provide high data rates for data transmission. By having a single control, that is a CBS, the unnecessary DBSs can be flexibly switched off for saving power consumption. The selection of DBSs for saving purpose is based on the predetermined algorithm. By switching off the DBSs, no holes of coverage occur because the CBS provides extensive connectivity to the DBSs. Since the CBS controls the network, the inactive DBSs can always be activated by the CBS whenever the DBS moves as long as it is within the CBS coverage area. The inactive DBSs can be activated earlier before the arrival of the mobile users at the inactive DBSs to ensure they are active for providing data transmission. The DBS always check for the most suitable DBS, based on the predetermined strategy, to associate with the mobile users.

Literally, the architecture was introduced by [89] and has been used by other researchers to split logically between signalling and data transmission signals. Later on, in this thesis, the term macro BS will be used rather than CBS while the term small BS will be used rather than DBS. Under this separation architecture, the coverage of the network is guaranteed [45, 46, 50] as this architecture avoids coverage holes in the network. Besides that, the architecture allows macro BS (i.e. CBS) to control all activities including small BSs' activities in order to improve the energy efficiency of a heterogeneous network [50]. Since the macro BS provides high coverage as it operates on low capacity and low-frequency bands, the capabilities of the propagation are high in quality [20]. However, the small BS (i.e. DBS) offers high capacity and more spectrum resources as it operates on high-frequency bands [46]. The separation of control signalling and data transmission allows the macro BS to dynamically readjust the network via its control. Thus, any additional small BSs are allowed whether planned or ad-hoc cases.

Therefore, more studies that apply separation architecture were conducted. For instance, the architecture was applied in an ultra-dense network [90]. The purpose of deploying the architecture in the study was to enhance small BS's capabilities in order to accelerate the process of small BSs handover process. Besides that, the architecture was applied in other works as well such as in the radio access network (RAN) [91], in the cloud-radio access network (C-RAN) [92], and in fog-radio access network (F-RAN) [93].

Based on the above, here is the summary of the characteristics of the separation architecture or CDSA:

i. The separation of control and data plane allows the CBS to dynamically readjust the network via control signalling while the DBS obeys the instructions given by the CBS,

ii. The DBS will be activated by the CBS when it is needed. For example, when the mobile user moves to the inactive DBS coverage range area,

iii. Only CBS can manage the signalling activities and provide connectivity to the mobile users,

iv. CBS operates on low-frequency bands thus it can provide high coverage as compared to the DBS,

v. DBS operates on high-frequency bands thus it offers high capacity and more spectrum resources,

vi. The network can minimise the power and the energy consumption by minimising the number of BSs that are always in on mode,

vii. It is a reconfigurable and scalable architecture where the DBSs are flexible to be added to the network anywhere and anytime,

viii. It is dynamic to the traffic loads which means by switching it on or off could contribute to energy saving and energy efficiency.

2.2.7 Base Station Sleeping and Switching Off Strategies

One of the strategies in minimising energy consumption and maximising energy efficiency is that sending BSs to sleep mode [27, 28]. Most of the studies proved that by applying BS sleeping strategies, a network can obtain a higher energy efficient [43] and a higher energy-saving [94].

The BS sleeping strategies that are commonly used are random sleeping, strategic sleeping and partial sleeping [95]. A study done by [6] applied both random and strategic BS sleeping strategies. The former strategy had equal probability for sleeping selection while the latter strategy sent the BSs to sleep when they were low in traffic. Generally, in random sleeping, information like traffic load and cell's location are not required because the decision for which BS to be in sleeping mode is selected randomly. Since the random sleeping allows any small BSs to be switched off with equivalent probability, it can be implemented easily. Whilst, strategic strategy needs a specific approach and method that based on the problem. However, one more strategy was used in previous work: repulsive sleeping strategy where only the BSs that resided in a specific area were selected for sending to sleep mode [50].

On top of that, the BSs can be sent to sleep mode based on various reasons. For instance, in traffic-aware sleeping strategy, the BSs were sent to sleep mode if the BSs had no users in the coverage area to serve [43]. This is also known as passive sleeping strategy. However, a recent study done by [46] applied random and repulsive scheme of sleeping strategy in which, the random scheme allowed the small BSs to be an equal probability of switching off while the repulsive scheme allowed only the small BSs that were near to the macro BSs to be switched off. In another study, BS sleeping strategy applied a rule for sending BSs to sleep mode where the rule was set where the BSs would need to be sent to sleep mode when some mobile users were less than 10% during the peak hour [94]. The remarkable impact of implementing such a strategy was that the coverage was guaranteed to be 95% even though most of the BSs were in sleep mode.

Vertical and horizontal offloading were proposed to ensure that the QoS of the mobile users was satisfied within the sleeping small BSs [50]. Vertical offloading happens when the mobile users are offloaded from a lower tier to a higher tier or can also be said from a small BS to a macro BS. This can only happen if the mobile users are within the sleeping small BSs area. This situation is illustrated in Figure 2.8.

The horizontal offloading happens when the mobile users are offloaded to the same tier or can be based on a small BS to another small BS. However, it can only be done within a limited range due to the low transmit power of small BSs. This is illustrated in Figure 2.9. The horizontal offloading was implemented earlier by [6] in random and strategic BS sleeping strategies. However, the mobile users were offloaded between the macro BSs only since it was implemented in a homogeneous network.

BSs sleeping and switching off strategies are among the common strategies to minimise the total power consumption of BSs in a network. Instead of minimising the BSs' power consumption, it was also proven to maximise the energy of a network. Several studies applied sleeping strategy whilst the others applied switching off strategy. According to [33],

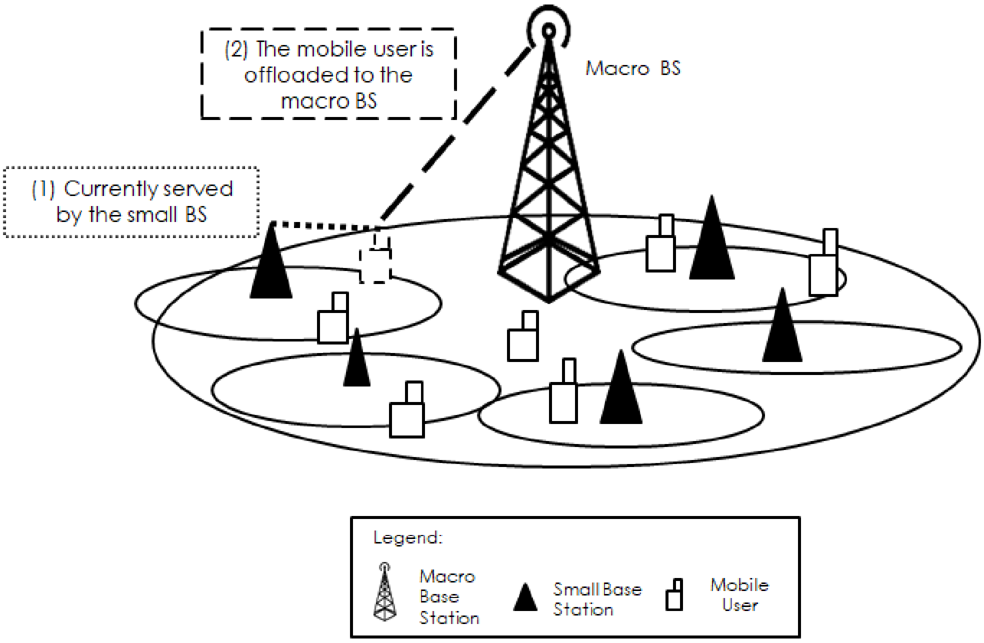

Figure 2.8: Vertical offloading

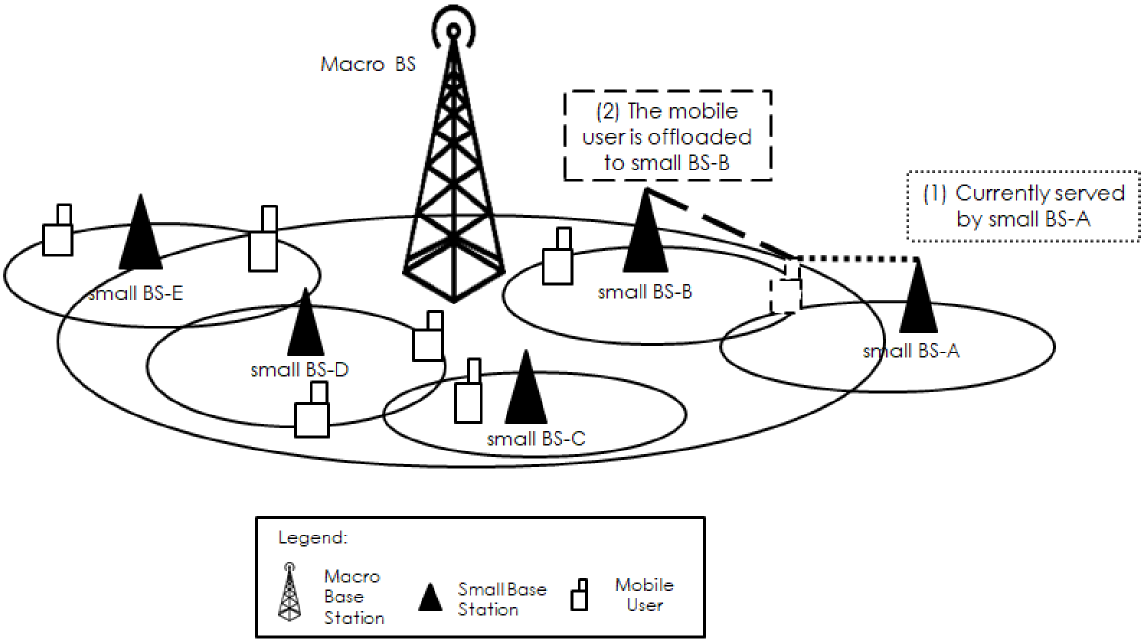

Figure 2.9: Horizontal offloading

a BS that is in sleeping mode consumes 10% of the power consumption but a BS that is in switching off mode consumes zero power consumption. However, by switching off certain BSs, it would tremendously help to reduce more than 50% of the power consumption as mentioned by the authors of [96].

Switching off strategy was studied by [48] to minimise the total energy consumption by switching off lightly loaded small BSs during low traffic load. The mobile users from the switched off BSs were offloaded to the neighbouring small BS. Similarly, this strategy was applied by [46] but the traffic was offloaded to macro BS instead of neighbouring small BS. A switching mechanism that considered increasing power consumption of the macro BS due to offloaded traffic from the switching off BSs was developed. The mechanism was for selecting the best set of small BSs to be switched off. An earlier research performed slightly different in switching off strategy where Mobile Network Operators (MNOs) switched off their macro BSs to save energy by offloading the traffic of its underutilised macro BSs to a third party [97]. The third-party is a company who leases the MNOs' capacity for small cell networks implementation.

Prior research used various modes of BSs that based on certain criteria for power and energy saving. Different power-saving modes were applied based on different depths. A higher power saving would be obtained when a sleep mode was deeper. However, a deeper sleep mode required a longer wake up time. Four different power-saving modes were applied based on: wake up time [34, 96, 98] and sleep time [23, 99, 100].

The examples of the wake-up time modes that have been studied are On, Standby, Sleep and Off modes. For switching off, the higher priority are given to the BSs that had lower energy efficiency as compared to the others. The mobile users that associated with the sleeping BSs would be reassociating with the neighbouring small BSs then. In contrast, the sleep time modes were studied based on four different times: 71 μs, 1 ms, 10 ms and 1 s. In this type of sleep modes were based on time depth that was how long it went to sleep in stages. A deep sleep mode meant longer latencies. Thus, more components such as signal processing power, amplifier inefficiency, and power losses would be deactivated. As a result, lower total power consumption can be obtained. On the contratry, one of the studies, that implemented sleep-time approach [100], applied a single depth mode but could be configured as many modes of depth based on temperature. The optimum depth was found using an exhaustive search.

2.2.8 Bias Factors for Adjusting Base Station Power Consumption

A bias factor is a positive biasing factor that has been used in many studies to adjust certain values. For example, to increase an average throughput [24], to maximise a number of mobile users [25], and to reduce a number of amplifier measurements [26]. According to [23], a bias factor could be applied to contribute to power saving as long as the constraints were fulfilled, especially, when the requirements of transmitting the power were reduced. Moreover, there was a study that set a bias factor at power amplifier [23] while another study controlled power using adaptive bias [101]. However, both studies reduced power consumption while maintaining high power output.

Generally, most of the previous studies applied bias factor to increase the received signal strength so that the users would be associated with the small BSs rather than the macro BS [102–104]. The reason is that most of the users tend to associate with a macro BS because the transmit power of a macro BS is higher than the small BSs. Therefore, by applying a bias factor at the small BSs, the coverage area could be extended, and this would help the small BSs to be selected for the user-cell association. As a result, more users were pushed from highly loaded macro BSs to lightly loaded small BSs [21, 22]. Besides that, CRE bias was implemented to minimise network energy consumption where small BSs could change their coverage by adjusting the user-cell association bias [105].

Like mentioned, most of the studies focused on applying bias factor for user-cell association purposes. Few studies were performed on bias power [101]. Based on the previous studies, a bias factor was set at Power Amplifier [101] while in this thesis, a bias factor will be set on each total power consumption of the BS mode. In a former study, the Direct Current (DC) was controlled by using adaptive bias where the mean value of the DC is reduced while maintaining high power gain [101]. In another work done by [106], a bias factor is set at each pico BS to adjust, either to increase or decrease, the coverage areas of pico BSs for load balancing. However, the authors in [21] added a positive bias factor to the small BSs' transmit power in order to increase coverage range where the users received power than it supposed to.

Chapter 3

Optimal Probability of Activating Base Stations

3.1 Overview

This chapter explains the three factors that lead to a two-tier network's higher energy efficiency [107]. The energy efficiency is formulated based on [27] and the optimisation problem was solved using a Genetic Algorithm. Section 3.1 starts with an overview of the chapter, and Section 3.2 explains the system model which describes SIR, and the power consumption model. Next, Section 3.3 describes further the problem formulation including the coverage probabilities of a BS and the performance metrics of the energy efficiency, and the problem formulation. Furthermore, Section 3.4 unfolds the problem solving in detail. The results obtained are analysed and extensively discussed in Section 3.5. Finally, the conclusion of this chapter is presented in Section 3.6.

3.2 System Model

The proposed system is a two-tier network deployment that consists of macro BSs and small BSs. Both tiers have different transmit powers where the macro BSs have a transmit power higher than the small BSs. The BSs are arranged according to some homogeneous PPP, Φ_m of intensity λ_m and Φ_s of intensity λ_s, for macro BSs and small BSs respectively. A closed-access configuration scheme is applied in the spectrum sharing network deployment where a portion of the spectrum is allocated for both macro BSs and small BSs.

While, the other portion is allocated for only the small BSs. This spectrum sharing is also known as partial spectrum reuse or PSR as described in Section 2.2.3. Since the closed-access configuration scheme is applied, the mobile users can only be associated with their respective tiers. For example, the macro BSs have their mobile users called macro BS mobile users or MUs, and the small BSs have their own mobile users called small BS mobile users or SUs. The MUs cannot connect to the small BSs and the SUs are unable to connect to the macro BSs.

The mobile users are located in the Voronoi cell and hence, each mobile user is associated with the nearest BS of its tier only. For instance, an MU can only be associated with the nearest macro BS while an SU can only be associated with the nearest small BS. Whether a mobile user belongs to a small BS or a macro BS is predetermined before joining the network. Besides, it is assumed that a BS can only serve one mobile user. Since spectrum sharing is applied, SUs are allowed to access the macro BSs' spectrum but MUs cannot access the small BSs' spectrum [27].

According to [83], it is impossible for all operators to install their own dedicated small BSs in all locations. The small BSs can be deployed by other companies or individuals to help the operator to serve the mobile users, and this small BSs can be mobile, it is known as mobile femtocell [108]. The small BSs are overlaid on the same area as the macro BSs' network. However, the situation would cause severe inter-tier interference and thus the interference between the small and macro BSs needs to be managed wisely.

Therefore, closed-access network is implemented to avoid inter-tier interference. In this system model, it is considered that each tier to have its own traffic where the macro BSs are having a number of MUs while the small BSs are having a number of SUs to serve. The MUs and the SUs are predetermined where it is assumed that they have been registered to their respective tiers. The macro BSs operate in their spectrum and they have the right of ownership. While, the small BSs need to get permission from the macro BSs to operate in the spectrum. Since the macro BSs agreed the small BSs to use their spectrum, the small BSs have to agree that the macro BSs can give the instruction for sending them to sleep mode when necessary.

It is assumed that the proposed two-tier network has two different constants transmit power. The transmit power of the macro BSs is $1/\mu$ while the small BSs is $1/c\mu$. It means that a macro BS's transmit power is assumed to be c times higher than a small BS's. The received power at a typical MU and SU in a distance r_m and r_s are described as $h_m r_m^{-\alpha}$ and $h_s r_s^{-\alpha}$, respectively. h_m and h_s represent the channel fading coefficients of the macro BSs and small BSs, respectively. Both h_m and h_s are assumed to follow exponential distribution $h_m \sim \exp(\mu)$ and $h_s \sim \exp(c\mu)$, respectively. r_m and r_s are mobile users' distances to the associated macro BSs and small BSs, respectively. In this paper, the path loss exponent is assumed to be larger than 2, that is, $\alpha > 2$.

