Energy Efficient Topology Management for Next Generation Mobile Broadband Systems

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Abstract

This thesis examines how sleep modes can be used in next generation mobile broadband systems (BuNGee) to substantially improve energy efficiency. Such systems employ a high degree of overlapping small cells in order to deliver very high throughput density for 5G networks in dense areas. It is shown how by limited exchange of information between neighbouring base stations it is possible to maintain quality of service (QoS), over a range of traffic loads, while enabling inactive base stations to sleep. Dynamic distributed topology management schemes are used here to switch off the small cells at low traffic load levels, while the remaining local traffic can be forwarded by their adjacent cells.

A novel analytical model is generated using multi-dimensional Markov processes and is used to predict the theoretical system performance and potential energy reduction when a set of parameters are varied. The parameters discussed include the traffic load thresholds to switch off/on a base station. This new model provides an understanding of how to obtain the maximum energy reduction while guaranteeing QoS by choosing suitable parameter values in such a network.

Performance of distributed energy efficient topology management schemes with a sleep mechanism are compared against the system without topology management. Results show the schemes deliver a significant energy reduction in energy consumption in the network, which is 35%-70% depending on the strategies used.

The corresponding simulation models are used to verify the analytical model. It is shown how traffic load based thresholds (used to switch on/off base stations) measured on adjacent base stations have a higher impact than the threshold on the base station itself. The latter threshold has very limited influence on the system energy efficiency.

An energy efficient topology management scheme employing combined sleep modes with handover for a BuNGee system is investigated as a way of providing further improvements to energy efficiency. Performance is examined using both analytical and simulation based models. A key aspect of this scheme is that a base station can redeploy its traffic load to its neighbours and then switch off itself when the local traffic is at a low/medium level.

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Last but not least, I wish to express my deepest gratitude to my parents and my wife, for their selfless love and support. Their dedication provided the foundation of this work.

Declaration

Some of the research presented in this thesis have resulted in publications or have submitted or are preparing for submitting to journals, conference proceedings. A list of the publications is provided below and at the end of the thesis.

All contributions presented in this thesis as original are as such to be the best knowledge of the author. References and acknowledges to other researchers have been given as appropriate.

List of Publications

Y. Han, D. Grace, P.D. Mitchell, "Energy Efficient Topology Management for Beyond Next Generation Mobile Broadband Systems," in *International Symposium on Wireless Communication Systems (ISWCS 2012)*, Paris, Aug. 2012.

Y. Han, D. Grace, P.D. Mitchell, T. Clarke, "Energy Efficient Traffic Load based Topology Management for Beyond Next Generation Mobile Broadband Systems," submitted to *IEEE Transactions on Wireless Communications* in May 2013.

Y. Han, D. Grace, P.D. Mitchell, T. Clarke, "Optimal Control for Traffic Load based Topology Management for Beyond Next Generation Mobile Broadband Systems," submitted to *IEEE Transactions on Vehicular Technology* in July 2013.

Y. Han, D. Grace, P.D. Mitchell, T. Clarke, “Energy Efficient Topology Management with Handover Mechanism for Beyond Next Generation Mobile Broadband Systems,” being prepared for submitting to *IEEE Transactions on Mobile Computing* in Dec. 2013 or Jan. 2014 (draft completed).

Chapter 1. Introduction

Contents

1.1 Overview

A report from the Office of Communications, UK (Ofcom) has shown that the traffic over network routers of a typical UK internet service provider has increased nearly eight times from 2007 to 2012. This is also true for mobile networks where the volume of data has increased around 38 times in only three years (2010 to 2012) [1]. In next generation mobile broadband systems, researchers are considering small cell networks in order to deliver high throughput densities or extend coverage in a cost effective manner [2]. This requires a large number of fixed base stations or relays to be deployed in the service area with high degree of overlap. These kinds of communication systems are usually designed to meet the challenges of service quality [3], where energy efficiency is not a primary consideration. However, every year, more than 120,000 new base stations are deployed servicing 400 million new subscribers worldwide [4]. The growth in the number of base stations have the potential to substantially increase energy demands, which directly results in increased greenhouse gas (GHG) emissions and a high operational cost for industry [5]. In some telecommunications markets, the energy costs take nearly half of a mobile operator's operational expenditure (OPEX) [6]. In the report [7, 8], the Information and Communication Technology (ICT) industries consume 3%

of global energy consumption and contribute 2% of the worldwide CO_2 emissions. In particular, 37% of the total ICT emissions are due to Telecommunications infrastructure and devices, while data centres and user terminals are responsible for the remaining part [9]. Thus, it has led to an emerging trend of research focused on how to achieve 'energy efficiency' for wireless networks, aiming to reduce the OPEX for industry and the environmental impact. The European Union (EU) is adopting a roadmap for the gradual reduction of GHG with a target of at least 20% reduction by 2020 and 40% by 2030 [10], with respect to 1990 levels. Several mobile operators promise to reduce their carbon footprints worldwide by 50% by 2020 [11].

In wireless cellular networks, the power consumption comes from many components. As shown in Figure 1.1 [12], the base stations or access points consume most of the energy in cellular networks. Thus, the energy efficient schemes in our scheme will mainly focus on improving energy efficiency for base stations.

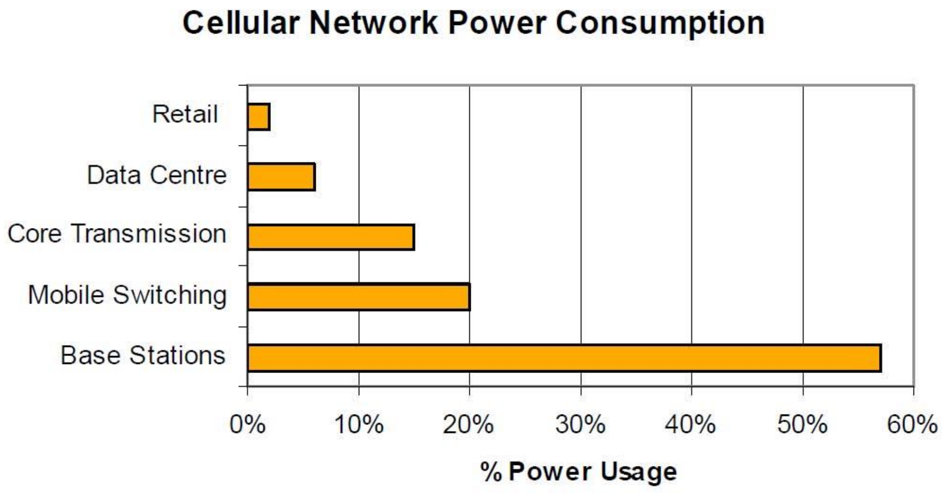

Figure 1.1 Power consumption of a typical wireless cellular network, directly reproduced from[12]

An overview of network energy saving studies is provided in [13] for 3GPP LTE. The authors classify the energy saving technologies using the time, frequency and spatial domains. In the time domain, they indicate that base station power amplifiers (PAs) can be turned off when a downlink is not sending any symbols and the operating time of power PAs can be reduced by redesigning the structure of the reference signals. In the frequency domain, bandwidth reduction and carrier aggregation techniques are used when the traffic load is low. In the spatial domain, a layered structure is proposed that uses different radio access technologies (RATs) for different layers. For example, wireless wide area networks (WWANs) are deployed in macro cells with wireless local area networks (WLANs) used in femto/micro cells. Another choice is to switch cells on and off dynamically, depending on the traffic loads in a specific area.