The SINR received at an MU from a macro BS, γ_m, and the SINR received at an SU from a small BS, γ_s, respectively, can be expressed as

$$\gamma_m = \frac{h_m \, r_m^{-\alpha}}{I_{mm} + I_{ms} + \sigma^2} \tag{3.1}$$

$$\gamma_s = \frac{h_s \, r_s^{-\alpha}}{I_{ss} + I_{sm} + \sigma^2} \tag{3.2}$$

where $I_{mm} = \sum\limits_{i \in \Phi_m \backslash m_o} g_m \, d_m^{-\alpha}$ is the interference power coming from other macro BSs to the typical MU. $I_{ms} = \sum\limits_{i \in \Phi_s} g_s \, d_s^{-\alpha}$ is the interference power coming from all small BSs to the typical MU. $I_{ss} = \sum\limits_{i \in \Phi_s \backslash s_o} g_s \, d_s^{-\alpha}$ is the interference power coming from other small BSs to the typical SU. $I_{sm} = \sum\limits_{i \in \Phi_m} g_m \, d_m^{-\alpha}$ is the interference power coming from all macro BSs to the typical SU. m_o and s_o are the typical MU and SU located at origin, respectively. g_m and g_s denote the fading coefficients of the interfering macro BSs and small BSs. They are assumed to experience Rayleigh fading where $g_m \sim \exp(\mu)$ and $g_s \sim \exp(c\mu)$. d_m and d_s are the distances between the typical user and the interfering macro BSs and small BSs, respectively.

The power consumption is modelled in two categories. There are power consumptions either with sleeping BSs or without sleeping BSs. The power consumption of the two-tier network without sleeping BSs which considers BSs to be active all the time can be expressed as

$$P_{\text{active}} = \lambda_m(P_0^m + \mathcal{P}_m) + \lambda_s(P_0^s + \mathcal{P}_s) \tag{3.3}$$

The active BSs are presented by the density of macro BSs and small BSs, λ_m and λ_s, respectively. The power consumption of the two-tier network with sleeping BSs which considers BSs to be active some of the time and to be sleeping at other times can be expressed as

$$\begin{aligned} P_{\text{total}} = \lambda_m(&\mathcal{P}_m P_0^m + \mathcal{P}_m P_m + (1-\mathcal{P}_m)P_{\text{sleep}}^m) \\ &+\lambda_s(\mathcal{P}_s P_0^s + \mathcal{P}_s P_s + (1-\mathcal{P}_s)P_{\text{sleep}}^s) \end{aligned} \tag{3.4}$$

where $\mathcal{P}_m$ and $\mathcal{P}_s$, respectively represent the probabilities of activating a macro BS and a small BS. Therefore, the probability of inactive macro BS and small BS can be written as $1-\mathcal{P}_m$ and $1-\mathcal{P}_s$. P_0^m and P_0^s are the static power expenditure of macro BS and small BS, respectively. P_m and P_s are the radio frequency (RF) output power of macro BS and small BS, respectively. P_{sleep}^m and P_{sleep}^s are the power consumption of sleeping macro BS and small BS, respectively. The sleeping BSs are considered as inactive BSs as well.

3.3 Problem Formulation

In this section, the proposed scheme will be described further. There are three parameters: the probability of activating a macro BS, the probability of activating a small BS, and the PSR factor. The parameters can be adjusted to obtain the maximum coverage probability to maximise the energy efficiency of a two-tier heterogeneous network. The work can be summarised as follows

i) Deriving the coverage probabilities of the two-tier network that consists of the probabilities to activate the BSs for both small BSs and macro BSs as well as the PSR factor,

ii) Formulating a maximisation problem of the energy efficiency,

iii) Obtaining the fitness value known as an optimal value of the energy efficiency by using Genetic Algorithm that optimises the activating probabilities and the PSR, and

iv) Evaluating and comparing the energy efficiency performance of the proposed scheme with an existing work [27].

3.3.1 Coverage Probability of a Base Station

For both tiers, a BS's coverage probability is defined as a probability that a randomly chosen user can achieve a target SINR, T, from a serving BS. Mathematically, it can be written as $\mathbb{P}(\mathrm{SINR} > T)$.

Thus, the coverage probability for both macro cell network, $\mathbb{P}_m(\mathrm{SINR}_m > T)$, and small cell network, $\mathbb{P}_s(\mathrm{SINR}_s > T)$, can be defined as the following [27]

$$\begin{aligned}\mathbb{P}_m(\mathrm{SINR}_m > T) & \\ &= \pi\mathcal{P}_m\lambda_m \times \int_0^\infty e^{-\pi\mathcal{P}_m\lambda_m(1+\rho(T,1))v-\pi\mathcal{P}_s\kappa\lambda_s\rho(T,c)v-\mu T\alpha^2 v^{\frac{\alpha}{2}}}\,dv\end{aligned} \tag{3.5}$$

$$\begin{aligned}\mathbb{P}_s(\mathrm{SINR}_s > T) & \\ &= \pi\mathcal{P}_s\lambda_s \times \int_0^\infty e^{-\pi\mathcal{P}_s\lambda_s(1+\rho(T,1))v-\pi\mathcal{P}_m\lambda_m\kappa\lambda_s\rho(T,\frac{1}{c\kappa})v-c\mu T\alpha^2 v^{\frac{\alpha}{2}}}\,dv\end{aligned} \tag{3.6}$$

where

$$\rho(T,x) = T^{\frac{2}{\alpha}} \int_{T^{\frac{-2}{\alpha}}}^{\infty} \frac{1}{1+xu^{\frac{\alpha}{2}}} \tag{3.7}$$

We introduce two new parameters where $\lambda = \lambda_m/\lambda_s$ to represent the ratio of the macro BS density to the small BS density and $\mathcal{P} = \mathcal{P}_m/\mathcal{P}_s$ to represent the ratio of the probability of activating a macro BS to the probability of activating a small BS. The optimal ratio of the probability of activating the BSs can be written as $\mathcal{P}^* = \frac{\mathcal{P}_m}{\mathcal{P}_s}$.

We consider the interference-limited [42, 109] scenario in our work because the noise power is too small (i.e. $\sigma \to 0$) compared to the interference power that comes from other BSs regardless of the tier. Hence, the impact of noise in the network can be ignored and the SINR becomes signal-to-interference ratio (SIR). As a result, the coverage probability can be simplified as follows [27]

$$\mathbb{P}_m(\mathrm{SIR}_m > T) = \frac{1}{1 + \rho(T,1) + \frac{1}{\mathcal{P}\lambda}\kappa\rho(T,c)} \tag{3.8}$$

$$\mathbb{P}_s(\mathrm{SIR}_s > T) = \frac{1}{1 + \rho(T,1) + \mathcal{P}\lambda\rho(T,\frac{1}{c\kappa})} \tag{3.9}$$

When $\alpha = 4$, the coverage probability of both tiers can be simplified as in (3.10) and (3.11) [27].

$$\mathbb{P}_m(\mathrm{SIR}_m > T) = \frac{1}{1 + \sqrt{T}\left(\frac{\pi}{2} - \arctan\left(\frac{1}{\sqrt{T}}\right)\right) + \frac{\lambda_s}{\mathcal{P}\lambda_m}\kappa\sqrt{\frac{T}{c}}\left(\frac{\pi}{2} - \arctan\left(\sqrt{\frac{c}{T}}\right)\right)} \tag{3.10}$$

$$\mathbb{P}_s(\mathrm{SIR}_s > T) = \frac{1}{1 + \sqrt{T}\left(\frac{\pi}{2} - \arctan\left(\frac{1}{\sqrt{T}}\right)\right) + \frac{\mathcal{P}\lambda_m}{\lambda_s}\sqrt{cT\kappa}\left(\frac{\pi}{2} - \arctan\left(\frac{1}{\sqrt{cT\kappa}}\right)\right)} \tag{3.11}$$

3.3.2 Performance Metric for Energy Efficiency

The throughput obtained at a given BS-user link is given by $\mathbb{P}(\mathrm{SIR} > T)\log_2(1 + \mathrm{SIR})$ and the network throughput or here the average rate is used. The average rate is taken over all the links in the network. In each tier, the average rate is defined as the density of the BS of each tier multiplies by average probability and the achievable data rate i.e. $\lambda\,\mathbb{P}(\mathrm{SIR} > T)\log_2(1 + \mathrm{SIR})$. Therefore, the average rate of both macrocell network and small cell network can be written as follows

$$\begin{aligned} \text{Average Rate}_{\text{hetnet}} = {} & \lambda_m\mathbb{P}_m(\mathrm{SIR}_m > T)\log_2(1+T) \\ & + \lambda_s\mathbb{P}_s(\mathrm{SIR}_s > T)\log_2(1+T) \end{aligned} \tag{3.12}$$

The unit for this is $\mathrm{bits/sec}$ in the unit area. The average power consumption is measured in Watt. Therefore, the performance metrics of the two-tier network's energy efficiency are $\mathrm{bits/sec/Watt}$ in the unit area.

Consequently, the energy efficiency of a heterogeneous network is defined as the average rate of macrocell networks and small cell networks that are divided by the total power consumption of macrocell networks and small cell networks [6] as follows

$$\mathrm{EE}_{\mathrm{hetnet}} = \frac{\text{Average Rate}_{\mathrm{hetnet}}}{\text{Average Power}_{\mathrm{total}}} \tag{3.13}$$

Therefore, it is proposed to maximise the energy efficiency of a two-tier network by optimising the probabilities of activating a small BS ($\mathcal{P}_s$) and a macro BS ($\mathcal{P}_m$), as well as the PSR factor, (κ).

$$\begin{aligned} &\max_{\mathcal{P}_s, \mathcal{P}_m, \kappa} \ \mathrm{EE}_{\mathrm{hetnet}} \\ &\text{subject to} \\ &\qquad \mathrm{C1} : \mathcal{P}_s \in [0,1] \\ &\qquad \mathrm{C2} : \mathcal{P}_m \in [0,1] \\ &\qquad \mathrm{C3} : \mathbb{P}_s(\mathrm{SIR}_s > T)\, \kappa \log_2(1+T) \geq \omega_s;\ \kappa \in (0,1] \\ &\qquad \mathrm{C4} : \log_2(1+T) \geq \omega_m \end{aligned} \tag{3.14}$$

where $\mathcal{P}_s$ and $\mathcal{P}_m$ are between 0 (including) and 1 (including), $\kappa\ \log_2(1+T)$ is the rate of a small cell's user (that shares the entire spectrum) that must be larger than its threshold value, ω_s, $\log_2(1+T)$ is the rate of a macro cell's user that must be larger than its threshold value, ω_m. However, the PSR factor, κ, must be between 0 (excluding) and 1 (including). This indicates that the sharing must not be 0 (means nothing is shared) and 1 (shares 100% of the spectrum).

3.4 Problem Solving

In the following subsection, the best target SIR that works for obtaining the highest energy efficiency is identified. The value is used to solve the problem by using a Genetic Algorithm. Therefore, the best value of energy efficiency will be achieved by using the best SIR for all cases.

3.4.1 Identifying the Best Target SIR

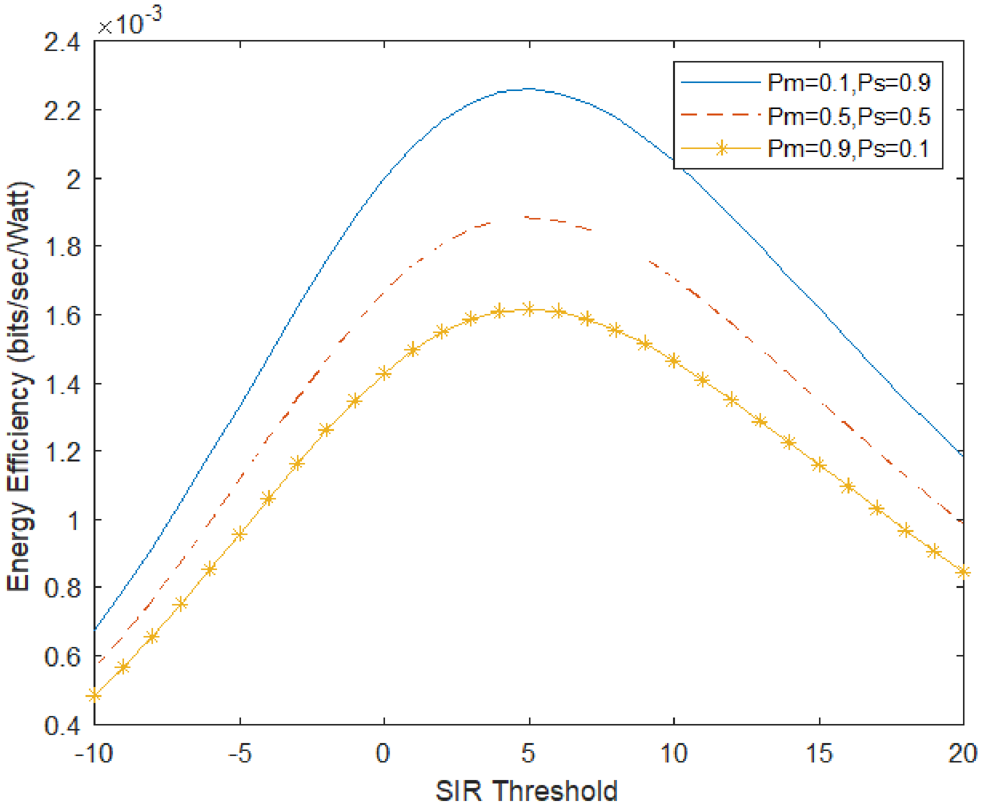

Figure 3.1: Energy Efficiency vs. SIR Threshold

In order to find the best target SIR that works for our proposed scheme, the probabilities of activating the BSs and the PSR factor are fixed as shown in Figure 3.1. As a result, the best target SIR is obtained as 5 dBm regardless of the probabilities. This value will be used for the rest of this chapter unless stated otherwise. Since we found the best SIR that works for this model is 5 dBm, the T is fixed to be 5 dBm to obtain the best energy efficiency by optimising the three parameters: the probability of activating macro BS, the probability of activating small BS and the PSR factor.

3.4.2 Genetic Algorithm for Optimal Solutions

Genetic Algorithm has been widely used in various fields such as wireless sensor network [49, 110], cognitive radio network [57], super-dense heterogeneous network [111], and renewable energy area [112]. However, less work applying the Genetic Algorithm was carried out in maximising a heterogeneous cellular network's energy efficiency.

The examples of studies that applying the Genetic Algorithm in wireless sensor network were minimising energy during packet transmission [49], extending network life [110], and maximising energy efficiency [33]. Nevertheless, in a cognitive radio network, the Genetic Algorithm was improved by proposing a two-tier crossover Genetic Algorithm to improve the conventional Genetic Algorithm such as extending the crossover. According to [110], the conventional algorithm has limited searching space, slow convergence speed, and not entirely stable. Similarly, optimum energy efficiency value was discovered by using an improved version of the Genetic Algorithm in super-dense heterogeneous network [111]. Nevertheless, only the conventional algorithm was used to increase energy efficiency in renewable energy areas [112] and heterogeneous cellular network [48] without having the algorithm to be improved. However, the algorithm was used together with a gradient-based method that removes the computation of derivation to find the optimum system capacity in the spectrum sharing case [113].

In recent work, a Genetic Algorithm was used to centralise management process by selecting the appropriate mode of each BS depending on the daily traffic load [33]. This helped the network's energy efficiency to be increased. Besides that, a Genetic Algorithm was also used to find an optimal solution for minimising energy consumption [49] and used as a mechanism to dynamically switch off/on and improve energy efficiency [48]. The energy consumptions minimisation was implemented by switching off BSs that were lightly loaded.

Once we obtained the best target SIR that the proposed system works best, the objective problem is solved by using Genetic Algorithm. By running the Genetic Algorithm, the

Algorithm 1: Genetic Algorithm

```
START
Generate the initial population, $populate = 200$;
Compute the fitness i.e. $\mathrm{EE}_{\mathrm{hetnet}}$ Equation (3.13);
while $i \leq populate$ do
    Select the two fittest values;
    Crossover the fittest values at $80\%$ of probability rate;
    Mutate the selected random genes that change the value;
    Compute the fitness i.e. $\mathrm{EE}_{\mathrm{hetnet}}$ Equation (3.13) ;
END
```

best combination of the three parameters P_s, P_m and κ, that optimise the energy efficiency is obtained. The first population, that comprises of P_s, P_m and κ, was randomly initialised by the Genetic Algorithm. Then, it is used to calculate the energy efficiency as in Equation (3.13). Technically, the Genetic Algorithm processes the values through selection, crossover, and mutation. In selection, the Genetic Algorithm selects the two combinations of the three parameter values that contribute to an optimal energy efficiency. Then, the values undergo crossover process where the parameters would be exchanged to each other to get a new result, which is normally better. This new result is added to the population. After that, the parameters go through the last process which is mutation. During this process, the values of the parameters are flipped such as the value 0 is flipped to 1 and 1 to 0. Finally, a new value of the energy efficiency is calculated based on value the parameter values after undergone mutation process. This cycle is repeated until the final population is reached or until it is converged. Once converged, the values obtained are considered optimal, and it is said that the best solution has found.

As a result, the optimal values of the three combination parameters: the probability of activating a small BS $\mathcal{P}_s$, probability of activating a macro BS $\mathcal{P}_m$ and a PSR factor κ that could maximise the energy efficiency were discovered. The lower limit was set to be 0 for all parameters $\mathcal{P}_s$, $\mathcal{P}_m$ and κ. However, the upper limit was set to be 1 for $\mathcal{P}_s$, $\mathcal{P}_m$. While, 1 is set for κ to indicate that the whole spectrum macro BS can be shared for the best energy efficiency and coverage. The main idea of the Genetic Algorithm can be illustrated in Algorithm 1.

3.5 Results and Discussion

After running the Genetic Algorithm as shown in Algorithm 1, it is found that the optimum values of the energy efficiency can be obtained after the population reached 50 and the fittest value is 4.6904x10^{-3}. This result was contributed by the three combination parameters and the values are $\mathcal{P}_s = 0.977$, $\mathcal{P}_m = 0.65$ and $\kappa = 0.999$. The results are shown in Table 3.1. Based on the result, a higher $\mathcal{P}_s$ and κ would give a higher energy efficiency. The combination of the three parameters will be used in this section unless stated otherwise, to compare with current work.

Table 3.1: Optimal values of each parameter that contribute to the maximum energy efficiency of the two-tier network.

$\mathcal{P}_s$	$\mathcal{P}_m$	κ	**GA**	**Existing**
0.977	0.65	0.999	4.6904x10^{-3}	2.4x10^{-3}

The proposed scheme was compared with the existing scheme that was studied in [27]. The difference between our scheme and the existing scheme is that the proposed scheme uses the probabilities of activating BSs to be random and the values were found by using Genetic Algorithm. Then, the ratios of both probabilities were calculated. While, the existing scheme calculated the probabilities of activating BSs and ratios based on assumptions and mathematical derivations. Based on the Genetic Algorithm result, it can be concluded that the Genetic Algorithm produces better results than the assumptions and mathematical derivations.

Table 3.2 shows the parameter value that are used in getting the optimum values by the Genetic Algorithm.

Table 3.2: Parameter values that are used in numerical results .

Variables	**Values**	**Variables**	**Values**
λ_m	0.5 BS/km^2 [27]	$\mathcal{P}_m$	$[0, 1]$
λ_s	0.1 BS/km^2 [27]	$\mathcal{P}_s$	$[0, 1]$
P_0^m	130 Watt [55]	P_0^s	4.8 Watt [55]
P_m	20 Watt [55]	P_{sleep}^m	75.0 Watt [55]
P_s	0.05 Watt [55]	P_{sleep}^s	2.9 Watt [55]

Coverage Probability vs. SIR

The coverage probabilities were plotted in a graph and compared with the reference [27] using the obtained values shown in Table 3.1. In general, reference [27] applied PSR scheme and base station sleeping model for minimising the energy consumption in closed-access network where interference-limited case was considered. The probabilities for both macro-tier and micro-tier networks were derived by using stochastic geometry. Then, the coverage probabilities for both tiers were maximised for optimising both the PSR factor and the Active Probability Ratio (APR) of the tiers. The relationship between the optimal PSR factor and APR was analysed for minimising energy consumption. The target SINR was set to be 20 dB. Consequently, the energy consumption can be saved up to 50% by using the proposed optimisation method where the macro BSs' transmit power was five times than the micro BSs'. However, the authors did not maximise the network's energy efficiency.

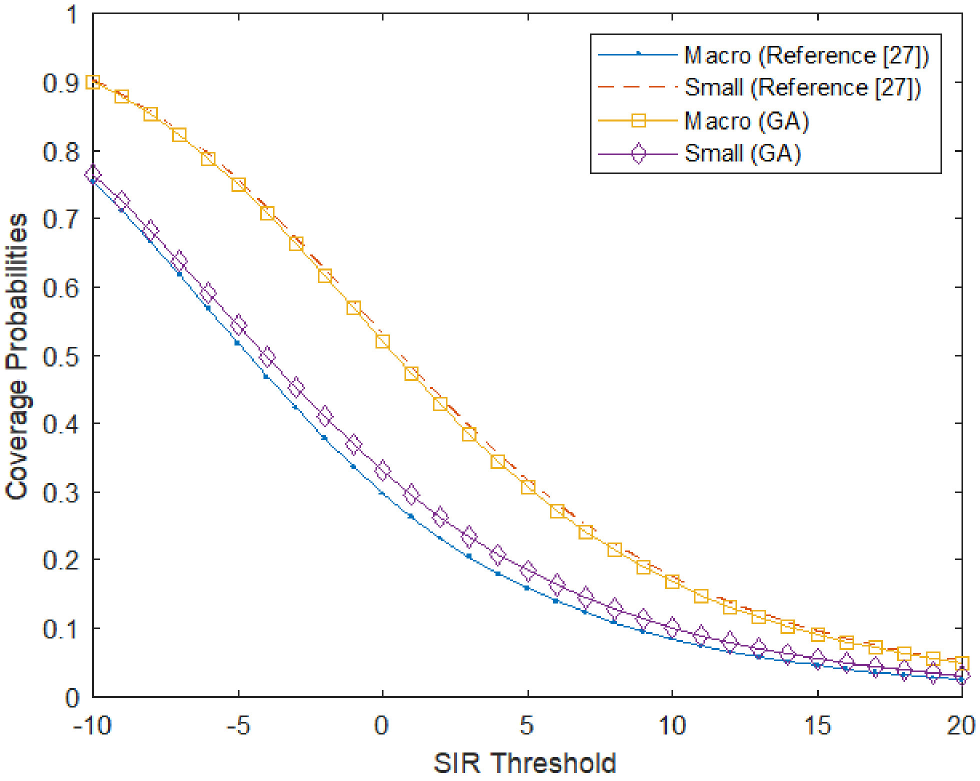

Figure 3.2: Coverage Probability vs. SIR Threshold

Referring to Figure 3.2, the macro BS's coverage probability of the proposed scheme performed better than the macro BS's coverage probability of the existing work. In contrast, the small BS's coverage probability of the current scheme performed better than our proposed scheme. The proposed scheme lets the probability of activating macro BSs and small BSs to be random and the Genetic Algorithm obtained the optimal values.

The Impact of Energy Efficiency towards Probabilities of Activating Macro BS and Small BS

The probabilities of activating a macro BS and the probabilities of activating a small BS were compared in terms of energy efficiency. The probability of activating a small BS ($\mathcal{P}_s = 0.977$) was fixed when measuring the probability of activating a macro BS. On the other hand, the probability of activating a macro BS ($\mathcal{P}_m = 0.65$) was fixed when measuring the probability of activating a small BS.

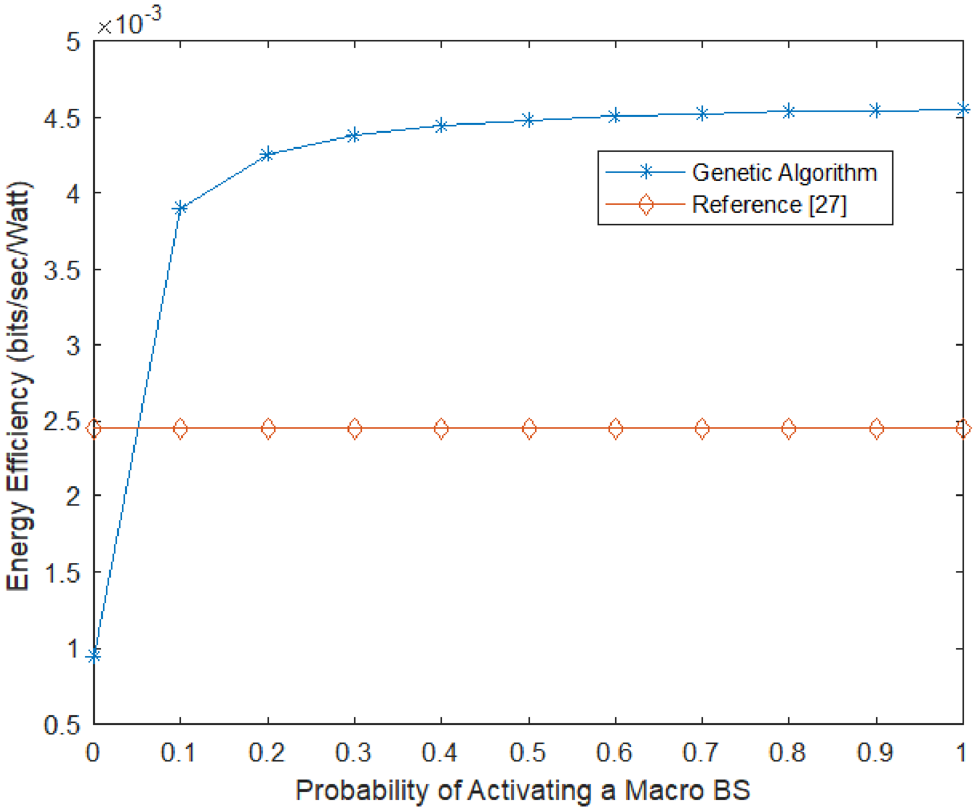

Figure 3.3: Energy Efficiency vs. Probability of Activating a Macro BS

Figure 3.3 shows that energy efficiency decreases as the probability of activating a macro BS increases. When the probability is 0, the energy efficiency is above 0.9449x10^{-3} because there is a value for $\mathcal{P}_s$. However, the best probability of activating a macro BS is at 1 because it gives the highest energy efficiency. The graph shows that the highest energy efficiency that the proposed scheme can achieve is 4.6x10^{-3}. Comparing to the current work, the highest energy efficiency that the two-tier network can achieve is only 2.4x10^{-3}.

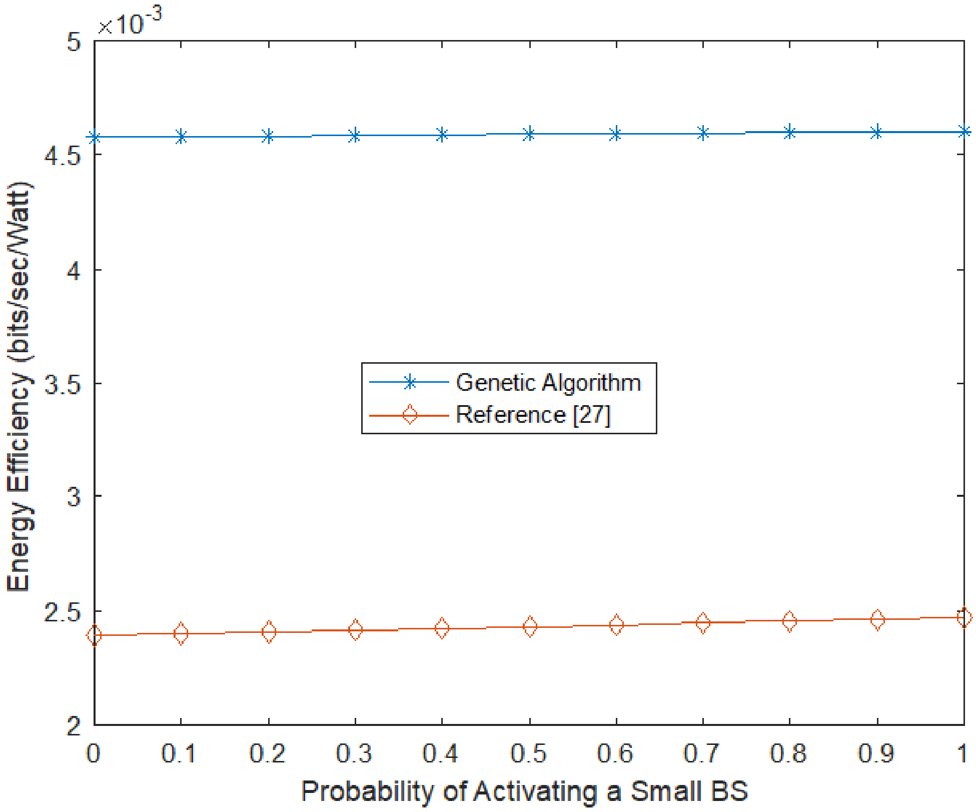

Figure 3.4: Energy Efficiency vs. Probability of Activating a Small BS

Figure 3.4 shows energy efficiency vs. probability of activating a small BS where the value of activating a macro BS is fixed to 0.65 based on the Genetic Algorithm result in Table 3.1. As a result Figure 3.4 indicates that energy efficiency increases as the probability of activating a small BS increases. Finally, the energy efficiency reached 4.6x10^{-3} when the probability of activating a small BS is 1, where at the same time the probability of activating a macro BS is 0.65. Comparing to the current work, the highest energy efficiency that the two-tier network can achieve is only $2.4\text{x}10^{-3}$. Therefore, this proves that our proposed scheme outperformed the existing work in terms of the whole network's energy efficiency.

3.6 Summary

In this chapter, the system model according to the current work was presented. Based on the system model, three main factors that contributed to higher energy efficiency were determined. There are activation probability of a small BS, a macro BS's activation probability and a PSR factor. Finally, the optimisation problem was solved by using Genetic Algorithm. In the next chapter, an optimal density of active BSs will be discovered to obtain a higher energy efficiency of a two-tier network in separation architecture or CDSA environment.

Chapter 4

Decision Making of Switching Off Small Base Stations

4.1 Overview

This chapter explains the proposed algorithm namely Switching Off Decision and User Association (SODUA) to maximise the energy efficiency of a two-tier network [114]. The first objective of the thesis was presented in the previous chapter that is different from this chapter. Chapter 3 is about maximising energy efficiency of a two-tier network that consists of a set of macro BSs and a set of small BSs in a closed-access configuration. Only users that belong to each tier can be connected to the BS that belongs to the same tier. However, this chapter's model considers only one macro BS at origin and several small BSs that scattered over a network in an open-access configuration. Besides, Chapter 3 did not consider CDSA but it only considered the activation probability of a small BS and activation probability of a macro BS as well as PSR factor. Nevertheless, in this chapter, the proposed algorithm maximises the energy efficiency by jointly optimising the decision making of switching off active small BSs and the user-cell association. The difference between this chapter to the previous is that a CDSA is applied, where a macro BS controls all the small BSs under its coverage. The details about the CDSA was explained in Chapter 2. Section 4.1 starts with an overview of the chapter and followed Section 4.2 which describes SIR, achievable downlink rate, user-cell association, energy efficiency, and power consumption model. Section 4.3 describes further the proposed SODUA algorithm including problem formulation and problem solving. Section 4.4 explains and analyses the result while Section 4.5 concludes this chapter.

4.2 CDSA Implementation

This chapter models small BSs and mobile users to be randomly located on a mathematical space. In contrast, only one macro BS is deployed where the macro BS is located at the origin, or known as the network center.

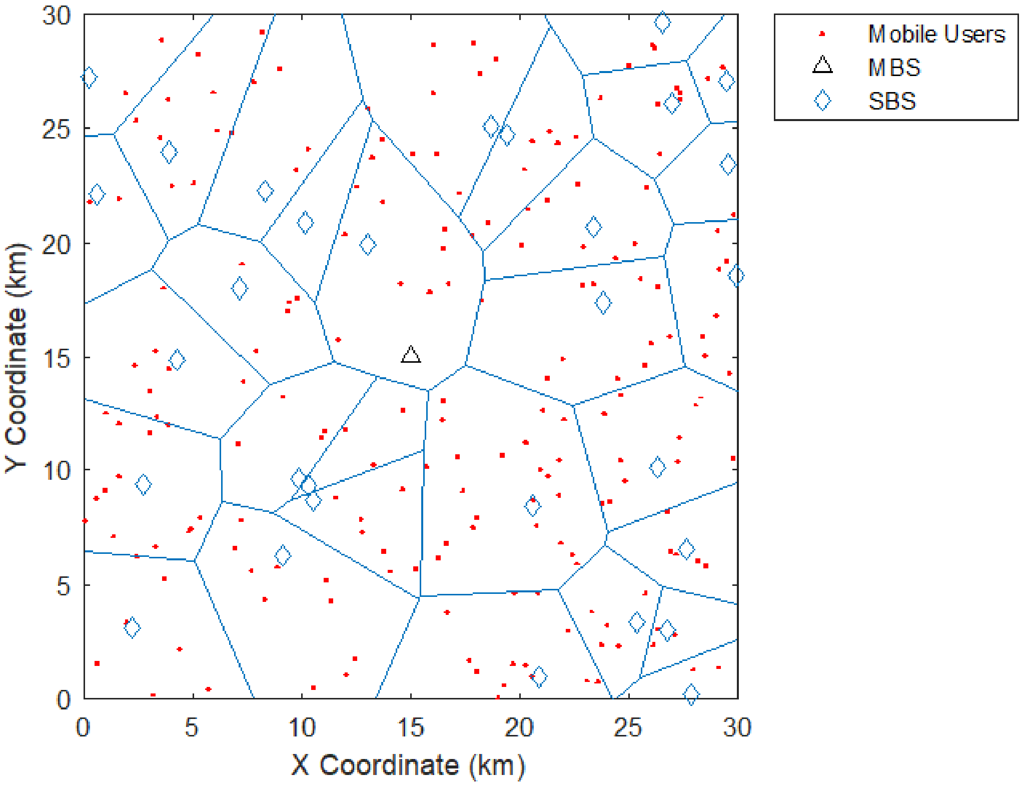

Figure 4.1: Distributions of small BSs and mobile users with macro BS at origin

The proposed network deployment is a two-tier network that comprises one macrocell network (MCN) and several small cell networks (SCNs). As the macro BS is located at the origin, o, the small BSs are arranged according to an independent PPP where the set of small BSs is represented by $\mathcal{S}$. Similarly, the mobile users are arranged according to another independent PPP where the set of mobile users is represented by $\mathcal{U}$. Hence, S and U, respectively represent the number of small BSs and mobile users. In Chapter 3, the network deployment was closed-access configuration scheme but in this chapter, the network is deployed in an open-access configuration scheme. Therefore, the mobile users can be associated with any tiers of BSs depending on the user-cell association method described here in this chapter.

As for the user-cell association, every single mobile user can be associated with only one small BS that offers the highest SIR value. The mobile users are associated with the small BS that offers the highest signal strength of a given set of $\mathcal{S}$ and $\mathcal{U}$. The small BSs and the mobile users are located in Voronoi tessellation where all the points are randomly located. This can be illustrated in Figure 4.1.