1.2 Communication Architecture

This thesis examines energy efficient topology management schemes for next generation mobile broadband (typical BuNGee) architecture. A Manhattan grid layout is assumed here to provide service in dense areas, and all users are located on the street or 5m within the building walls.

The tiers of one possible next generation mobile broadband network are illustrated in Figure 1.2, which has been proposed by the FP7 BuNGee Project [3]. This two-hop novel architecture is used to provide high throughput densities in dense urban areas. Our energy efficient topology management schemes will be developed for the next generation mobile broadband networks (5G).

The first tier of the system is the backhaul links, where the Hub Base stations (HBSs) are deployed on roof tops, and the Access Base Stations (ABS) are located at the street crossroads. The HBS serves the data stream wirelessly from or to the large number of low cost ABSs. The second tier of the system is the access links, which are formed by ABSs and Mobile Subscribers (MSs), where ABSs are used to provide services for MSs.

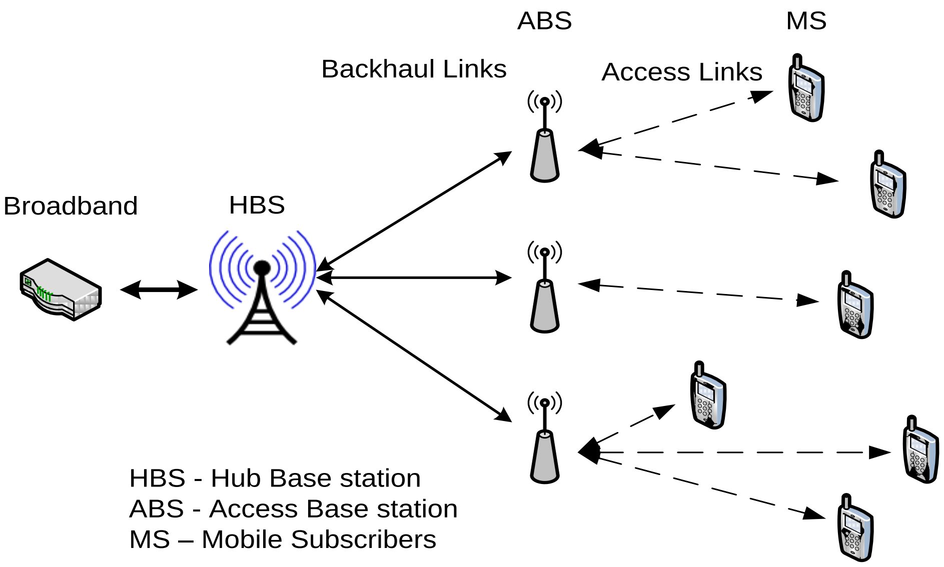

Figure 1.2 The tiers of a Next Generation Mobile Broadband Network

The BuNGee architecture in a typical network is shown in Figure 1.3. Each ABS forms a small cell, and there is a high degree of potential overlap between adjacent base stations due to the geography and close proximity of the ABSs, which is illustrated in Figure 1.4. Directional antennas are employed in ABSs, which are directed towards the street. Every ABS has two or four directional antennas depending on their positions. The shadows are the potential coverage areas for each ABS (ellipse areas). A MS has potentially more than one ABS suitable for access.

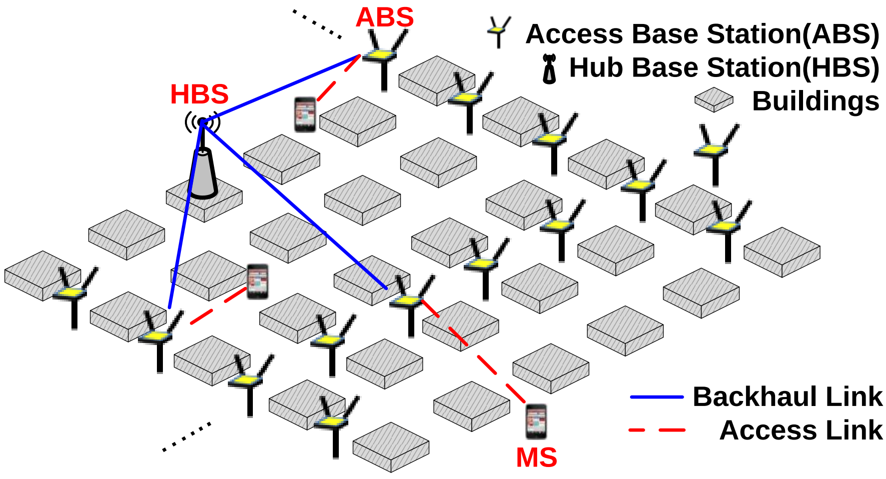

Figure 1.3 Typical Next Generation Mobile Broadband Architecture

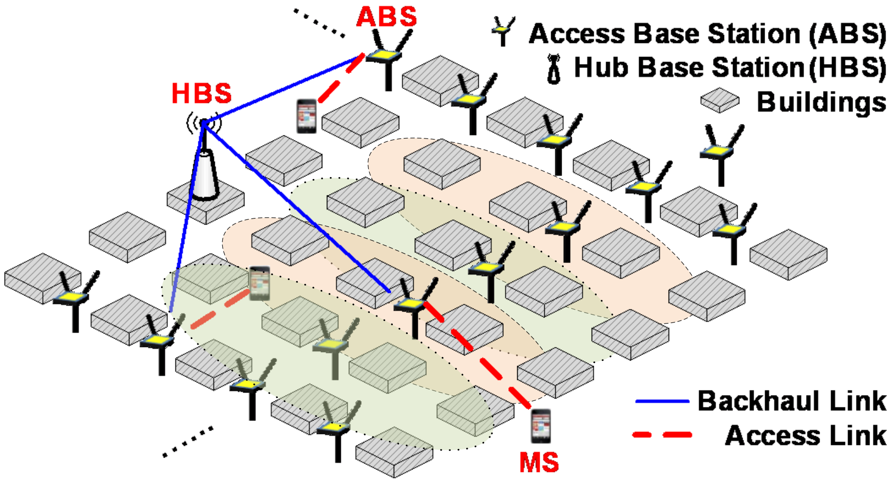

Figure 1.4 Potential coverage areas for ABSs in BuNGee archiecture

The next generation mobile broadband architecture in a large network is shown in Figure 1.5.

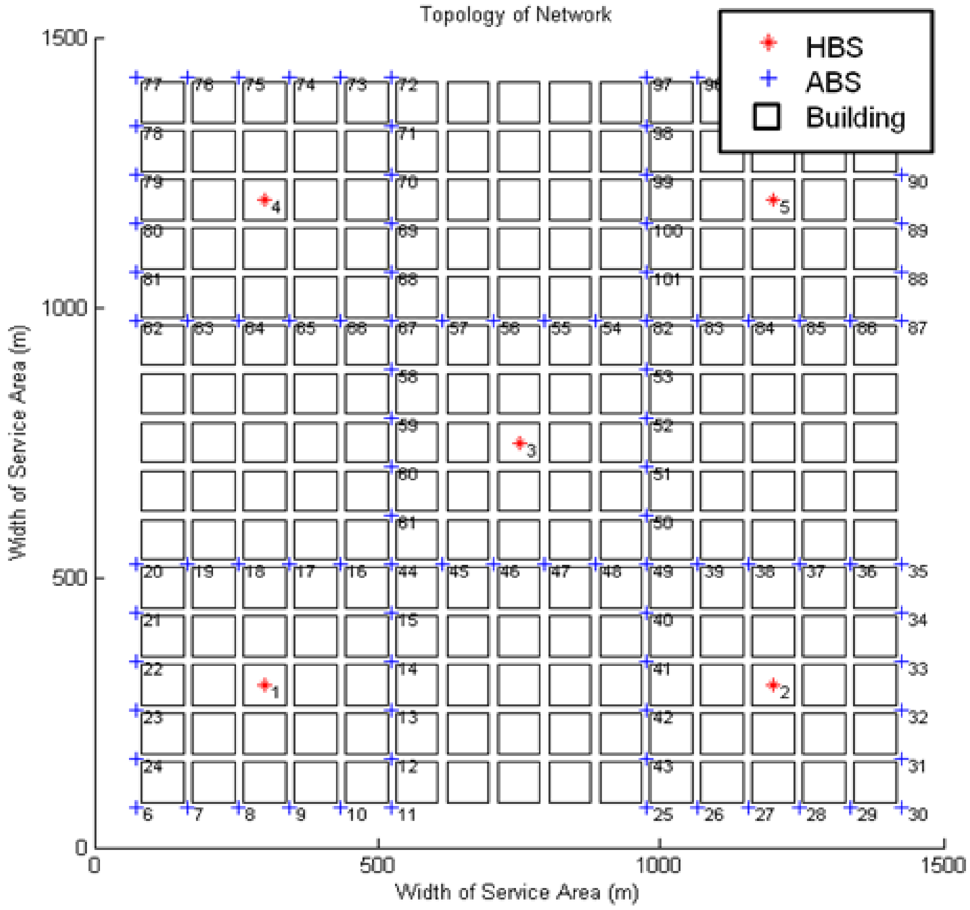

Figure 1.5 Next Generation Mobile Broadband Architecture in a large network

The typical BuNGee architecture is applied in chapter 4 in order to obtain an understanding of how energy efficient topology management schemes work and how to model them in simulation. A simplified BuNGee architecture is then used in chapter 5, chapter 6 with a normal degree of overlapping (which is equal to two) for a *three*-ABS sub-network model, in order to discuss and model the energy saving strategies and predict the system performance. In chapter 7, we increase the complexity and flexibility of our analytical models with a high degree of overlapping (which is equal to three) for a *four*-ABS sub-network, and then apply to a large network area.

1.3 Hypothesis

The hypothesis of this thesis is that sleep modes can be used as a way of improving the energy efficiency of next generation systems (BuNGee), which are likely to employ a high number of overlapping small cells to achieve high capacity densities.

The small cells in the BuNGee project can be justified as a large number of light weight low cost base stations with directional antennas. Unlike traditional cellular networks, there is a high degree level of overlapping existing between adjacent small cells to provide high throughput densities for 4G/5G systems in dense areas.

Dynamic distributed topology management schemes are used here to switch off small cells at low traffic load levels by limited exchange of information between neighbouring base stations. A novel analytical model is generated using multi-dimensional Markov processes and is used to predict the theoretical system performance and potential energy reduction when a set of parameters are varied. This provides an understanding of how to achieve the maximum energy reduction while guaranteeing QoS by choosing suitable parameters in such a network. An energy efficient topology management scheme employing combined sleep modes with handover for a BuNGee system is also investigated as a way of providing further improvements to energy efficiency.

1.4 Thesis Outline

The rest of this thesis is structured as follows:

Chapter 2 provides the background information and a literature review of the subject. A summary of the potential approaches on reducing energy consumption are presented first, and then several traditional energy efficient topology management schemes are given. After that, the related projects in the area of green communications are reviewed.

In chapter 3, the system modelling methodology, simulation techniques, the system performance measurements and the verification strategy are introduced. Both analytical models and simulation are used in this work in order to characterise the system performance accurately.

Chapter 4 proposes a distributed dynamic efficient topology management scheme for next generation mobile broadband systems. We introduce sleep/wake up mechanisms in this work. Whether an access base station should be ON or switched OFF is fully determined by the local information an access base station receives itself (or from neighbours), rather than being controlled by its hub base station. An access base station will be switched off to save energy when the local traffic load is low.

Chapter 5 employs an analytical model to describe the energy efficient strategy and predict the system performance based on the work in previous section. This analytical model is discussed with the aid of a multi-dimensional Markov process in a simple *three*-base station network, and is then applied to a larger BuNGee network when the system traffic load is low. Discussions on how suitable parameter values can be determined for the traffic load based topology management scheme to achieve a trade-off between system performance and energy efficiency are given.

The foundations of the analytical model in chapter 5 are then used in chapter 6. An analytical model is developed to combine the energy efficient topology management scheme with a handover mechanism. Here, the handover mechanism is considered as one of the important approaches to reduce the system energy consumption. Unlike the work in previous chapters, here, the work in this chapter focuses on how handover influences the system which is again characterised with aid of a multi-dimensional Markov process.

In chapter 7, several solutions are developed to improve the accuracy of the analytical model when the system traffic load is at medium/high level over a large service area. We model such a system using a *four*-base station network and provide flexibility for the degree of overlap between adjacent small cells firstly with the aid of a four-dimensional Markov chain, and then optimise the sleep/wake up strategies based on the information on traffic loads. Next, we develop three approaches to apply this analytical model to a large service area in order to obtain a more accurate result compared to the work in chapter 5.

In chapter 8, the ideas of how to take the research work in forward are discussed, and finally chapter 9 presents the main conclusions of the thesis and identifies the novel contributions made.

Chapter 2. Literature Review

Contents

2.1 Introduction

The purpose of this chapter is to provide the related background information to this thesis. The information introduced in this chapter will help to understand the techniques and approaches discussed later in this thesis. In section 2.2, several approaches to reduce energy consumption are introduced. A brief review of the typical energy efficient topology management schemes is provided in section 2.3. The green communication/energy efficiency related projects and research around the world are followed in section 2.4. Finally, conclusions are given in section 2.5.

2.2 Approaches to Reduce Energy Consumption

There has been a significant interest in energy efficiency in communication systems in the last few years. There are several papers that provide an overview of current energy saving techniques in a wide range of communication networks.