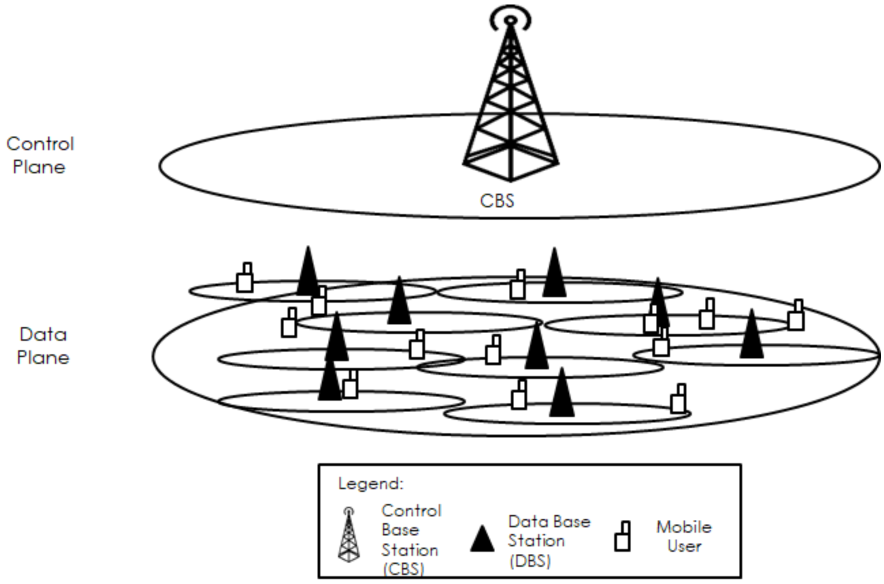

Figure 4.2: Control-Data Separation Architecture (CDSA)

On top of that, CDSA, or the concept of signalling and data separation, is proposed as introduced by [89]. Conceptually, the separation architecture allows a macro BS to control all the small BSs in the network and transmits the signalling information separately to provide full coverage and transmit a high data rate. The proposed architecture of the CDSA is illustrated in Figure 4.2.

In CDSA, the two layers or planes divide the small BSs and the macro BS. The macro BS area located is called Control Plane (CP) while, the area where the small BSs are located is called Data Plane (DP). The macro BS, also known as a Control Base Station (CBS), has its territory where it has full control toward the small BSs, also known as Data Base Stations (DBSs) that are under its coverage (see Figure 4.2). The CBS has the needed primary information such as the location of the DBSs, the location of the mobile users and the SIR of each communication link.

4.2.1 Channel Model

The proposed two-tier network has two different parameters of transmit powers. First, the transmit power of macro BS is denoted by P_0 at the origin. Second, the transmit power of small BSs that is denoted by P_s for all small BS s. The received power at a typical mobile user connected to one of the small BSs in the distance r_s is described as $P_s h_s {r_s}^{-\alpha}$ where h_s represents the channel fading coefficient of the small BSs. The channel fading is an attenuation of a signal due to various obstacles that affect the signal propagation. The effect of the signal propagation was discussed in Chapter 2.1.3. The fading coefficient of the small BS h_s is best described to follow exponential distribution $h_s \sim \exp(\mu)$. The r_s is the distance from the mobile user u to the associated small BS s. The path loss exponent is assumed to be larger than 2, $\alpha > 2$. Further explanation on the path loss exponents was explained in Section 2.1.3.

4.2.2 User-cell Association in CDSA

As explained in Section 2.2.2, the user-cell association indicator variable indicates that a mobile user is connected to a small BS. The indicator variable, a_{su}, is set to 0 if no user is associated with small BS s, and it is set to 1 if the mobile user u is associated with small BS s. Similarly, the user-cell association can be mathematically written as in Equation (2.13). However, in this system model, the user-cell association based on the highest SIR is controlled by the macro BS either to let the small BS remain active or to switch it off in CDSA. If small BS is switched off, no energy is consumed by the small BS [45]. In this case, $P_s^{\text{stat}} + P_s = 0$ when $a_{su} = 0$; $\forall u \in \mathcal{U}$ of that particular small BS. P_s^{stat} is the static power consumption of the small BSs and P_s is the small BS's transmit power.

The user-cell association can be described similar to the one that described in Chapter 2. Nevertheless, each mobile user in set $\mathcal{U}$ can only be associated with one of the small BSs in set $\mathcal{S}$. Referring to the user-cell association in Equation (2.11), if the small BS s is not in the set of active small BSs, $\mathcal{S}^{\text{act}}$, the indicator variable, a_{su}, is set to 0 for all users since the small BS cannot serve any mobile users. This situation can be represented as $\mathbb{A}_{\mathcal{S}^{\text{act}}} = \{a \mid \forall u \in \mathcal{U},\ a_{su} = 1 \text{ if } s \in \mathcal{S}^{\text{act}} \text{ and } a_{su} = 0 \text{ if } s \notin \mathcal{S}^{\text{act}}\}$. Since this model is applied in the CDSA where the macro BS is the centre of controlling the whole network, it must always be active all the time [115]. However, the small BSs with low traffic load will be switched off to save the energy and keep the network's power consumption at an optimum level.

4.2.3 Signal-to-interference Ratio

In a CDSA, both macro BS and small BSs use different spectrum [20]. Hence, the mobile users are experiencing interference coming from the other small BSs only because the mobile users are served by the small BS only. Different from closed-access scheme, no interference is coming from macro BS because the macro BS does not serve any mobile users. Besides, the interference-limited environment is considered because the noise power is too small and it is approaching zero (i.e. $\sigma \to 0$) as compared to the interference coming from the other small BSs. Thus, SIR is used rather than SINR and this can be expressed as follows

$$\gamma_{su} = \frac{P_s \mid h_{su} \mid^2 \, r_{su}^{-\alpha}}{\sum\limits_{i \in \mathcal{S} \setminus s} \sum\limits_{u \in \mathcal{U}} P_i \, h_{iu} \, r_{iu}^{-\alpha}} \tag{4.1}$$

where index-i represents the other small BSs, except the serving small BSs, that are interfering the typical mobile user.

4.2.4 Achievable Downlink Rate per Mobile User

The data rate over a specified bandwidth of each communication in the presence of interference power, between mobile user u and small BS s, can be achieved by the following expression.

$$R_{su} = B\log_2\left(1+\gamma_{su}\right)a_{su}\ ;\ \forall s \in \mathcal{S}, u \in \mathcal{U} \tag{4.2}$$

where B is the system bandwidth. Consequently, the total achievable data rate of all mobile users that are associated to their respective small BSs can be calculated as follows

$$R^{\text{tot}} = \sum_{s\in\mathcal{S}}\sum_{u\in\mathcal{U}} B\log_2\left(1+\gamma_{su}\right)a_{su}. \tag{4.3}$$

This chapter focuses on high data rate services which is offered by small BSs. Since a macro BS offers low data rate services and it does not serve any mobile users, the rate of the macro BS is not considered in this chapter. Therefore, only the small BSs' rates are considered.

4.2.5 Power Consumption Model in the CDSA

Since the macro BS is always active to control the whole two-tier network, the macro BS's power consumption must always have a value. However, the small BS can be switched on or off depending on the load of the traffic. The transmit powers of the small BSs vary between the minimum and the maximum allowable transmit power as $P_s^{\min} \le P_s \le P_s^{\max}$. The minimum and the maximum values have been described in Chapter 2. To calculate the power consumption of the two-tier network, both the power consumption of the macro BS, P_0^{tot}, and the total power consumption of the small BSs, P_s^{tot}, are added and this can be expressed as follows.

$$P_0^{\text{tot}} = P_0^{\text{stat}} + P_0 \tag{4.4}$$

$$P_s^{\text{tot}} = \sum_{s\in\mathcal{S}}\sum_{u\in\mathcal{U}} \left(P_s^{\text{stat}} + P_s\right)a_{su} \tag{4.5}$$

$$P^{\text{tot}} = P_0^{\text{tot}} + P_s^{\text{tot}} \tag{4.6}$$

where P_0^{stat} and P_s^{stat} are the static power consumption of the macro BS and the small BSs. WhileP_0 and P_s are the transmit power of the macro BS and small BS s. The user-cell association indicator, a_{su}, in Equation (4.5), indicates that the user is associated to a small BS if $a_{su} = 1$ as explained in Section 4.2.2. Finally, when the values of the indicator are summed up, the number of users that are connected to each small BS can be obtained.

4.2.6 Energy Efficiency

Since the macro BS does not serve any mobile users in CDSA, no achievable data rate is considered for communications. The total power consumption of macro and small BSs are considered because the macro BS is always active to serve the whole network. In this chapter, a two-tier network's energy efficiency is defined as how much data can be transferred from all BSs to all associated mobile users over a two-tier network's total power consumption. Alternatively, it can be said as the total achievable data rate of the small BSs, in $\mathrm{bit/sec}$, over the total power consumption of both macro BS and small BSs, in Watt. For better network performance, a higher energy efficiency is needed. Therefore, the equation can be expressed as follows

$$\begin{aligned}\mathrm{EE}(\mathcal{S}, a_{su}) &= \frac{\sum_{s\in\mathcal{S}}\sum_{u\in\mathcal{U}} B\ \log_2(1+\gamma_{su})a_{su}}{P_0^{\mathrm{stat}} + P_0 + \sum_{s\in\mathcal{S}}\sum_{u\in\mathcal{U}}(P_s^{\mathrm{stat}} + P_s)a_{su}} \\ &= \frac{R_{\mathrm{tot}}}{P_0^{\mathrm{tot}} + P_s^{\mathrm{tot}}}\end{aligned} \tag{4.7}$$

Substituting Equation (4.3), (4.4), and (4.5) into Equation 4.7, the equation can be written as

$$\mathrm{EE} = \frac{R^{\mathrm{tot}}}{P^{\mathrm{tot}}}. \tag{4.8}$$

The unit measurement of the energy efficiency performance is $\mathrm{bits/sec/Watt}$ or $\mathrm{bits/Joule}$.

4.3 Switching Off Decision and User Association Algorithm

In this section, the problem formulation of the proposed Switching Off Decision and User Association Algorithm (SODUA) is discussed in detail. The algorithm focuses on the number of small BSs in a given service area. Hence, the number of small BSs and the size of the area are given. The algorithm decides whether or not the small BSs should be switched off based on the traffic load. Once the small BSs are switched off, all the users that are associated with them will be offloaded to the other active small BSs that offer the highest SIR. It means that the algorithm finds the best small BSs associated with the mobile users subject to some constraints to achieve a higher energy efficiency. The constraints will be described further in Section 4.3.2.

4.3.1 Switching Off Strategy

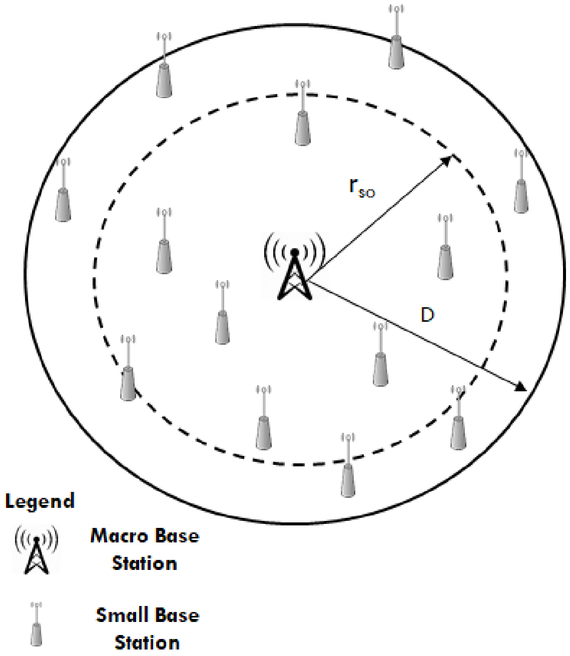

Figure 4.3: Switching off area

The small BSs' switching off strategy that is applied, in this research, is based on a repulsive scheme. This repulsive scheme was explained in Section 2.1.5 under Small BS Sleeping Area that was applied by [50]. However, in this chapter, the repulsive scheme based switching off strategy is applied instead of the sleeping strategy. As described in the previous section, this scheme allows the macro BS to switch off only the small BSs that reside in the switching off radius, r_{so}, and, is within the macro BS's coverage radius, D as illustrated in Figure 4.3. The macro BS is at the origin while the small BSs are located randomly on the plane. The macro BS sets its allowable switching off area to allow only the selected small BSs in the area to be switched off. Meanwhile, the small BSs outside the area will not be switched off to ensure the mobile users outside the area are served by them. This is because the farther the radius, the weak the macro BS's transmit power signal is. Similar to [50], the average switching off ratio, $\overline{\Lambda}$, can be calculated based on the switching off area to the macro BS's coverage area as

$$\overline{\Lambda} = \frac{\pi r_{\mathrm{so}}^2}{\pi D^2}. \tag{4.9}$$

4.3.2 Problem Formulation

The proposed SODUA problem can be formulated as follows.

$$\begin{aligned}
&\max_{\mathcal{S}^{\mathrm{act}},\, a_{su}} \quad \mathrm{EE} \\
&\text{subject to} \\
&\qquad \mathrm{C1}: \sum_{u\in\mathcal{U}} R_{su} \geq R_s^{\min} \; ; \; \forall i \in \mathcal{S}^{\mathrm{act}} \\
&\qquad \mathrm{C2}: P_0^{\min} \leq P_0 \leq P_0^{\max} \\
&\qquad \mathrm{C3}: P_s^{\min} \leq P_s \leq P_s^{\max} \; ; \; \forall s \in \mathcal{S}^{\mathrm{act}} \\
&\qquad \mathrm{C4}: \sum_{s\in\mathcal{S}} a_{su} \leq 1 \; ; \; \forall u \in \mathcal{U} \\
&\qquad \mathrm{C5}: a_{su} \in \{0,1\} \\
&\qquad \mathrm{C6}: \sum_{u\in\mathcal{U}} a_{su} \geq \underline{U} \; ; \forall s \in \mathcal{S}^{\mathrm{act}} \\
&\qquad \mathrm{C7}: \mathrm{count}\left(\sum_{u\in\mathcal{U}} a_{su} \geq \underline{U}\right) \leq \overline{\Lambda}; \; \forall s \in \mathcal{S}^{\mathrm{act}}
\end{aligned} \tag{4.10}$$

where the constraints $\mathrm{C1} - \mathrm{C7}$ can be described as follows.

C1: The total data rate of each active small BS, $\mathcal{S}^{\mathrm{act}}$, must be larger than the minimum data rate of each small BS,

C2: The transmit power of the macro BS must be between the minimum, $P_0^{\min}$, and the maximum, $P_0^{\max}$, allowable transmit power where $P_0^{\min} = 0$ Watt and $P_0^{\max} = 20$ Watt or $P_0^{\max} = 43$ dBm [55],

C3: The transmit power of each active small BS must be between the minimum, $P_s^{\min}$, while the maximum, $P_s^{\max}$, allowable transmit power. In this research, a femto BS is used, hence, $P_s^{\min} = 0$ Watt and $P_s^{\max} = 0.05$ Watt or $P_s^{\max} = 17$ dBm [55],

C4: Only one-to-one association is allowed for communication. Thus, one mobile user can only be connected to a single small BS,

C5: The user association indicator, a_{su}, is a binary digit variable, where 0 indicates that no association and 1 indicates that mobile user u is associated with small BS s, and

C6: To allow the small BS to remain active, the number of mobile users of each small BS must be larger than the minimum number of mobile users of each small BS, $\underline{U}$, which is automatically calculated by the algorithm. In other words, the small BSs will be switched off if the number of mobile users is less than the threshold value that is calculated by the algorithm, and

C7: The average number of small BSs active must be less than the average switching off ratio, $\overline{\Lambda}$. The numerical calculation will be shown in Section 4.4 Equation (4.11).

4.3.3 Problem Solving

Algorithm 2: Switching Off Decision and User Association (SODUA) Algorithm

```
START
while $m < M$ do
    $\gamma_{su} = \text{rand}(U, S)$
    $\gamma_{sj}^{\max} = \max \gamma_{su};\ j \in \mathcal{U}_{\gamma}^{\max}$
    $\gamma_{su}^{2} = \gamma_{su}$
    while $j \in \mathcal{U}_{\gamma}^{\max}$ do
        $a_{sj} = 1$
        $R_{sj} = W_{su} \log_2(1 + \gamma_{sj}^{\max})$
        $\gamma_{sj}^{2} = 0$
        END
    $P_s = \text{rand}(1, S)$
    $a^{\text{tot}} = \sum_{j \in \mathcal{U}_{\gamma}^{\max}} a_{sj};\ \forall s \in \mathcal{S}$
    $\underline{U} = \text{average}(a^{\text{tot}})$
    Offloading Section
    $\mathcal{S}_{k}^{\text{ina}} = \text{find}(a^{\text{tot}} < \underline{U})$
    $\mathcal{S}^{\text{act}} = \text{find}(a^{\text{tot}} \geq \underline{U})$
    $S_{\text{sbs}}^{\text{ina}} = \text{count}(\mathcal{S}_{k}^{\text{ina}})$
    $S_{\text{sbs}}^{\text{act}} = \text{count}(\mathcal{S}^{\text{act}})$
    $S_{\text{user}}^{\text{ina}} = \text{count}(\sum_{u \in \mathcal{U}} a_{su} = 1;\ \forall s \in \mathcal{S}_{k}^{\text{ina}})$
    if $S_{\text{sbs}}^{\text{ina}} > \overline{\Lambda}$ then
        $P_{\text{last}} = 1$
        END
    $\gamma_{sk}^{\max 2} = \max \gamma_{su}^{2}$
    $R_{sk}^{\text{ina}} = W_{su} \log_2(1 + \gamma_{sk}^{\max});\ \forall k \in \mathcal{U}_{\gamma}^{\max}, s \in S_{k}^{\text{ina}}$
    $R_{sk}^{\text{act}} = W_{su} \log_2(1 + \gamma_{sk}^{\max 2});\ \forall k \in \mathcal{U}_{\gamma}^{\max 2}, s \in S^{\text{act}}$
    $R_{sj}^{\text{new}} = R_{sj} + \sum_{k \in \mathcal{U}_{\gamma}^{\max 2}} R_{sk}^{\text{act}} - \sum_{k \in \mathcal{U}_{\gamma}^{\max}} R_{sk}^{\text{ina}}$
    END

$\text{EE} = \frac{R_{sj}^{\text{new}}}{P_0^{\text{tot}} + P_{\text{act}}^{\text{tot}}}$
END
```

The SODUA algorithm is proposed to determine which small BSs to be switched off based on the traffic load. The user-cell association is based on the highest SIR received by each mobile user in the network. The algorithm associates a mobile user with a small BS that offers the highest SIR and calculates each small BS load. The algorithm, then, decides to switch off the small BSs that have fewer mobile users than the threshold value. Consequently, the mobile users will be offloaded to the other active small BSs that offer the highest SIR.