In [5], the framework of trade-offs for green communication are introduced, including deployment-energy, spectrum-energy, bandwidth-power and delay-power. The potential approaches of improving the energy efficiency of wireless networks can be considered from these four aspects. In the deployment-energy trade off, the authors aim to balance the deployment cost, throughput, and energy consumption together. In the spectrum-energy trade off, it is important to balance the transmission rate and energy cost of the system. In the bandwidth-power trade off, several new resource management algorithms are proposed which combine cognitive radio techniques. In the delay-power trade off, an in-depth discussion is presented concerning the relationship between the average end-to-end delay and the average power consumption.

The authors introduce the opportunities and challenges for green mobile networks in [14]. They think that the studies of energy efficient mobile networks can be classified by five components: data centres in backhaul, macro cells, femto cells, end-hosts and services. Next, they discuss the green techniques for the previous five components and categorize them into three aspects: processing techniques, such as resource allocation and scheduling algorithms; communication techniques, such as power control and system techniques, such as cooling.

In [15], the case studies in green techniques are divided into three aspects: resource allocation strategies, interference management & mitigation and energy efficient routing & multi-hop. The resource allocation techniques which make the most efficient use of the RF amplifier can increase system energy efficiency significantly. In addition, it is possible to change the spare bandwidth depending on traffic load conditions to improve the energy efficiency. The next step of the studies will focus on optimizing scheduling techniques, like sleep modes. In the aspect of interference management and mitigation, one way which is considered as an efficient approach to reduce interference in cellular systems is to coordinate the multiple antennas of the adjacent base stations to form distributed antenna systems (DAS). In the last part, energy efficient routing & multi-hop, these schemes are used depending on reducing transmission distance, increasing data rates or permitting reductions in delivering energy.

The potential techniques for improving cellular radio base station energy efficiency is discussed in [16]. The authors explore approaches for improving energy efficiency in future wireless networks easing the burden on network operators. They discuss the solutions from several aspects: deploying femto cells or relays or both, sleep mode transmissions and improving energy efficiency of multiple antenna systems.

After reviewing the previous overall and survey publications, the most common approaches to reduce system energy consumption can be summarized as follows [17, 18]:

- Cell deployments
- Frequency management
- Multi-hop relay
- Base station radio efficiency
- Sleep modes

2.2.1 Cell Deployment

Unlike many energy efficient techniques employed in a single base station, the solution of cell deployment is extended to whole networks, and is therefore more flexible. At present, the main approaches used in this area are developed based on multi-cell and multi-base station scenarios.

Figure 2.1 and Figure 2.2 give an example of energy efficient cell deployments for a next generation mobile broadband system (5G system), which shows the deployment and behaviour of each base station during the day time and night time separately. Here, a Hub Base Station (HBS) is assumed to deploy on the top of building, which aims to provide service for a large coverage area. Several Access Base Stations (ABSs) are then deployed at some places, like shopping malls, industrial parks and residential areas. They aim to provide high throughput densities for the dense area. The potential energy reduction may occur when somewhere the traffic load is at low level. The local ABS can be switched off to save energy, while its traffic load can be served by HBS.

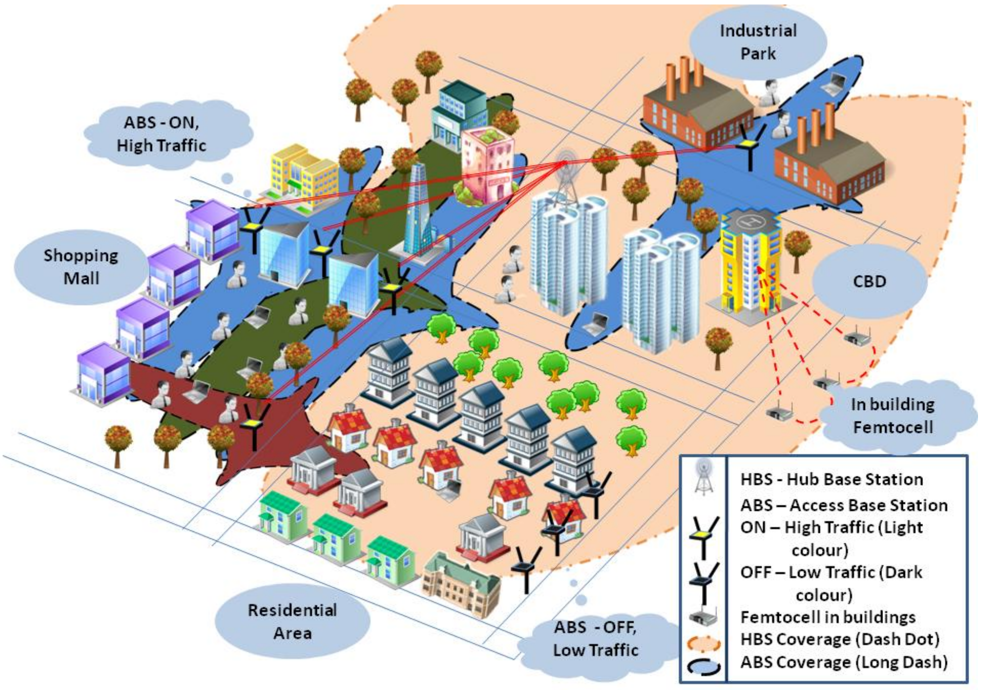

Figure 2.1 Potential energy efficient deployment (day time)

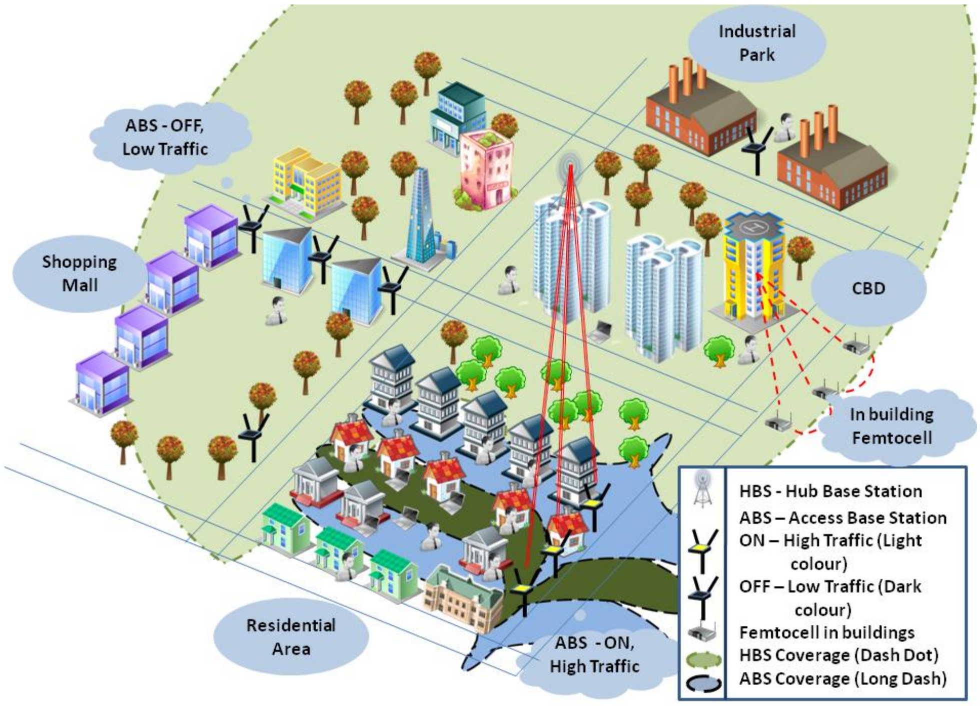

Figure 2.2 Potential energy efficient deployment (night time)

In our thesis, cell deployment is one of the key issues. Thus, the details of cell deployment techniques and related publications will be reviewed in section 2.3.

2.2.2 Frequency Management

From the view of frequency management, the possible approach to reduce the energy consumption is carrier aggregation [13].

Carrier aggregation, which means to transmit the data on the multiple sub-bands contiguously located by using single radio frequency (RF) transmitter [19]. Figure 2-3 shows the basic structure of carrier aggregation. In green communication, it is assumed that the carriers in a base station can be aggregated by groups in some wireless networks, and every group is provided service by individual power amplifiers (PAs). It is possible to switch off certain PAs when the corresponding carriers are not in use.

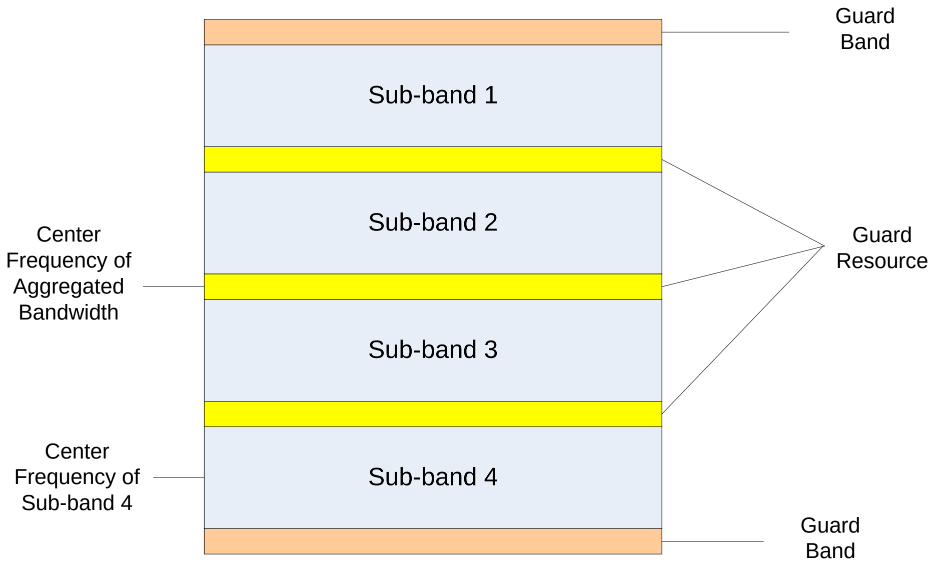

Figure 2.3 Structure of carrier aggregation

In [20], the author thought that future mobile systems must find a balance between infrastructure deployment, spectrum and energy components. They propose a high-level framework for a total cost analysis taking into account new spectrum opportunities, and energy efficient physical layers to minimize the overall energy cost for future mobile broadband systems.

Partial Spectrum Reuse (PSR) in the second tier of two-tier heterogeneous cellular networks is considered as a potential way to improve spectrum efficiency by reducing inter-cell interference, and thus improve energy efficiency as well by deploying less or switching off more BSs [21]. The authors derive the optimal PSR scheme, and then analyze the BS density problem jointly with PSR schemes in heterogeneous cellular networks. They find a threshold of the micro BS energy cost to determine which type of BSs' optimal choice is preferable to achieve energy efficiency based on the numerical results:

1) Deploying more micro BSs, and switching off more macro BSs.
2) Deploying more macro BSs, and switching off more micro BSs.

2.2.3 Multi-hop Relay

As is well known, the power consumption of a base station will increase when the distance between the transmitter and the receiver increases [22]. Thus, it is possible to use two or more short distance hops (multi-hop relay) instead of one long distance hop to reduce the energy consumption.

Figure 2.4 gives a simple example of multi-hop network, where source node S would like to transmit data to the destination node D2. It has two choices, one is from S-D2 and another is from S-D1-D2. Assuming that *P1*, *P2* and *P3* are the power consumed for link S-D1, D1-D2 and S-D2 separately.

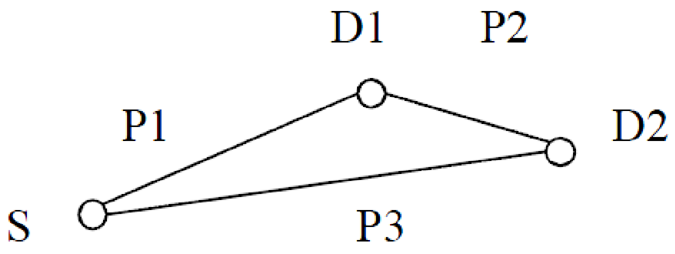

Figure 2.4 Simple example of multi-hop network

The total energy consumption can be reduced when:

$$\boldsymbol{P_1 + P_2 < P_3}$$

In [23], the energy efficient routing problems have developed to find out the minimum energy cost routes in multi-hop wireless ad hoc/sensor networks. The authors introduce a cooperative mechanism to achieve more energy savings benefit and alleviate the scalability problem in such wireless networks. However, the remaining battery life is not considered. An energy efficient relay based multi-hop clustering protocol for wireless sensor networks is discussed in [24], the authors develop a cluster head selection algorithm to collect the residual energy information aiming to reduce the system energy consumption. Unlike most of the work in this area, the authors develop an energy efficient unified routing algorithm for multi-hop systems in [25]. They take into account four key elements: transmission power, interference, residual energy and energy replenishment.

In the work of [26], the authors introduce a mixed-integer optimization framework that aimed at providing the optimal transmission policy for minimum energy routing in wireless sensor networks. The proposed strategy provides the best set of relays, the optimal broadcasting power and the optimal power values for the cooperative transmission phase. A low complexity implementation approach of the proposed framework is provided with an explicit solution to the optimization problem.

2.2.4 Base Stations Radio Efficiency

In the aspect of base station radio efficiency, power amplifiers account for a significant portion of energy consumption of a base station in wireless communication systems [15, 27]. The PAs are especially important for some mobile applications which battery lives are limited. A report from [13] shows the radio frequency (RF) PAs consume around one third of the total input power consumption of a GSM base station and the efficiency of PA (output power versus input power) is around 20%. Thus, there are two potential approaches to reduce energy consumption in this aspect: improving the efficiency of PAs and switching off certain PAs at suitable time periods.