The proposed algorithm generates 1000 times samples and it is shown in Algorithm 2. For all possible links between the mobile users and the small BSs in $U \times S$ matrix, the SIRs are generated randomly, γ_{su}. Then, the highest SIR, $\gamma_{sj}^{\max}$, is sought for each mobile user where j is the user's index that received the highest SIR, $j \in \mathcal{U}_{\gamma}^{\max}$. In order to perform offloading later, the γ_{su} is copied to a new variable γ_{su}^{2}.

Then, the user-cell association indicator variable, a_{su} is assigned to 0 or 1 depending on the association value. The indicator variable is set to 1 if mobile user u is associated with small BS s. Otherwise, the indicator variable is set to 0. Remember, this is a one-to-one connection only where one user is associated with only one small BS but one small BS can serve more than one mobile user. Next, the data rate of each user, R_{sj} is calculated by using $\gamma_{sj}^{\max}$. All the elements in the array γ^{2}, where the small BS's location is s and the location of the user is j, are set to 0. This allows the algorithm to find the subsequent highest SIR if the mobile users need to be offloaded to the other active small BSs.

Here, the transmit power of the active small BSs (i.e. femto BS), P_s are randomly set within $0\ \mathrm{Watt}$ and $0.75\ \mathrm{Watt}$. In this chapter, the transmit power of each small BS is set to be random within the allowable transmit power, and the mobile users will be associated with the highest SIR offered by a small BS. The random power of small BSs and the selection of a small BS by SODUA algorithm contribute to a higher energy efficiency. However, the transmit power of a macro BS is set to the maximum limit because considering the heavy task that it has to carry out as explained in Section 2.2.6. Next, the number of mobile users that are attached to each small BS, a^{tot} is counted. The average number of mobile users that each small BS serves in the whole network is then found. This becomes the benchmark of the minimum number of mobile users that each small BS should serve, $\underline{U}$. By identifying the small BSs to be switched off, $\mathcal{S}_{k}^{\mathrm{ina}}$, and to be active, $\mathcal{S}^{\mathrm{act}}$, where k is the index of the inactive users, will help the algorithm to count them. Besides, the algorithm counts the number of active small BSs, $S_{\mathrm{sbs}}^{\mathrm{act}}$, the number of inactive small BSs, $S_{\mathrm{sbs}}^{\mathrm{ina}}$, and the number of mobile users in the inactive small BSs, $S_{\mathrm{user}}^{\mathrm{ina}}$. If the number of inactive small BSs, $S_{\mathrm{sbs}}^{\mathrm{ina}}$, is larger than the average switching off ratio, $\overline{\Lambda}$, the last few small BSs will be switched back on. However, this is not our focus but significantly, the number of small BSs that can be switched off must not exceed the average switching off ratio, $\overline{\Lambda}$. The average switching ratio is a ratio of the allowable maximum coverage area to the actual coverage area as described in Section 2.1.5. The ratio is used to determine whether or not the small BSs can be switched off. By switching off several small BSs, the mobile users are experiencing larger spectrum efficiency as the distance to the macro BSs is shorter.

Before offloading, the highest SIR, $\gamma_{sk}^{\max 2}$, of the inactive small BSs from γ_{su}^{2} is sought. Next, the data rates of the users that associated with the inactive small BSs, R_{sk}^{ina}, and the users that associated with the active small BS, R_{sk}^{act} are calculated. These will be used for calculating the new total data rates, R_{sj}^{new}, of the whole network. Finally, the energy efficiency of the two-tier network, EE, is calculated.

4.4 Results and Discussion

In order to run the simulation, the parameter values are set first as shown in Table 4.1.

Table 4.1: Parameter values

Parameter	**Value**	**Parameter**	**Value**
B_m	20 MHz [55]	B_s	20 MHz [55]
P_m^{stat}	130 Watt [55]	P_m	20 W [55]
P_s^{stat}	4.8 Watt [55]	P_s	[0 0.05] W [55]
r_{so}	30 km	D	40 km

In this simulation, the number of users, U, and the number of small BSs, S, were set to be 200 and 30, respectively, in the whole network. For all cases, the small BSs' transmit power value was fixed to $0.75\ \mathrm{Watt}$ unless stated otherwise. The simulation was run for 105 iterations to observe the consistency of the proposed algorithm. The simulation result in Figure 4.4 shows that the ”After Offloading” is always above the ”Before Offloading”. This can be explained as

i. The algorithm switched off the small BSs that had fewer mobile users. This caused the small BSs to be inactive and thus, the total power consumption became zero, 0,

ii. The mobile users were offloaded from the inactive small BSs to the other active small BSs which offered the highest SIR, $\gamma_{sk}^{\max 2}$,

iii. The new data rates for the new association between the mobile users and the small BSs were calculated based on the above item (ii)

Due to this scenario, the energy efficiency of the whole two-tier network could be increased. The reason was that the increment of the data rates was small but the power consumption decrement was sufficient enough to cause the increase of network's energy efficiency.

To sum up, the small BSs that had fewer users would be switched off before offloading activity took place. After that, the algorithm would connect the users to the other active small BSs that offered the highest SIR $\gamma_{sk}^{\max 2}$.

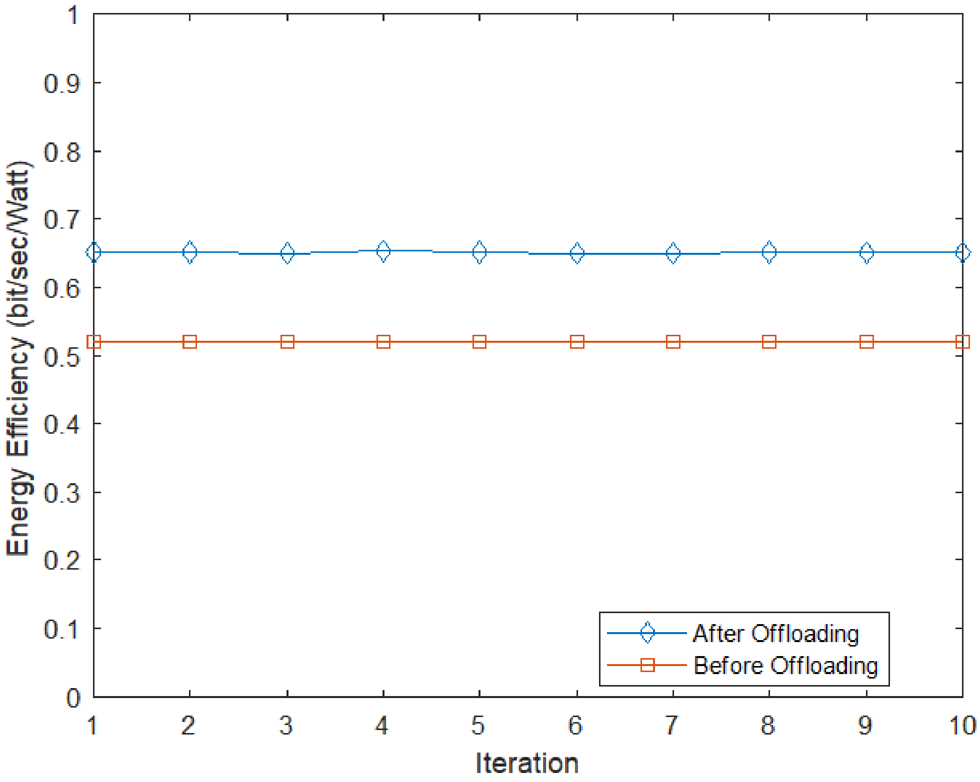

Figure 4.4: Energy Efficiency vs. Iteration

Before proceed to the next step, the average switching off ratio, $\overline{\Lambda}$, is needed to be calculated by using Equation (4.9) as

$$\begin{aligned}\overline{\Lambda} &= \frac{\pi r_{so}^2}{\pi D^2} \\ &= \frac{\pi \times 30^2}{\pi \times 40^2} \\ &= \frac{\pi \times 900}{\pi \times 1600} \\ &= \frac{2827.4333}{5026.5482} \\ &= 0.56\end{aligned} \tag{4.11}$$

Based on the calculation in the above steps in Equation (4.11), only 56% of the total number of small BSs could be switched off that based on the repulsive scheme. As mentioned previously, the number of small BSs is set to be 30. For simplicity, we assumed that all the 30 small BSs to be in the switching off area. Therefore, the maximum number of small BSs that could be switched off was

$$56\% \times 30 = 17$$

small BSs, or can be mathematically written as

$$S_{\text{sbs}}^{\text{ina}} \leq 17$$

.

The proposed algorithm produced an average minimum number of users of each small BS, $\underline{U} = 7$, several active small BSs, $S_{\text{sbs}}^{\text{act}} = 16$ and the number of inactive small BSs, $S_{\text{sbs}}^{\text{ina}} = 14$. The result of the three parameters, that generated by the algorithm, where $\underline{U} = 7$, $S_{\text{sbs}}^{\text{act}} = 16$ and $S_{\text{sbs}}^{\text{ina}} = 14$ resulting the highest energy efficiency as compared to the others as shown in Figure 4.5. However, if the average minimum number of users $\underline{U}$ was increased by 1 (from 7 to 8), the energy efficiency would be increased because the more chances small BSs would be switched off, too. Nevertheless, this did not correspond to the average switching off ratio, $\overline{\Lambda}$, where $S_{\text{sbs}}^{\text{ina}} = 19$ (refer to Table 4.2) i.e. $S_{\text{sbs}}^{\text{ina}} > 17$. If $\underline{U}$ was decreased by 1 (from 7 to 6), the energy efficiency would be decreased because the fewer chances small BSs would be switched off, too. Refer to Table 4.2 for the result of the optimal inactive small BSs is 11 if $\underline{U}$ is reduced from 7 to 6, while if $\underline{U}$ is 7, the inactive small BS is 14 i.e. just right before 17.

Table 4.2: The optimal number of active/inactive small BSs.

Avg. No. of Users	**Avg. of Active small BSs**	**Avg. of Inactive small BSs**
7	16	14
8	11	19
6	19	11

In a nutshell, reducing $\underline{U}$ would reduce the energy efficiency performance and would just waste the energy because more small BS could be switched off and maximise the energy efficiency simultaneously. In contrast, increasing $\underline{U}$ would improve the energy efficiency performance but the issue is that the average number of inactive small BSs, $S_{\text{sbs}}^{\text{ina}} = 19$, is exceeding the average number of small BSs $\overline{\Lambda} = 17$. Hence, the best $\underline{U}$ is 7 that would maximise the whole network's energy efficiency performance subject to the predefined constraints as in Equation (5.7). The result is summarised in Table 4.2.

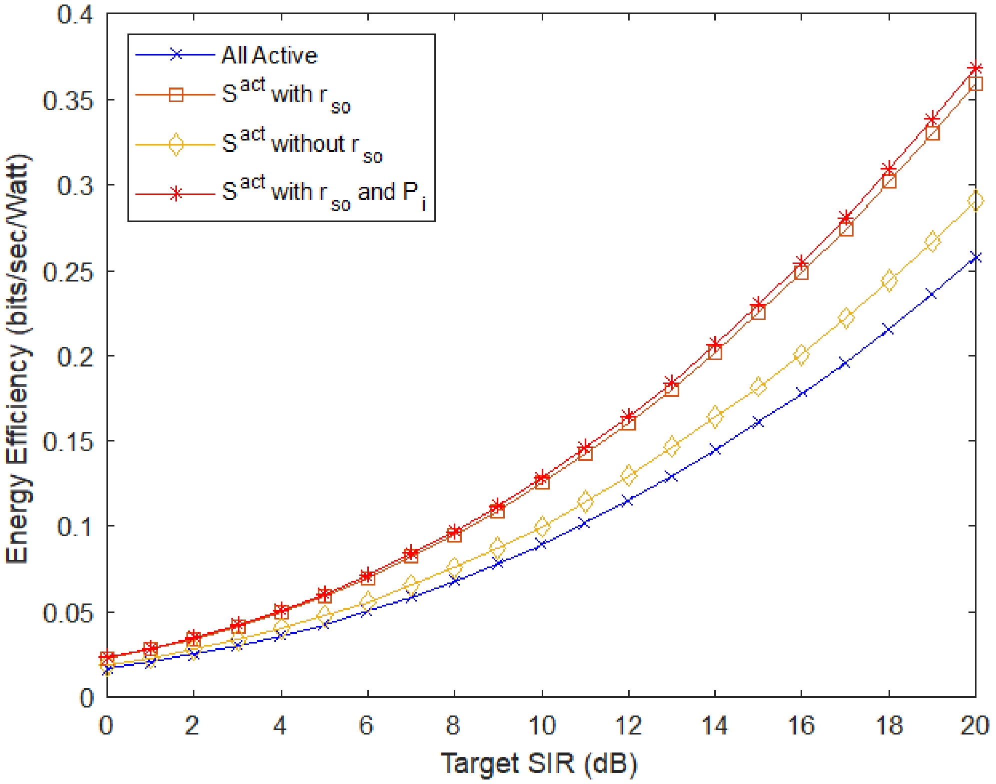

Figure 4.5: Energy Efficiency vs. SIR with Various Number of Active Small BSs

The result in Figure 4.5 shows four different cases. Case 1: All Active. All small BSs were considered active in all traffic conditions and no offloading was considered. Case 2: $S^{\text{act}}\,\text{with}\,r_{\text{so}}$ where the small BSs would be switched off if the number of mobile users associated with the small BS was less than the minimum number of mobile users. Mathematically, this can be written as $\sum_{u\in\mathcal{U}} a_{sj} < \underline{U}$. From the simulation, the number of small BSs that were active was 16 and inactive (i.e. switched off) was 14. This corresponded to the average sleeping ratio, $\overline{\Lambda}$. Case 3: S^{act} without r_{so}. Like Case (2), the small BSs with fewer users, $S^{\text{ina}}_{\text{user}}$, than the average minimum number of users were switched off. However, the number of small BSs that can be switched off was not restricted. The small BSs can be switched off as many as the algorithm found necessary. Case 4: S^{act} with $r_{\text{so}}\,\text{and}\,P_s$. The proposed algorithm was applied. In the proposed algorithm, each small BS has random transmit power from 0 to 0.75 (i.e. $P_s = [0\ 0.75]$). On top of that, the average number of small BSs, $S^{\text{ina}}_{\text{sbs}}$, that can be switched off was restricted to be less than $\overline{\Lambda}$. Based on the result, the algorithm switched off 14 small BSs with 7 users (for each small BS in average). This corresponded to $\overline{\Lambda}$ and it showed that the proposed algorithm outperformed the others.

4.5 Summary

In this chapter, the system model that considering the CDSA was presented and algorithm with switching off strategy namely SODUA was proposed. Finally, the optimisation problem was solved by using the proposed algorithm. In the next chapter, bias factors on power consumption will be considered to adjust based on several constraints to obtain a higher energy efficiency of a two-tier network in CDSA.

Chapter 5

Optimal Bias Factors for Different Modes of Base Stations

5.1 Overview

This chapter explains the proposed Power Mode Variant Selection (PMVS) algorithm to maximise a two-tier energy efficiency. This chapter's main focus is to enhance the proposed strategy of the previous two objectives where various modes of BS sleeping are considered, and Genetic Algorithm is used with the proposed algorithm. However, the user-cell association is based on Chapter 4 with some modifications that will be explained later in this chapter. Section 5.1 starts with an overview of the chapter followed by the system model's description such as the ranking strategy in CDSA, channel model, bias factor, and power consumption model with the bias factor in Section 5.2. Then, section 5.3 describes further the proposed PMVS algorithm including problem formulation and problem solving. Section 5.4 explains the results and finally, Section 5.5 summarises this chapter.

5.2 System Model

The system model in this chapter is similar to Chapter 4 where a two-tier network that consists of a macro cell and multiple small cells are considered. The location of the macro BS is set at the origin. While, the set of small BSs, $\mathcal{S}$, and the mobile users $\mathcal{U}$ are spatially distributed. Since the small BSs and the mobile users are scattered randomly, each cell consists of a small BS and several mobile users known as Voronoi cell. As for the user cell association, each mobile user is associated with the nearest small BS which is different from Chapter 4. Similar to Chapter 4, this chapter applies an open-access configuration scheme. The mobile users can access all the small BSs' spectrum since the whole spectrum is shared for all mobile users. This means a user can access any small BSs' spectrum as the whole spectrum sharing is applied.

5.2.1 Ranking Strategy in CDSA

Similar to Chapter 4, this chapter applies CDSA, or also known as the concept of signalling and data separation. The macro BS plays a vital role in providing the necessary information such as the location of the small BSs and the mobile users, determining the power modes decision and finally, calculating the energy efficiency of the whole network.

In Chapter 4, the macro BS determines whether or not to switch off the small BSs based on SODUA algorithm results. However, in this chapter, the macro BS determines each small BS's power mode in the network. When mobile users initially join the network, they will be connected to the macro BS. The macro BS calculates the distance of all possible connections between the mobile users and the small BSs. Next, the macro BS decides the appropriate serving small BS for each mobile user. Simultaneously, the macro BS determines the power mode for each small BS to the mobile user according to the ranking as follows

i. For each user, all possible distances to all small BSs are calculated,
ii. Based on the above step (i), the distances are sorted from the nearest to the farthest, in other words, in ascending order,
iii. Then, to rank them, they are labelled as 1 (On) for the shortest, 2 (Standby) for the second shortest, 3 (Sleep) for the third shortest and 4 (Off) for the rest of the small BSs,
iv. It is assumed that the small BSs and the macro BS transmit power levels are at the maximum which will be adjusted later by the proposed algorithm.

5.2.2 Channel Model

The channel model is similar to Chapter 4 where there are two different transmit power levels for a macro BS and the small BSs. The SIR model, the achievable downlink rate, and the energy efficiency are also similar to Chapter 4. In contrast, the user-cell association is based on the nearest BS instead of the highest SIR as compared to Chapter 4. However, the formulation is similar to the one described in Section 2.2.2 Equation (2.11).