In [28], the authors present a tunable matching network that enhances both the efficiency and linearity of power amplifiers. They demonstrated their works under 3GPP WCDMA modulated input. The results show that the PA with a dynamically controlled tunable matching network can achieve up to 5% improvement compared with a PA employing a fixed matching network. In the work of [29], an approach of improving the efficiency of RF Power Amplifiers with digital predistortion (DPD) is designed. The authors provide a way (DPD system) to operate amplifiers efficiently while improving linearity and minimizing spurious emission. A hardware related work is discussed in [30], a DC-DC converter is designed here to provide supply voltage modulation and efficiency enhancement. The use of this type integrated converters in low power wireless networks could increase transmitter efficiency and extend battery life.

2.2.5 Sleep Modes

Sleep modes or sleep mechanisms are one of the key issues in our thesis. It is always considered as one of the most common schedule management techniques. This refers to a low power mode for base stations in wireless networks because the base stations consume most of energy in transmission [31]. These modes save significantly energy consumption when the local traffic load is at low level. In green communication, this technique is always combined with the other energy efficient techniques to generate a hybrid solution.

In [32], a discrete time queuing model for IEEE 802.16e sleep mode operation is proposed and analysed. This mechanism can extend the battery life of mobile devices by turning the devices to sleep mode if necessary, but increases the delay at the base station buffer.

In [33], a system selection algorithm is developed for cooperative 2G/3G networks in order to minimize the system power consumption whilst ensuring the required QoS is met. In addition, a network scale ‘sleep mode’ is proposed in the system where the algorithm can achieve a large energy reduction.

In the work of [34], the authors aim to reduce the base station power consumption in the wireless cellular network using a base station sleep mode to serve consumers in periods of low traffic. The article focuses on the design of BS sleep and wake up transients. A practical case study is used to evaluate the performance of this technique. A similar work is carried out in [35]. The idea of green base station sleep mode design is proposed in both the time and spatial domains according to the LTE standards. The authors try to switch off the base station transmission during certain sub-frames in each radio frame periodically. The radio frequency (RF) energy consumption can be reduced significantly.

A distributed cell breathing technique is used in [36] for energy efficient cellular networks. When a base station attempts to go into its sleep mode, it tries to redistribute the traffic to its adjacent cells if they are not overloaded. The authors developed green cell breathing algorithms to avoid a centralized coordination and initialize the load thresholds.

An in-depth discussion of Sleep/Wake Up mechanisms is presented in [20]. The authors develop Sleep/Wake Up schemes for the base stations of a network comprising femto cells deployed within macro cells for the purpose of offloading part of its traffic. They use Markov Decision Processes (MDPs) to optimise the schemes based on information about traffic loads and user location in the cell.

Several attempts have been carried out to reduce the energy consumption for BuNGee systems with sleep mechanisms. The authors in [37] introduced a green topology management scheme by switching off as many underutilised base stations as possible for BuNGee networks depending on local traffic loads. In addition, different green channel assignment schemes are considered in order to further increase energy efficiency when combined with the green topology management schemes. The results show an additional average of 15% energy consumption at all traffic levels can be achieved compared to the schemes without green channel assignment.

In [38] two novel energy efficient resource allocation schemes are proposed for BuNGee networks. The schemes take into account the clustering capability of base stations when assigning new arrivals to the base stations. One scheme, Normalized Clustering Capability Rating (NCCR) achieves up to 67% overall energy saving at low traffic load levels but has poor QoS performance at high traffic levels. Another scheme, Controllable Quality Clustering Capability Rating (CQ-CCR), has the capability of maintaining a balance between energy efficiency and QoS over a wide range of traffic loads.

2.3 Typical Energy Efficient Topology Management Schemes

The details of energy efficient topology management schemes and related publications are reviewed in this section. Generally speaking, cell deployment can be divided into the following components [17]: cell topology and macro/femto cells.

2.3.1 Cell Topology

There are several publications discussing the related techniques. In [39], the authors claim that future network planning and operation should be more energy efficiency. They propose a new framework named Traffic Aware Network planning and Green Operation (TANGO) to reduce the energy consumption from the view of system level. Dynamic cell planning is one of the key issues in TANGO. Results show that TANGO can improve the energy efficiency of wireless networks significantly with a certain QoS level.

Several different LTE base station deployment strategies are considered in [40], where the impact of power reduction on the coverage and the capacity of cellular networks is evaluated. The authors show how the global power density can be optimised without decreasing the QoS by increasing the base station density.

2.3.2 Macro/Micro cells

Marco/Micro cells are popular in the design of energy efficient architectures [41, 42]. As shown in Figure 2.5, a macro cell is deployed in the service area in order to guarantee the coverage. A small number of femto/micro cells are deployed in high traffic areas to provide high speed connections. Usually, the femto/micro cells will be turned off when the local traffic is at a low level [43]. The remaining traffic can be forwarded to the macro cell.

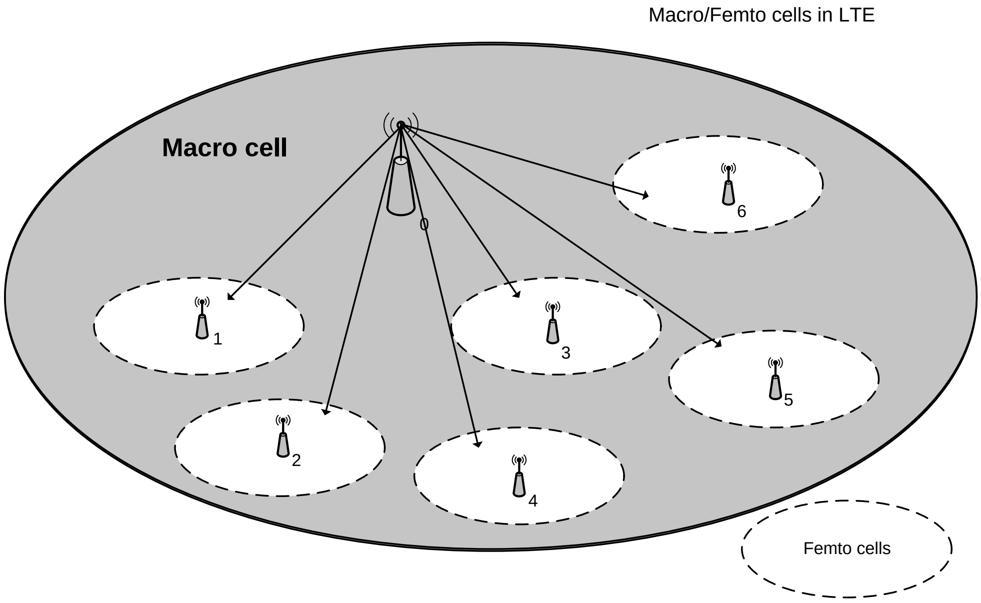

Figure 2.5 Marco/Femto cells in LTE

Several radio deployment solutions are proposed in [44] to both reduce radio access network (RAN) operational energy and improve transmission efficiency. The paper proposes a vertical sector deployment scheme and there is a significant operational energy and transmission efficiency savings, as well as insight into the trade-off relationship between energy consumption and network performance.

Two new deployments employing dynamic sleep modes have been designed for LTE-Advanced (LTE-A) to reduce energy consumption [45]: macrosectorized-cell deployment with low power relays and macro-single-cell deployment with high power directional relays.

A different LTE energy saving solution is proposed in [46], where two cells are located in the same service area. One macro cell provides service for a large coverage area, while other femto/micro cells are deployed to increase system capacity for hot spot areas. The authors represent a vertical sector antenna deployment scheme, switching off certain antennas depending on the network conditions.

Several energy efficient base station deployment strategies are introduced in [47] for cellular networks based on Long Term Evolution (LTE). They consider layouts featuring varying numbers of micro base stations per cell in addition to conventional macro sites. Thus, the traffic loads can be forwarded by micro base stations if the users are located far away from macro sites. The energy consumption on macro sites is thereby reduced.

In addition, a set of energy efficient vertical handover schemes are introduced for heterogeneous integrated networks (WiMAX-WiFi and LTE-WLAN) in [48, 49], where WLAN is used to provide short range broadband service for user, WiMAX/LTE are considered to provide global service. The handover schemes are aimed to help users choose a network and reduce the energy consumption for mobile devices.

2.4 Energy Efficiency in Wireless Communication related Projects and Research

Green communications is an emerging research area. There has been a rapid growth in the green communications/energy efficiency related activities worldwide in the past few years. A large number of energy efficient related projects and researches have been funded globally. Many aspects of green communication have been investigated. New architectures, deployment strategies, radio amplifier design, network coding and cognitive networks are the most popular topics in the area.

1) Energy Aware Radio and Network Technologies (EARTH)

The Energy Aware Radio and Network Technologies (EARTH) project [50] started in January 2010 and finished in June 2012, which was funded by the European Union as part of the European Union's Framework 7. The EARTH project focussed on investigating the energy efficiency of mobile communication systems in the base stations but was also addressing wider network and system aspects [51]. Several 3GPP mobile broadband technologies are discussed in EARTH project, such as LTE and LTE-A. The tangible results of the project are: energy efficient deployment strategies, energy efficient network architectures, new network management mechanisms, innovative component designs and new radio and resource management protocols. EARTH set itself the ambitious goal to reduce the total energy consumption of a typical mobile broadband networks by 50% and to significantly reduce carbon dioxide emission and operational expenditure [52].

2) Green Touch

The Green Touch consortium started in 2010 and supported by corporation and government [53], which aims to fundamentally reinvent information and communications technology (ICT) networks, making them 1000 times more energy efficient than they were in 2010. They define the network energy efficiency as [54]:

$$Network\ Energy\ Efficiency = \frac{Total\ traffic\ Delivered\ to\ User}{Total\ Power\ per\ User}$$

Here, the total traffic delivered to user is considered. The network energy efficiency may increase while the total traffic delivered to user increase and the total power cost per user reduces. An early goal is to realize the fundamental redesign of networks, including reference architecture, specification, technology development roadmap and demonstrations of key components. Unlike the work in EARTH, Green Touch has analyzed the fundamental limits of the global telecommunication systems. It turns out that fundamental physical limits would allow for a system to be designed that is several orders of magnitude more efficient than today's networks [55].

3) **Green Radio – Mobile Virtual Centre of Excellence in Mobile and Personal Communications Ltd (Mobile VCE)**

   The green radio programme for Mobile VCE studied how future mobile wireless networks and in particular radio base stations can be more energy efficiency [56]. This project started from Jan. 2009 and ended in July 2012, which was a part funded EPSRC project [12]. They studied the approaches to improve energy efficiency from many aspects, such as transmitter power amplifier, heterogeneous networks of base stations and femto cells, bandwidth expansion techniques, network coding, multi-hop relay etc. Up to 60%-70% energy consumption could be achieved in some cases.

4) **Greenet**

   The Greenet project is an Initial Training Network (ITN) Marie Curie project that is focused on the analysis, design, and optimization of energy efficient wireless communication systems and networks [57]. The project will offer a cross sectorial environment to shape their long term research, such as cooperative communication, cognitive networks and network coding. This ongoing FP 7 project started in July 2011. The consortium is formed by 3 Universities, 3 Research Institutes and 4 Private Companies.

5) **Low Energy Consumption NETworks (ECONET)**

The ECONET project is a three year FP7 project running from October 2010 to September 2013, which aims at studying and exploiting dynamic adaptive technologies (based on standby and performance scaling capabilities) for wired network devices that allow saving energy when a device (or part of it) is not used [58]. The ECONET project focuses on the wired network only. They try to reduce the energy requirements of wired network equipment by 50%. They redesigned the wired network equipment and infrastructures in order to reduce the overall system energy consumption with energy-sustainable and eco-friendly technologies.

6) **FIT4GREEN**

The FIT4GREEN project is a 30 months EU FP7 project which was started in January 2010, and has reached the end of its final phase [59]. The main achievement of this project is to create an energy saving layer for data centre automation frameworks, which moves computation and services around a federation of IT data centre sites in order to achieve energy efficiency. Particularly, this energy aware layer operates on top of data centre management tools only, and will not optimize the QoS metrics.

They introduced their energy models into 4 phases: Data centre Modelling, Server Modelling, Storage Modelling and Service Modelling. The potential energy reduction occurred when the unused equipments are turned off, such as servers, storage devices and network equipments.

7) **Energy Efficiency in Large Scale Distributed Systems (IC0804)**

The IC0804 project started in January 2009 and finished in May 2013, which was funded by EU FP7. The main objective of this project was to propose an energy efficient solution in a large scale distributed systems for wired networks [60]. They adapted current hardware and developed innovative algorithms to take into account the energy efficient dimension problem. They found the trade-off between energy reduction and functional and non-functional parameters, including the economic dimension.

8) **Power Amplifiers aNd Antennas for Mobile Applications (PANAMA)**

   The goal of PANAMA project is to design future multi-band, multi-mode more efficient power amplifiers to reduce system energy consumption [61]. The power amplifiers play a very important role in mobile communication, which have an impact on handset battery life, operation cost, system coexistence and etc. It can be applied into a wide range of areas, such as cellular handsets, base transceiver stations, avionics and mobile satellite communication. The Celtic-Plus PANAMA project started in January 2009 and finished in September 2012. It brought a set of European partners from the semiconductor, test tools, electronic design automation and academic.

9) **Optimizing Power Efficient in mobile Radio Networks (OPERA-Net)**

   The OPERA-Net project started in June 2008 and finished in May 2011, which is funded by Celtic-Plus project [62]. The major achievement of the OPERA-Net project is to improve the energy efficient of mobile broadband cellular networks through a holistic approach considering an end-to-end system, identifying all related network components. They optimized cooling and energy recovery from the base stations. There are few detailed objectives discussed in this project:

   - Radical improvement in energy efficiency at system, infrastructure and terminal level;
   - Develop metrics and key performance indicators for mobile broadband networks;

- Enable EU industry to take leadership in energy efficient mobile networks.