5.2.3 The Bias Factor

The main factor contributing to a higher energy efficiency of the two-tier network in this chapter is the bias factors. A bias factor is added to each mode of the small BS including the macro BS instead of applying on only small BS. The representative of each mode that is applying a bias factor is shown in Table 5.1.

Table 5.1: The bias factors

Type of BS	**Mode**	**Bias Factor**
Small BS	On	q_{on}
Small BS	Standby	q_{sby}
Small BS	Sleep	q_{sl}
Small BS	Off	q_{of}
Macro BS	On	q_{mbs}

5.2.4 Achievable Downlink Rate

For each communication between small BS s and mobile user u, we define the achievable data rate as follows.

$$R_{su} = B \log_2 \left(1 + (a_{su} \cdot \gamma_{su})\right) \;\; ; \; \forall s \in \mathcal{S}, u \in \mathcal{U} \tag{5.1}$$

where B is the bandwidth between small BS s and mobile user u. Similar to Chapter 4, the user-cell association indicator, a_{su}, in Equation (5.1) can be used to obtain the number of users. The total achievable data rate of all mobile users is expressed as follows.

$$R_{\text{sbs}} = \left[q_{\text{on}} \times \sum_{s \in \mathcal{S}_{\text{on}}} R_{su} \right] + \left[q_{\text{sby}} \times \sum_{s \in \mathcal{S}_{\text{sby}}} R_{su} \right] + \left[q_{\text{sl}} \times \sum_{s \in \mathcal{S}_{\text{sl}}} R_{su} \right] + \left[q_{\text{of}} \times \sum_{s \in \mathcal{S}_{\text{of}}} R_{su} \right] \tag{5.2}$$

5.2.5 Power Consumption Model with the Bias Factor

As mentioned previoulsy, the macro BS is always in active mode due to controlling the small BSs in CDSA and other network activities [115]. Therefore, the total power consumption of the macro BS, P_{mbs}, is expressed as

$$P_{\text{mbs}} = q_{\text{mbs}} \times \left(P_m^{\text{stat}} + P_m \right) \cdot \tag{5.3}$$

The power consumption of small BSs varies based on the power modes. So, the total power consumption of small BSs, P_{sbs}, is modelled as

$$\begin{aligned} P_{\text{sbs}} = & \left[q_{\text{on}} \times \sum_{s \in \mathcal{S}_{\text{on}}} \left(P_s^{\text{stat}} + P_s \right) \times a_{su} \right] \\ & + \left[q_{\text{sby}} \times \sum_{s \in \mathcal{S}_{\text{sby}}} \left(P_s^{\text{stat}} + P_s \right) \times 0.5 \times a_{su} \right] + \left[q_{\text{sl}} \times \sum_{s \in \mathcal{S}_{\text{sl}}} \left(P_s^{\text{stat}} + P_s \right) \times 0.15 \times a_{su} \right] \\ & + \left[q_{\text{of}} \times \sum_{s \in \mathcal{S}_{\text{of}}} \left(P_s^{\text{stat}} + P_s \right) \times 0 \times a_{su} \right] \end{aligned} \tag{5.4}$$

where the 0.5, 0.15 and 0 are percentage of the power consumption that will be further explained in Section 5.3.1. Since the percentage of small BS off mode is 0, the power consumption of the small BS can be eliminated. Therefore, the bias factor of the small BS off will be ignored for the rest of this chapter. The bias factors of each small BS's mode and the macro BS as in Equation (5.3) and (5.4) are used to adjust the power consumption when necessary based on the proposed algorithm. Finally, the total power consumption of the two-tier network is expressed as

$$P_{\text{all}} = P_{\text{sbs}} + P_{\text{mbs}}. \tag{5.5}$$

5.3 The Proposed Power Mode Variant Selection Algorithm

In this section, the problem formulation of the proposed Power Mode Variant Selection (PMVS) algorithm is discussed in detail. The objective of this algorithm is to find the optimum values of the bias factors in order to maximise the energy efficiency of a two-tier network. The Genetic Algorithm based PMVS algorithm decides the appropriate mode for each small BS by using the ranking as described in Section 5.2.1.

First, the bias factors are determined randomly by the Genetic Algorithm during the initial population. Then, the PMVS algorithm is called and the bias factors are passed to calculate the energy efficiency. From here, the PMVS algorithm processes the main steps such as calculating all possible distances, sorting them in ascending order, associating the mobile users with the small BSs, determining the mode of the small BSs, and calculating the total power consumptions, and ultimately, calculating the energy efficiency of the whole two-tier network. Then, the value of the energy efficiency is passed back to the Genetic Algorithm where it is called. Next, the Genetic Algorithm uses the bias factors obtained during the initial population phase, to do the following selection, crossover, and mutation phases. The new bias factors result after going through the phases are used to recalculate the new energy efficiency. This process continues until the Genetic Algorithm converged, where there is no other better solution for the bias factor.

5.3.1 The Power Mode Selection Strategy

In this chapter, the macro BS decides which power mode is appropriate for the small BSs based on the ranking. The four different modes of operation with the percentage of the power consumptions as studied by [34] are considered as follows i On: During this active operation mode, the small BSs consume 100% power,

ii Standby: When the small BSs are in this operation mode, they consume 50% power and can wake up quickly when instructed by the macro BS,

iii Sleep: Here, small BSs consume 15% power and will take some time to wake them up when instructed by the macro BS, and

iv Off: Small BSs that are switched off and the total power consumption is nearly zero and thus it is approximated as zero.

The BSs' modes can be classified into two, active small BSs and inactive small BSs. The active small BSs are the small BSs that are On and consume 100% of power consumption. Whereas, the inactive small BSs include the small BSs in Standby, Sleep and Off modes. They consume 50%, 15%, and 0% of the power consumption, respectively. Nevertheless, the macro BS is always in On mode as it needs to serve the small BSs all the time. Table 5.2 summarises the mode of the BSs, the status and the percentage of the power consumption.

Table 5.2: The variant of power modes

BS and Mode	**Status**	**Power Consumption (%)**
Small BS - On	Active	100
Small BS - Standby	Inactive	50
Small BS - Sleep	Inactive	15
Small BS - Off	Inactive	0
Macro BS - On	Active	100

Like Chapter 4, a repulsive scheme is applied where the decision of power mode is considered if the small BSs reside in the PMVS radius, r_{pmvs}, within the macro BS's coverage radius, D (Figure 5.1). The rest of the small BSs will remain On. The average power mode ratio, $\overline{\Lambda}$, can be calculated based on the PMVS area to the macro BS's coverage area as [50, 114]

$$\overline{\Lambda} = \frac{\pi r_{\text{pmvs}}^2}{\pi D^2}. \tag{5.6}$$

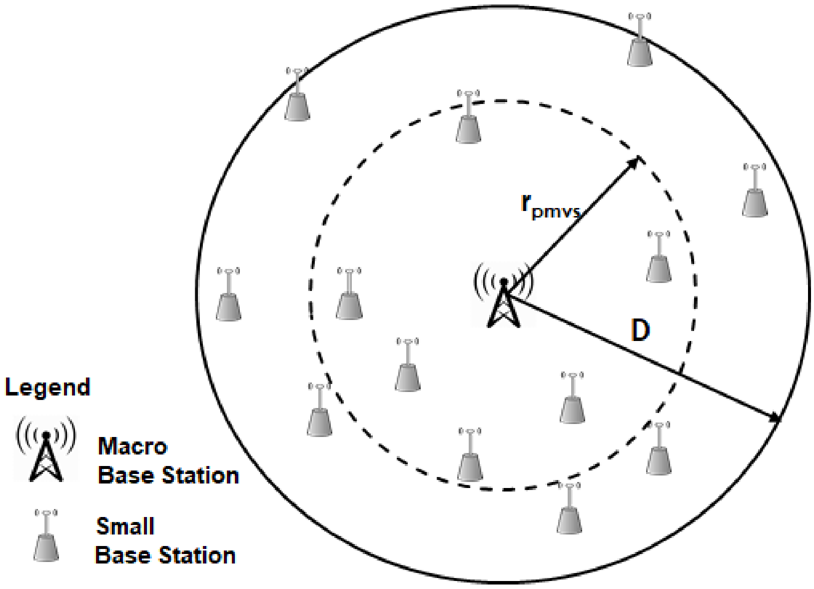

Figure 5.1: PMVS Area

5.3.2 Problem Formulation

The proposed PMVS problem can be formulated as follows

$$\max_{q_{\text{on}},q_{\text{sby}},q_{\text{sl}},q_{\text{of}},q_{\text{mbs}}} \quad \text{EE} = \frac{R_{\text{sbs}}}{P_{\text{all}}}$$

subject to

$$\begin{aligned}
&\text{C1} : 0 \leq q_{\text{on}} \leq 0.9 \\
&\text{C2} : 0 \leq q_{\text{sby}} + q_{\text{sl}} + q_{\text{mbs}} \leq 0.1 \\
&\text{C3} : q_{\text{on}} + q_{\text{sby}} + q_{\text{sl}} + q_{\text{mbs}} \leq 1 \\
&\text{C4} : \sum_{s \in \mathcal{S}} a_{su} \leq 1 \ ; \ \forall u \in \mathcal{U} \\
&\text{C5} : a_{su} \in \{0,1\} \, ; \forall s \in \mathcal{S}; \forall u \in \mathcal{U} \\
&\text{C6} : \text{count} \left(\sum_{u \in \mathcal{U}} a_{su} \neq 1 \right) \leq \overline{\Lambda}; \ \forall s \notin \mathcal{S}
\end{aligned} \tag{5.7}$$

where

C1: The bias factor for active small BSs, q_{on}, must not exceed 90% of the total bias factor value that is between 0 and 0.9. This ensures that a higher energy efficiency is obtained,

C2: The bias factors for inactive small BSs, $q_{\text{on}}, q_{\text{sby}}, q_{\text{sl}}$, and macro BS, $q_{\text{sby}} + q_{\text{sl}} + q_{\text{mbs}}$, must not more than 10% of the total bias factor value that is between 0 and 0.1. Combining those BSs is that there will be less small BSs that are in inactive mode as compared to the active mode. However, the macro BS's bias factor will have to be as minimum as we can due to its heavy tasks as mentioned earlier,

C3: The total of the bias factors of active small BSs, inactive small BSs and macro BS must be less than or equal to 100% that is 1,

C4: One mobile user can only be connected to a single small BS,

C5: The user association indicator, a_{su}, is a binary digit variable,

C6: The number of small BSs that can be sent to inactive modes must be less than the average inactive ratio, $\overline{\Lambda}$.

5.3.3 Problem Solving

Genetic Algorithm

In general, the steps in Genetic Algorithm are summarised in Algorithm 3. First, the Genetic Algorithm generates an initial population randomly that consists of a set of solutions. The solutions are the bias factors on each mode of small BSs and the macro BS earlier (q_{on}, q_{sby}, q_{sl}, q_{mbs}). For better understanding, the solutions, the set of solutions and the population are illustrated in Figure 5.2. Second, the Genetic Algorithm computes the solution's fitness by calling Algorithm 4 (i.e. the PMVS algorithm) to obtain the value of the energy efficiency. Third, the iteration, $counter$, starts until the total population is reached but the algorithm will also stop once the set of solutions is converged. Here, the Genetic Algorithm performs the selection, crossover, mutation and finally computes the energy efficiency by invoking Algorithm 4. The Genetic Algorithm keeps doing the processes until the fittest set of solutions is found.

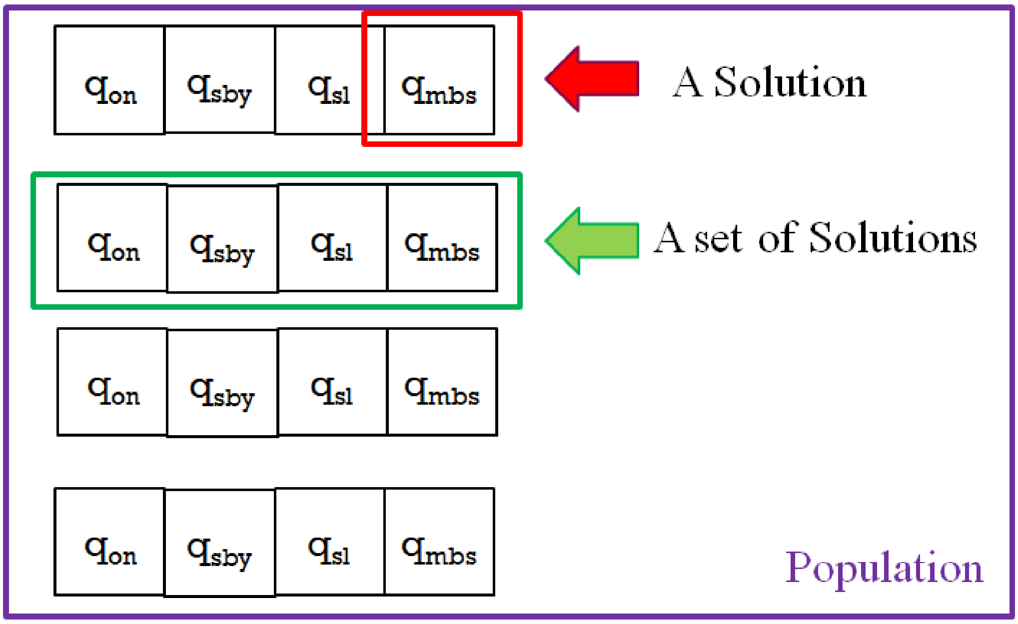

Figure 5.2: A solution, a set of solutions and a population

```
Algorithm 3: Genetic Algorithm
START
1. Generate the initial population, $populate$;
2. Compute the fitness i.e. Algorithm 4: The PMVS Algorithm;
3. while $counter \leq populate$ do
    4. Select the fittest solutions;
    5. Crossover the fittest solutions;
    6. Mutate the selected random genes that change the value;
    7. Compute the fitness i.e. Algorithm 4: The PMVS Algorithm;
8. END
```

PMVS Algorithm

The PMVS algorithm received input for bias factors from Algorithm 3. The PMVS algorithm shown in Algorithm 4 executes the main tasks such as calculating all possible distances between the mobile users and the small BSs, sorting the distance in ascending order, associating the users with the selected small BSs, assigning the appropriate mode to each small BSs that based on the ranking that has been explained earlier, calculating the power consumptions, and finally, calculating the energy efficiency of the two-tier network. The energy efficiency value is, then, passed to Algorithm 3 where it is called.

```
Algorithm 4: The PMVS Algorithm
START
1. Get bias factor values ($q_{\text{on}}, q_{\text{sby}}, q_{\text{sl}}, q_{\text{mbs}}$) from Algorithm 3 at step 1;
2. Generate random coordinates of small BSs and users;
3. Calculate all possible distances between the users and the small BSs, $r_{su}$;
4. Sort the distances in ascending order;
5. Number the distances in ascending order from $1$ to $4$;
6. Associate user $u$ with small BSs $s$ that is numbered as $1$;
7. Calculate the number of users of each small BS which is numbered as $1$. If the
   small BSs have no users, assigned them to one of the inactive power mode
   according to their highest rank $2$ (Standby), $3$ (Sleep) or $4$ (Off));
8. Calculate the power consumption of each mode of small BS;
9. Calculate the total of power consumption of small and macro BS, $P_{\text{all}}$. Equation
   (5.5);
10. Calculate the SIR $\gamma$ as in Equation (4.1), data rate $R$ as in Equation (5.2), and
   energy efficiency $\text{EE}$ of the whole network as in Equation (5.7);
END
```

5.4 Results and Discussion

In this simulation, the number of mobile users U is set to be 200 and the number of small BSs S is set to be 50 in the whole network. For simplicity, all the small BSs are assumed to be in the PMVS area. The rest of the parameter values are summarised in Table 5.3.

Table 5.3: Parameter values

Parameter	**Value**
P_m^{stat}	130 Watt
P_s^{stat}	4.8 Watt
P_m	20 W
P_s	0.75 W
B	10 MHz

As a result, the bias factor values are obtained as stated in Table 5.4 where q_{on} is maximum compared to the rest. Whilst the power consumption of the macro BS was only reduced at 0.003 of the total power consumption. The reason is that the macro BS has many tasks to handle as it functions as a controller of the network. Reducing more power will only disrupt the operational function of the macro BSs. Standby mode was reduced at 0.009, while the Sleep mode was reduced only at 0.001. This is the best result that the Genetic Algorithm based PMVS algorithm can produce.

Table 5.4: Number of users and bias factor values

BSs and Status	**Number of Users**	**Bias Factor**	**Value**
Small BS - On	45	q_{on}	0.9
Small BS - Standby	4	q_{sby}	0.009
Small BS - Sleep	1	q_{sl}	0.001
Macro BS - On	1	q_{mbs}	0.003

Technically, if all the bias factors are set to be small, P_{sbs} will be small. Since the total achievable data rate of all mobile users, R_{sbs}, includes the bias factors too, the rate will be small too. Consequently, the total energy efficiency will be decreased.

After getting the value of the bias factors shown in Table 5.4, a graph is generated by using the parameter values as shown in Table 5.3. As a result, it is showed that the proposed algorithm outperformed the previous work [114]. The previous work proposed SODUA to find an optimal number of small BSs in a given service area where it was implemented in CDSA, too. It looked for the small BSs that were lightly loaded and switched them off to save power consumption. The mobile users, that were connected to the small BSs that were switched off, are offloaded to the other small BSs that were active. No Genetic Algorithm, no various power modes selection, and no bias factors were considered.

This proved that by considering the four different modes of small BSs i.e. power modes, the energy efficiency could be maximised by having the bias factors for adjusting the power consumptions. The power adjustment was needed as all BSs transmit their power at the maximum level. The macro BS that acted as a controller of the two-tier network controls all activities including the power adjustment.

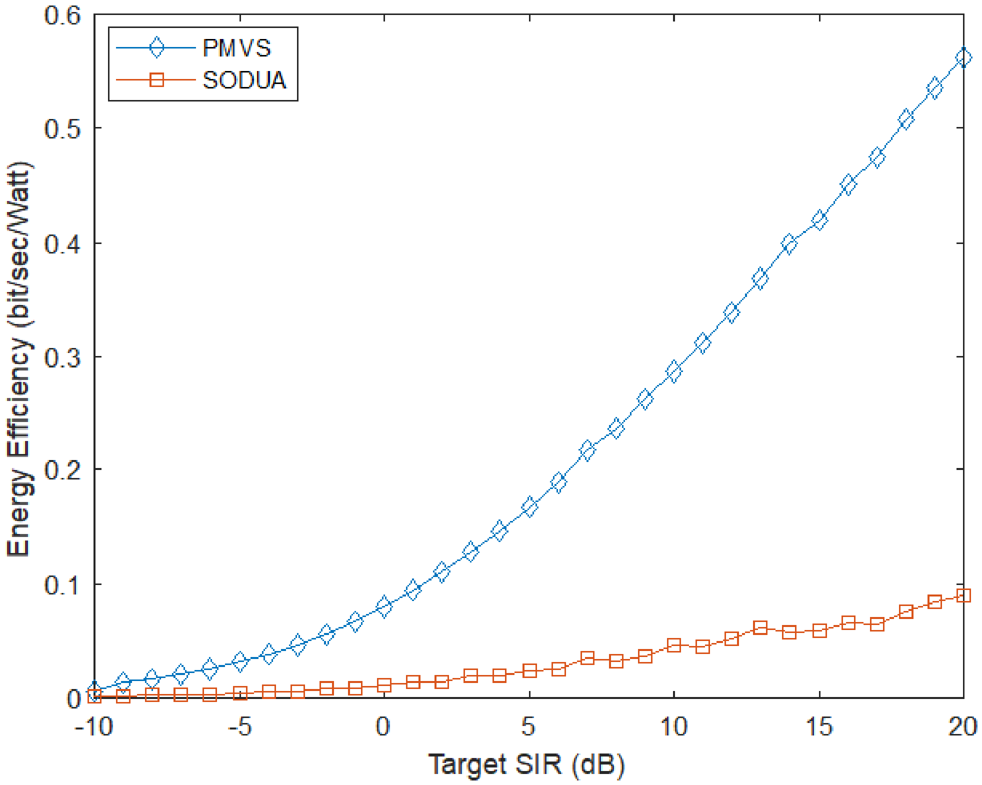

Figure 5.3: Energy Efficiency vs. Target SIR: The comparison between PMVS and SODUA algorithm.

5.5 Summary

In this chapter, the system model was presented where the CDSA was slightly similar to Chapter 4. However, the PMVS algorithm that based on ranking strategy was proposed where the bias factors in all BS modes were applied. Finally, the optimisation problem was solved by using the Genetic Algorithm based PMVS algorithm. In the next chapter, the conclusion and future works will be discussed.

Chapter 6

Conclusion and Future Work

This chapter concludes the works that were carried out in this thesis. Above all, recommendations are highlighted here for future works that can be carried out. Each technical chapter above (Chapter 3, 4 and 5) presented the system model, the solutions and the results which were proved to be better than the previous works.

6.1 Conclusion

The system model of the first objective, which was presented in Chapter 3, was designed with multiple macro BSs and multiple small BSs in a two-tier heterogeneous network. The network applied a closed-access configuration scheme where both tiers use different spectrum to mitigate inter-tier interference. However, to fully utilise the macro BSs' spectrum, PSR is deployed where the small BS can access a portion of the macro BSs' spectrum. As a result, the energy efficiency of a two-tier network has been maximised.

In order to contribute more to a higher energy efficiency, BS sleeping was applied with probabilities of activating a BS. The energy efficiency was calculated based on these factors: the probability of activating a macro BS, the probability of activating a small BS, and the PSR. An optimal energy efficiency was then investigated using a Genetic Algorithm where the above-mentioned factors were optimised. The proposed scheme was compared with the current work and the finding showed that the proposed scheme outperformed the existing scheme in terms of energy efficiency. Therefore, a conclusion for the first objective is that a higher activation probability of a small BS and PSR factor but a lower activation probability of a macro BS would contribute to higher energy efficiency.

The system model of the second and the third objective, presented in Chapter 4 and 5, respectively, was quite different from the first objective. The second and the third objectives applied CDSA that allows a macro BS to control small BSs in a two-tier heterogeneous network. In CDSA, a macro BS and small BSs operate in different spectrum. Thus, no interference coming from different tiers would contribute to a lower energy efficiency.

Specifically, in second objective, a two-tier network's energy efficiency was maximised by jointly optimising the density of active small BSs and the user-cell associations. However, the published paper was developed based on the number of active small BSs in a given area, which can be translated to be as density of active small BSs. Therefore, the SODUA algorithm was proposed to determine which small BSs to be switched off in a given service area in order to achieve a higher energy efficiency.

In brief, the SODUA algorithm determined a small BS that offered the highest SIR to be associated with a mobile user where a mobile user could only be associated with one small BS. The algorithm found the small BSs which had fewer mobile users to be switched off. Then, the mobile users would be offloaded to the other active small BSs. The achievable data rate of each connection between the mobile users and the small BSs was recalculated for getting the accurate data rates. Finally, the results were compared with the one "without offloading" because the proposed algorithm was the one "with offloading". Based on the proposed algorithm, the results were compared between the other algorithms that considered the following.

i. When all small BSs were active and no offloading was considered,

ii. Switched off the small BSs that had fewer number of mobile users and there must be a limit,

iii. Switched off the small BSs that had fewer number of mobile users and there was no limit, and

iv. Like Similar to item (ii) above, however, in this last algorithm, the transmit power of the small BSs were randomly deployed.

Consequently, the simulation results showed that the proposed algorithm with random transmit power outperformed the other algorithms.

Similar to the second objective, the third objective also applied a CDSA to allow a macro BS to control the small BSs in a two-tier network. However, the difference is that various power modes were applied on each small BS as compared to the second objective where the second objective applied only switching off BSs. The user-cell association was different from the second objective as well. The second objective's user-cell association was based on the highest SIR but the user-cell association of the third objective was based on the nearest BS. Moreover, the third objective applied a ranking strategy to determine the user-cell association which is not applied by the second objective.

Therefore, in the third objective, a two-tier network's energy efficiency was maximised by applying a Genetic Algorithm based PMVS algorithm. In short, the proposed PMVS algorithm decided the appropriate mode for each small BS by using the ranking method from the nearest to the farthest. It also investigated for an optimal bias factor of each BS mode for adjusting the transmit power of the BSs including the macro BS. The simulation results showed that the proposed algorithm outperformed the previous work in the second objective.

6.2 Recommendation for Future Work

Due to some constraints, the works in this thesis are not fully matured and completed. Thus, something else can be added to the works such as redesigning, comparing and analysing. The works can be summarised as follows:

i. In the first objective, the system was deployed in a closed-access configuration scheme. However, it would be best if considered in an open-access configuration scheme since more implementation is in open-access configuration scheme in the real situation. However, the implementation in the open-access scheme suffers from severe interference due to other neighbouring BSs. Hence, mitigating interference needs to be considered for the open-access configuration.

ii. In the second objective, a CDSA that allows a macro BS to control the small BSs has been applied. Thus, the macro BS controls which small BSs to be switched off and the mobile users that attached to them will be associated with the other active small BSs. However, it is necessary if the mobile users to be associated with the macro BS to reduce the burden of the other active small BSs since the macro BS has no user to serve.

iii. Besides, the overloaded small BSs have not been included in this thesis due to the constraints to achieve higher energy efficiency. This might help to check whether the small BSs are overloaded with mobile users or overburden by any other activities.

iv. In this thesis, the circle shape area was used to show the transmission area's coverage instead of hexagonal shape. However, this is not as important because only a single macro BS was considered. If more than one macro BS is considered, the hexagonal shape is appropriate to show the coverage area without overlapping. In future work, this work could be extended to multiple macro BSs.

v. Specifically, for the second objective, the algorithm was developed based on the number of small BS in a given service area. Therefore, it is more useful if the algorithm was designed to be flexible for several small BSs in any areas or best known as the density of BSs. In such a way that, the area size can be decided later and the proposed algorithm can determine the number of small BSs.

vi. The BS sleeping strategy in this thesis was carried out separately in different objective. Hence, it would be consequential if a comparison between different BS sleeping strategies is done in one work to see the result clearly, to which one performs well.

Bibliography

[1] W. Nie, F.-C. Zheng, X. Wang, W. Zhang, and S. Jin, "User-centric cross-tier base station clustering and cooperation in heterogeneous networks: Rate improvement and energy saving," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 5, pp. 1192–1206, 2016.

[2] T. Han, Y. Han, X. Ge, Q. Li, J. Zhang, Z. Bai, and L. Wang, "Small cell offloading through cooperative communication in software-defined heterogeneous networks," *IEEE sensors journal*, vol. 16, no. 20, pp. 7381–7392, 2016.

[3] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: a survey," *IEEE Communications magazine*, vol. 46, no. 9, 2008.

[4] F. Ye and X. Zhang, "Cooperative dynamic spectrum access for small cell networks with interference mitigation and qos guarantee," in *2013 IEEE 11th Malaysia International Conference on Communications (MICC)*, Kuala Lumpur, Malaysia, Nov. 2013, pp. 396–400.

[5] A. Argyriou, M. Erol-Kantarci, and Y. Liu, "Spectrally-efficient cooperative video delivery in 5g heterogeneous wireless networks," in *2016 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2016, pp. 1–6.

[6] Y. S. Soh, T. Q. Quek, M. Kountouris, and H. Shin, "Energy efficient heterogeneous cellular networks," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 5, pp. 840–850, 2013.

[7] F. Pantisano, M. Bennis, W. Saad, M. Debbah, and M. Latva-Aho, "Improving macrocell-small cell coexistence through adaptive interference draining," *IEEE transactions on wireless communications*, vol. 13, no. 2, pp. 942–955, 2013.

[8] Z. Yan, S. Chen, Y. Ou, and H. Liu, "Energy efficiency analysis of cache-enabled two-tier hetnets under different spectrum deployment strategies," *IEEE Access*, vol. 5, pp. 6791–6800, 2017.

[9] M. Inomata, M. Sasaki, W. Yamada, Y. Takatori, K. Kitao, and T. Imai, "Effects of building shapes on path loss up to 37 ghz band in street microcell environments," in *Computational Electromagnetics (ICCEM), 2017 IEEE International Conference on*. IEEE, 2017, pp. 249–251.

[10] H. S. Dhillon, R. K. Ganti, and J. G. Andrews, "A tractable framework for coverage and outage in heterogeneous cellular networks," in *Information Theory and Applications Workshop (ITA), 2011*. IEEE, 2011, pp. 1–6.

[11] H. Shimodaira, G. K. Tran, K. Sakaguchi, K. Araki, S. Kaneko, N. Miyazaki, S. Konishi, and Y. Kishi, “Optimization of picocell locations and its parameters in heterogeneous networks with hotspots,” *IEICE transactions on communications*, vol. 96, no. 6, pp. 1338–1347, 2013.

[12] G. H. Carvalho, I. Woungang, A. Anpalagan, M. Jaseemuddin, and E. Hossain, “Intercloud and hetnet for mobile cloud computing in 5g systems: Design issues, challenges, and optimization,” *IEEE Network*, vol. 31, no. 3, pp. 80–89, 2017.

[13] X. Chen, L. Jiao, W. Li, and X. Fu, “Efficient multi-user computation offloading for mobile-edge cloud computing,” *IEEE/ACM Transactions on Networking*, vol. 24, no. 5, pp. 2795–2808, 2016.

[14] H. Zhang, H. Liu, J. Cheng, and V. C. Leung, “Downlink energy efficiency of power allocation and wireless backhaul bandwidth allocation in heterogeneous small cell networks,” *IEEE transactions on communications*, vol. 66, no. 4, pp. 1705–1716, 2018.

[15] A. Khandekar, N. Bhushan, J. Tingfang, and V. Vanghi, “Lte-advanced: Heterogeneous networks,” in *Wireless Conference (EW), 2010 European.* IEEE, 2010, pp. 978–982.

[16] N. Trabelsi, C. S. Chen, R. El Azouzi, L. Roullet, and E. Altman, “User association and resource allocation optimization in lte cellular networks,” *IEEE Transactions on Network and Service Management*, vol. 14, no. 2, pp. 429–440, 2017.

[17] Q. Chen, G. Yu, R. Yin, A. Maaref, G. Y. Li, and A. Huang, “Energy efficiency optimization in licensed-assisted access,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 723–734, 2016.

[18] H. U. Sokun, E. Bedeer, R. H. Gohary, and H. Yanikomeroglu, “Optimization of discrete power and resource block allocation for achieving maximum energy efficiency in ofdma networks,” *IEEE Access*, vol. 5, pp. 8648–8658, 2017.

[19] D. Cao, S. Zhou, and Z. Niu, “β-psr: A partial spectrum reuse scheme for two-tier heterogeneous cellular networks,” in *2012 1st IEEE International Conference on Communications in China (ICCC)*, Beijing, China, Aug. 2012, pp. 459–463.

[20] R. I. Ansari, H. Pervaiz, C. Chrysostomou, S. A. Hassan, A. Mahmood, and M. Gidlund, “Control-data separation architecture for dual-band mmwave networks: A new dimension to spectrum management,” *IEEE Access*, vol. 7, pp. 34 925–34 937, 2019.

[21] Z. H. Abbas, F. Muhammad, and L. Jiao, “Analysis of load balancing and interference management in heterogeneous cellular networks,” *IEEE Access*, vol. 5, pp. 14 690–14 705, 2017.

[22] M. Fereydooni, G. B. Eslamlou, and M. Rupp, “Performance evaluation and resource allocation in hetnets under joint offloading and frequency reuse,” in *2017 IEEE 18th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC).* IEEE, 2017, pp. 1–5.

[23] B. Debaillie, C. Desset, and F. Louagie, “A flexible and future-proof power model for cellular base stations,” in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*. IEEE, 2015, pp. 1–7.

[24] T. Kudo and T. Ohtsuki, “Cell range expansion using distributed q-learning in heterogeneous networks,” *Eurasip journal on wireless communications and networking*, vol. 2013, no. 1, p. 61, 2013.

[25] Y. Lee, L. Park, W. Noh, and S. Cho, “Reinforcement learning based interference control scheme in heterogeneous networks,” in *2020 International Conference on Information Networking (ICOIN)*. IEEE, 2020, pp. 83–85.

[26] K. Katayama, K. Takano, S. Amakawa, T. Yoshida, and M. Fujishima, “14.4-db cmos d-band low-noise amplifier with 22.6-mw power consumption utilizing bias-optimization technique,” in *2016 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*. IEEE, 2016, pp. 1–3.

[27] X. Chai, Z. Zhang, and K. Long, “Joint spectrum-sharing and base station sleep model for improving energy efficiency of heterogeneous networks,” *IEEE Systems Journal*, vol. 12, no. 1, pp. 560–570, 2018.

[28] D. Cao, S. Zhou, and Z. Niu, “Improving the energy efficiency of two-tier heterogeneous cellular networks through partial spectrum reuse,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 8, pp. 4129–4141, 2013.

[29] Z. Cui, Q. Cui, W. Zheng, and Z. Li, “Energy-delay analysis for partial spectrum sharing in heterogeneous cellular networks with wired backhaul,” in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Valencia, Spain, Sep. 2016, pp. 1–6.

[30] A. Mohamed, O. Onireti, M. Imran, H. Pervaiz, P. Xiao, and R. Tafazolli, “Predictive base station activation in futuristic energy-efficient control/data separated ran,” in *2017 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2017, pp. 1–7.

[31] Y. Li, H. Zhang, J. Wang, B. Cao, Q. Liu, and M. Daneshmand, “Energy-efficient deployment and adaptive sleeping in heterogeneous cellular networks,” *IEEE Access*, vol. 7, pp. 35 838–35 850, 2019.

[32] Y. Kang, S. Dong, and J. Zhang, “An energy-efficient user offloading algorithm for cellular network in base station sleep mode,” in *2016 8th International Conference on Wireless Communications & Signal Processing (WCSP)*. IEEE, 2016, pp. 1–4.

[33] F. H. Panahi, F. H. Panahi, S. Heshmati, and T. Ohtsuki, “Optimal sleep & wakeup mechanism for green internet of things,” in *2019 27th Iranian Conference on Electrical Engineering (ICEE)*. IEEE, 2019, pp. 1659–1663.

[34] C. Liu, B. Natarajan, and H. Xia, “Small cell base station sleep strategies for energy efficiency,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 3, pp. 1652–1661, 2015.

[35] D. Cao, S. Zhou, and Z. Niu, “Optimal base station density for energy-efficient heterogeneous cellular networks,” in *2012 IEEE International Conference on Communications (ICC)*, Ottawa, ON, Canada, 2012, pp. 4379–4383.

[36] A. Shojaeifard, K.-K. Wong, K. A. Hamdi, E. Alsusa, D. K. So, and J. Tang, "Stochastic geometric analysis of energy-efficient dense cellular networks," *IEEE Access*, vol. 5, pp. 455–469, 2017.

[37] M. Awais, A. Ahmed, M. Naeem, M. Iqbal, W. Ejaz, A. Anpalagan, and H. S. Kim, "Efficient joint user association and resource allocation for cloud radio access networks," *IEEE Access*, vol. 5, pp. 1439–1448, 2017.

[38] D. Cao, S. Zhou, and Z. Niu, "Optimal combination of base station densities for energy-efficient two-tier heterogeneous cellular networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 9, pp. 4350–4362, 2013.

[39] R. Cai, W. Zhang, and P.-C. Ching, "Cost-efficient optimization of base station densities for multitier heterogeneous cellular networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 3, pp. 2381–2393, 2016.

[40] B. Yang, G. Mao, X. Ge, M. Ding, and X. Yang, "On the energy-efficient deployment for ultra-dense heterogeneous networks with nlos and los transmissions," *IEEE Transactions on Green Communications and Networking*, 2018.

[41] S. Lee and K. Huang, "Coverage and economy of cellular networks with many base stations," *IEEE Communications Letters*, vol. 16, no. 7, pp. 1038–1040, 2012.

[42] M. Di Renzo, A. Zappone, T. T. Lam, and M. Debbah, "System-level modeling and optimization of the energy efficiency in cellular networks—a stochastic geometry framework," *IEEE Transactions on Wireless Communications*, vol. 17, no. 4, pp. 2539–2556, 2018.

[43] L. Li, M. Peng, C. Yang, and Y. Wu, "Optimization of base-station density for high energy-efficient cellular networks with sleeping strategies," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 9, pp. 7501–7514, 2016.

[44] E. Mugume and D. K. So, "User association in energy-aware dense heterogeneous cellular networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1713–1726, 2017.

[45] Y. Zhu, Z. Zeng, T. Zhang, L. An, and L. Xiao, "An energy efficient user association scheme based on cell sleeping in lte heterogeneous networks," in *2014 International Symposium on Wireless Personal Multimedia Communications (WPMC)*. IEEE, 2014, pp. 75–79.

[46] A. I. Abubakar, M. Ozturk, S. Hussain, and M. A. Imran, "Q-learning assisted energy-aware traffic offloading and cell switching in heterogeneous networks," in *2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*. IEEE, 2019, pp. 1–6.

[47] C.-Y. Chang, W. Liao, H.-Y. Hsieh, and D.-S. Shiu, "On optimal cell activation for coverage preservation in green cellular networks," *IEEE Transactions on Mobile Computing*, no. 11, pp. 2580–2591, 2014.

[48] Y. El Morabit, F. Mrabti, and E. H. Abarkan, "Small cell switch off using genetic algorithm," in *2017 international conference on advanced technologies for signal and image processing (ATSIP)*. IEEE, 2017, pp. 1–4.

[49] Š. Bojan and Z. Nikola, “Genetic algorithm as energy optimization method in wsn,” in *2013 21st Telecommunications Forum Telfor (TELFOR).* IEEE, 2013, pp. 97–100.

[50] S. Zhang, J. Gong, S. Zhou, and Z. Niu, “How many small cells can be turned off via vertical offloading under a separation architecture?” *IEEE Transactions on Wireless Communications*, vol. 14, no. 10, pp. 5440–5453, 2015.

[51] S. Mishra and C. S. R. Murthy, “Increasing energy efficiency via transmit power spreading in dense femto cell networks,” *IEEE Systems Journal*, vol. 12, no. 1, pp. 971–980, 2018.

[52] K. Huang and J. G. Andrews, “An analytical framework for multicell cooperation via stochastic geometry and large deviations,” *IEEE transactions on information theory*, vol. 59, no. 4, pp. 2501–2516, 2012.

[53] J. G. Andrews, F. Baccelli, and R. K. Ganti, “A tractable approach to coverage and rate in cellular networks,” *IEEE Transactions on communications*, vol. 59, no. 11, pp. 3122–3134, 2011.

[54] H. S. Dhillon, R. K. Ganti, F. Baccelli, and J. G. Andrews, “Modeling and analysis of k-tier downlink heterogeneous cellular networks,” *arXiv preprint arXiv:1103.2177*, 2011.

[55] G. Auer, V. Giannini, I. Gódor, O. Blume, A. Fehske, J. Rubio, P. Frenger, M. Olsson, D. Sabella, M. Gonzalez *et al.*, “How much energy is needed to run a wireless network,” *IEEE Wireless Communications*, vol. 18, no. 5, pp. 40–49, 2011.

[56] X. Yang and A. O. Fapojuwo, “Coverage probability analysis of heterogeneous cellular networks in rician/rayleigh fading environments,” *IEEE Communications Letters*, vol. 19, no. 7, pp. 1197–1200, 2015.

[57] Y. Jiao and I. Joe, “Energy-efficient resource allocation for heterogeneous cognitive radio network based on two-tier crossover genetic algorithm,” *Journal of Communications and Networks*, vol. 18, no. 1, pp. 112–122, 2016.

[58] G. J. Sutton, R. P. Liu, and I. B. Collings, “Modelling ieee 802.11 dcf heterogeneous networks with rayleigh fading and capture,” *IEEE Transactions on Communications*, vol. 61, no. 8, pp. 3336–3348, 2013.

[59] A. Goldsmith, *Wireless communications.* Cambridge university press, 2005.

[60] N. A. M. Razali, M. H. Habaebi, N. Zulkurnain, M. R. Islam, and A.-H. Zyoud, “The distribution of path loss exponent in 3d indoor environment,” *International Journal of Applied Engineering Research*, vol. 12, no. 18, pp. 7154–7161, 2017.

[61] M. G. Kibria, G. P. Villardi, K. Nguyen, K. Ishizu, and F. Kojima, “Heterogeneous networks in shared spectrum access communications,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 1, pp. 145–158, 2017.

[62] L. An, T. Zhang, and C. Feng, “Stochastic geometry based energy-efficient base station density optimization in cellular networks,” in *2015 IEEE Wireless Communications and Networking Conference (WCNC).* IEEE, 2015, pp. 1614–1619.

[63] X. Liu, “Closed-form coverage probability in cellular networks with poisson point process,” *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 8206–8209, 2019.

[64] S. Singh, N. Saxena, A. Roy, and H. Kim, “Energy efficiency in wireless networks–a composite review,” *IETE Technical Review*, vol. 32, no. 2, pp. 84–93, 2015.

[65] J. Yang, M. Ding, G. Mao, Z. Lin, D.-G. Zhang, and T. H. Luan, “Optimal base station antenna downtilt in downlink cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 3, pp. 1779–1791, 2019.

[66] P. Xia, V. Chandrasekhar, and J. G. Andrews, “Open vs. closed access femtocells in the uplink,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 12, pp. 3798–3809, 2010.

[67] M. G. Kibria, K. Nguyen, G. P. Villardi, W.-S. Liao, K. Ishizu, and F. Kojima, “A stochastic geometry analysis of multiconnectivity in heterogeneous wireless networks,” *IEEE Transactions on Vehicular Technology*, vol. 67, no. 10, pp. 9734–9746, 2018.

[68] M. J. Alam, A. A. El-Saleh, C. K. Tan, I. Ku, Y. L. Lee, and T. C. Chuah, “Improved joint cell association and interference mitigation for lte-a heterogeneous networks,” in *2018 IEEE 4th International Symposium on Telecommunication Technologies (ISTT)*. IEEE, 2018, pp. 1–4.

[69] F. Shi, K. Sun, W. Huang, and Y. Wei, “User association for on-grid energy minimizing in hetnets with hybrid energy supplies,” in *2018 IEEE 18th International Conference on Communication Technology (ICCT)*. IEEE, 2018, pp. 778–783.

[70] P. Chang and G. Miao, “Optimal operation of base stations with deep sleep and discontinuous transmission,” *IEEE Transactions on Vehicular Technology*, vol. 67, no. 11, pp. 11 113–11 126, 2018.

[71] E. Pateromichelakis, M. Shariat, A. U. Quddus, and R. Tafazolli, “On the analysis of co-tier interference in femtocells,” in *2011 IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE, 2011, pp. 122–126.

[72] F. Fang, G. Ye, H. Zhang, J. Cheng, and V. C. Leung, “Energy-efficient joint user association and power allocation in a heterogeneous network,” *IEEE Transactions on Wireless Communications*, 2020.

[73] Y. Haddad and D. Porrat, “A two-tier frequency reuse scheme,” in *2010 IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops*. IEEE, 2010, pp. 203–207.

[74] W. Nie, X. Wang, F.-C. Zheng, and W. Zhang, “Energy-efficient base station cooperation in downlink heterogeneous cellular networks,” in *Global Communications Conference (GLOBECOM), 2014 IEEE*. IEEE, 2014, pp. 1779–1784.

[75] K. K. Mensah, R. Chai, D. Bilibashi, and F. Gao, “Energy efficiency based joint cell selection and power allocation scheme for hetnets,” *Digital Communications and Networks*, vol. 2, no. 4, pp. 184 – 190, 2016,

next Generation Wireless Communication Technologies. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2352864816301055

[76] M. U. Sheikh, J. Säe, and J. Lempiäinen, "Evaluation of spma and higher order sectorization for homogeneous sir through macro sites," *Wireless Networks*, vol. 22, no. 4, pp. 1079–1091, 2016.

[77] Y. Jiang, N. Lu, Y. Chen, F. Zheng, M. Bennis, X. Gao, and X. You, "Energy efficient non-cooperative power control in small cell networks," *IEEE Transactions on Vehicular Technology*, 2017.

[78] Z. Wang and W. Zhang, "A separation architecture for achieving energy-efficient cellular networking," *IEEE Transactions on Wireless Communications*, vol. 13, no. 6, pp. 3113–3123, 2014.

[79] S. Li, G. Zhu, S. Lin, Q. Gao, L. Xiong, W. Xie, and X. Qiao, "Energy efficiency and capacity tradeoff in cloud radio access network of high-speed railways," *Mobile Information Systems*, vol. 2017, pp. 5 816 862:1–5 816 862:12, 2017.

[80] N. Shahida, R. Nordin, M. Ismail *et al.*, "Improved water-filling power allocation for energy-efficient massive mimo downlink transmissions," *International Journal of Electronics and Telecommunications*, vol. 63, no. 1, pp. 79–84, 2017.

[81] P. Chand, R. Mahapatra, and R. Prakash, "Energy efficient radio resource management for heterogeneous wireless network using comp," *Wireless Networks*, vol. 22, no. 4, pp. 1093–1106, 2016.

[82] S. He, Y. Huang, H. Wang, S. Jin, and L. Yang, "Leakage-aware energy-efficient beamforming for heterogeneous multicell multiuser systems," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1268–1281, 2014.

[83] M. Hafeez and J. M. Elmirghani, "Green licensed-shared access," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 12, pp. 2579–2595, 2015.

[84] Y. Wu, K. Guo, J. Huang, and X. S. Shen, "Secrecy-based energy-efficient data offloading via dual connectivity over unlicensed spectrums," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 12, pp. 3252–3270, 2016.

[85] X. Chen, J. Wu, Y. Cai, H. Zhang, and T. Chen, "Energy-efficiency oriented traffic offloading in wireless networks: A brief survey and a learning approach for heterogeneous cellular networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 4, pp. 627–640, 2015.

[86] Y. Li, G. Su, P. Hui, D. Jin, L. Su, and L. Zeng, "Multiple mobile data offloading through delay tolerant networks," in *Proceedings of the 6th ACM workshop on Challenged networks*. ACM, 2011, pp. 43–48.

[87] W. Dong, S. Rallapalli, R. Jana, L. Qiu, K. Ramakrishnan, L. Razoumov, Y. Zhang, and T. W. Cho, "ideal: Incentivized dynamic cellular offloading via auctions," *IEEE/ACM Transactions on Networking*, vol. 22, no. 4, pp. 1271–1284, 2014.

[88] X. Zhuo, W. Gao, G. Cao, and S. Hua, "An incentive framework for cellular traffic offloading," *IEEE Transactions on Mobile Computing*, vol. 13, no. 3, pp. 541–555, 2014.

[89] A. Capone, A. F. Dos Santos, I. Filippini, and B. Gloss, "Looking beyond green cellular networks," in *2012 9th Annual Conference on Wireless On-Demand Network Systems and Services (WONS)*. IEEE, 2012, pp. 127–130.

[90] Y. Sun, Y. Chang, M. Hu, and T. Zeng, "A universal predictive mobility management scheme for urban ultra-dense networks with control/data plane separation," *IEEE Access*, vol. 5, pp. 6015–6026, 2017.

[91] A. Mohamed, O. Onireti, M. A. Imran, A. Imran, and R. Tafazolli, "Predictive and core-network efficient rrc signalling for active state handover in rans with control/-data separation," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1423–1436, 2016.

[92] S. Khalili and O. Simeone, "Uplink harq for cloud ran via separation of control and data planes," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 5, pp. 4005–4016, 2016.

[93] J. Kang, O. Simeone, J. Kang, and S. S. Shitz, "Control-data separation with decentralized edge control in fog-assisted uplink communications," *IEEE Transactions on Wireless Communications*, vol. 17, no. 6, pp. 3686–3696, 2018.

[94] J. Kim, H.-W. Lee, and S. Chong, "Traffic-aware energy-saving base station sleeping and clustering in cooperative networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 1173–1186, 2017.

[95] A. Yarali, *5G Mobile: From Research and Innovations to Deployment Aspects*, ser. Electronics and Telecommunications Research Series. Nova Science Publishers, Incorporated, 2017. [Online]. Available: https://books.google.co.uk/books?id=d8o2MQAACAAJ

[96] W. Vereecken, I. Haratcherev, M. Deruyck, W. Joseph, M. Pickavet, L. Martens, and P. Demeester, "The effect of variable wake up time on the utilization of sleep modes in femtocell mobile access networks," in *2012 9th Annual Conference on Wireless On-Demand Network Systems and Services (WONS)*. IEEE, 2012, pp. 63–66.

[97] A. Bousia, E. Kartsakli, A. Antonopoulos, L. Alonso, and C. Verikoukis, "Multi-objective auction-based switching-off scheme in heterogeneous networks: To bid or not to bid?" *IEEE Transactions on Vehicular Technology*, vol. 65, no. 11, pp. 9168–9180, 2016.

[98] W. Chang, W.-Y. Cheng, Z.-T. Meng, and S.-L. Su, "Energy-efficient sleep strategy with variant sleep depths for open-access femtocell networks," *IEEE Communications Letters*, vol. 23, no. 4, pp. 708–711, 2019.

[99] O. Onireti, A. Mohamed, H. Pervaiz, and M. Imran, "Analytical approach to base station sleep mode power consumption and sleep depth," in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. IEEE, 2017, pp. 1–7.

[100] S. Takeda, S. Miwa, K. Usami, and H. Nakamura, "Efficient leakage power saving by sleep depth controlling for multi-mode power gating," in *Thirteenth International Symposium on Quality Electronic Design (ISQED)*. IEEE, 2012, pp. 625–632.

[101] A. Serhan, E. Lauga-Larroze, and J.-M. Fournier, "Efficiency enhancement using adaptive bias control for 60ghz power amplifier," in *2015 IEEE 13th International New Circuits and Systems Conference (NEWCAS)*. IEEE, 2015, pp. 1–4.

[102] G.-T. Chou, K.-H. S. Liu, and S.-L. Su, "Load-based cell association for load balancing in heterogeneous cellular networks," in *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. IEEE, 2015, pp. 1681–1686.

[103] E. Mugume, D. K. So, and E. Alsusa, "Energy efficient deployment of dense heterogeneous cellular networks," in *2015 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2015, pp. 1–6.

[104] Y. Zhang, Z. Wei, Z. Feng, and Q. Zhang, "Network state motivated traffic offloading scheme in heterogeneous networks," in *2015 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2015, pp. 1446–1451.

[105] K. Yang, L. Wang, S. Wang, and X. Zhang, "Optimization of resource allocation and user association for energy efficiency in future wireless networks," *IEEE Access*, vol. 5, pp. 16 469–16 477, 2017.

[106] Q. Kong and B. Wang, "Adaptive cell range expansion for energy cost saving in heterogeneous cellular networks with hybrid energy supplies," in *2015 IEEE 29th International Conference on Advanced Information Networking and Applications*. IEEE, 2015, pp. 829–836.

[107] Z. M. P. A. Baidowi and X. Chu, "Energy-efficient joint optimization of activation probabilities and partial spectrum reuse factor in hetnets," in *2019 IEEE 9th International Conference on System Engineering and Technology (ICSET)*. IEEE, 2019, pp. 303–308.

[108] A. S. W. Marzuki, I. Ahmad, D. Habibi, and Q. V. Phung, "Mobile small cells: Broadband access solution for public transport users," *IEEE Communications Magazine*, vol. 55, no. 6, pp. 190–197, 2017.

[109] M. Rebato, M. Mezzavilla, S. Rangan, F. Boccardi, and M. Zorzi, "Understanding noise and interference regimes in 5g millimeter-wave cellular networks," in *European Wireless 2016; 22th European Wireless Conference*, Oulu, Finland, May 2016, pp. 1–5.

[110] M. Elhoseny, X. Yuan, Z. Yu, C. Mao, H. K. El-Minir, and A. M. Riad, "Balancing energy consumption in heterogeneous wireless sensor networks using genetic algorithm," *IEEE Communications Letters*, vol. 19, no. 12, pp. 2194–2197, 2014.

[111] Z. Niu and Z. Jiang, "Energy efficiency optimization of super dense heterogeneous network based on improved genetic algorithm," in *2020 International Conference on Intelligent Transportation, Big Data & Smart City (ICITBS)*. IEEE, 2020, pp. 435–439.

[112] X. Chen, W. Cao, and L. Xing, “Ga-aided power flow management in a multi-vector energy system,” in *2019 IEEE Symposium Series on Computational Intelligence (SSCI).* IEEE, 2019, pp. 3172–3176.

[113] J. Zhu, R. Wu, L. Tang, and S. Ji, “Spectrum sharing in heterogeneous networks based on multi-objective optimization,” in *2016 19th International Symposium on Wireless Personal Multimedia Communications (WPMC).* IEEE, 2016, pp. 530–535.

[114] Z. M. P. A. Baidowi and X. Chu, “An optimal energy efficiency of a two-tier network in control-data separation architecture,” *Journal of Communications*, vol. 15, no. 7, pp. 545–550, July 2020.

[115] Y. Wang, J. Zhang, and P. Zhang, “Energy-efficient power and subcarrier allocation in multiuser ofdma networks,” in *2014 IEEE International Conference on Communications (ICC).* IEEE, 2014, pp. 5492–5496.