10) **Cool Silicon**

The Cool Silicon project focuses on the optimization of individual aspects like the system architecture, communication algorithms and protocols as well as physical components in three main areas: Micro- and Nanotechnologies (Energy efficient computing platform), Communication Systems (Energy efficiency for infrastructure and mobile end devices) and Sensor Network (Quality controlling structural elements) [52, 63].

11) **UnCooRdinated network StrategieS for enhanced interference, mobility, radio Resource, and Energy saving management in LTE-Advanced networks (CROSSFIRE)**

CROSSFIRE is a Multi-Partner Initial Training Network (MITN) Marie Curie project that is focused on providing forward-looking solutions for Long Term Evolution-Advanced (LTE-A) network co-existence including aspects ranging from the physical layer such as co-channel interference and cognition to the user perception of the service [64]. The project will analyze and propose network virtualization solutions for LTE-A networks, a technology which is envisioned to transform operation of cellular networks in the years to come. This on-going project has stated in Sept. 2012.

12) **Communicate Green (COMGREEN)**

The project COMGREEN has started in Jan. 2011 and is still on-going, which is funded by the Federal Ministry of Economics and Technology (BMWi), Germany. COMGREEN is about implementing an adaptive, context-aware and technology-comprehensive power management in radio networks by maintaining the high quality of experience at the same time [65]. The decision and adaptation algorithms that are going to be implemented throughout the project are going to save energy in mobile networks by dynamically de- and reactivating network components and by reconfiguring the network to user needs based on context information aggregated from network components, end devices and other context sources. They aim to achieve a reduction of the operating time of network components up to 40% - 60%.

2.5 Conclusions

This chapter provides the background information related to this thesis. The typical approaches and techniques to reduce the system energy consumption are introduced first, where the energy efficient techniques are summarized into five aspects: cell deployment, frequency management, multi-hop relay, base station radio efficiency and schedule.

The related techniques for cell deployment were discussed deeply in section 2.3, because this thesis focuses on topology management. Furthermore, the energy efficiency/green communication related research projects have been reviewed in section 2.5.

Chapter 3. System Modelling and Performance Evaluation Methodology

Contents

3.1 Introduction

In this chapter, we present the system modelling techniques and the measurement methods used throughout this thesis. The system modelling techniques introduced in this chapter include simulations and analytical models. System modelling by professional simulation software is critically important in daily research. It is common sense to experiment with new ideas on a system model before we make changes for real with the aid of professional software and powerful computers [66]. Analytical models can be used to predict system behaviour. These are commonly used at the design stage and are much less expensive among the two system modelling techniques (simulation and analytical model) [67, 68]. In our thesis, the scenario is based on Next Generation Mobile Broadband Systems architectures. Both analytical model and simulation are carried out and the results are used to evaluate the system performance.

The system modelling techniques are introduced in next section, including simulation and analytical model. Section 3.3 introduces the performance measures in our thesis. Validation is then described in section 3.4. In section 3.5, our conclusions are presented.

3.2 System Modelling Techniques

3.2.1 Simulation

3.2.1.1 Simulation Tools

Professional simulation tools can improve the efficiency of system modelling. At present, several simulation tools are used for the research in engineering, such as MATLAB, C Programme, Java, OPNET and NS3. All of above tools have good performance in simulation, but have their own particular characteristics to provide advantages and disadvantages in different areas.

MATLAB, one of the industry standard computing platforms, is used for high powered scientific computing and algorithm testing [69]. One of the biggest benefits from MATLAB is that it is a tool that allows for quick prototyping of design ideas. There are a large number of functions and toolboxes developed for MATLAB, which can improve the efficiency of the code development for system modelling. It has similarities to C, both of them can be used to generate a series of programmes, from GUIs to physical simulation. MATLAB can even easily interface with C. The general logic of these two languages is quite similar but the syntax is different. The main disadvantage of MATLAB is that its execution speed is slow [70], which always results a poor processing performance compared to C and some other simulation tools. However, the execution speed is determined as less important factor in developing a system model due to the rapid growth of computing power. Thus, MATLAB is still considered as the most appreciate professional simulation tool in our work.

3.2.1.2 Monte Carlo Simulation

A definition of Monte Carlo simulation was given in [71] as “representing the solution of a problem as a parameter of a hypothetical population, and using a random sequence of numbers to construct a sample of the population, from which statistical estimates of the parameter can be obtained.” That means the more number of times the trials are repeated, the more accurate simulation results we obtain. An event based strategy is applied here, which means the simulation is only carried out when a specific discrete event occurs, instead of time-continuous simulation. The total simulation time can be significantly reduced because the programme only works when a new event happens. The event here can include a user arriving, departing, blocking, dropping, and retransmission. The general process of the Monte Carlo simulation is illustrated in Figure 3.1. The simulator initializes parameters firstly, such as position information, traffic model, and topology management scheme. Next, the simulator passes through every event and takes measurement of the network until the final simulation result obtained.

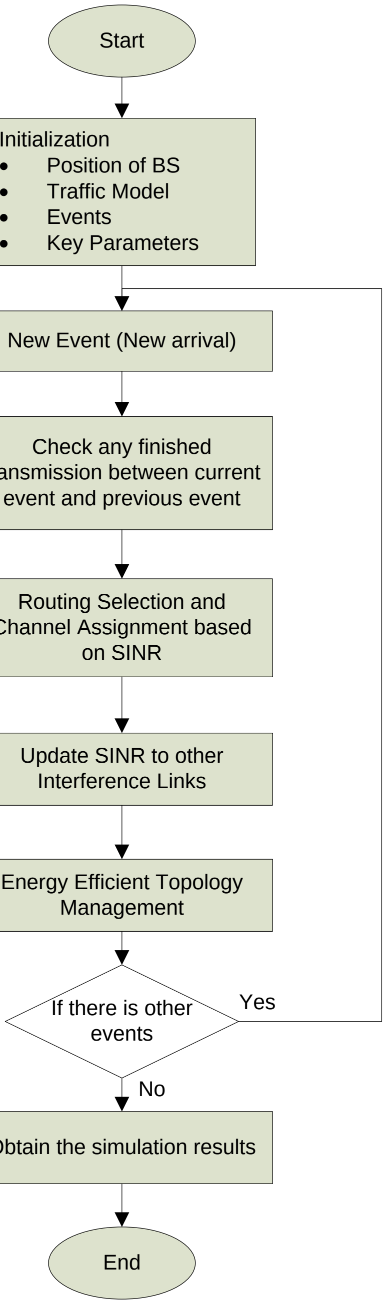

Figure 3.1 Flow chart of Monte Carlo simulation process

The Monte Carlo simulation will be widely used in next few chapters, and its results will compare to the results from analytical models.

3.2.2 Analytical Model - Markov Process

A definition of a Markov process is given in [72]:

- A random process in which the probabilities of states in a series depend only on the properties of the immediately preceding state or the next proceeding state, independent of the path by which the preceding state was reached. It is distinguished from a Markov chain in that the states of a Markov process may be continuous as well as discrete.

A Markov process is used to look at a sequence of events, and to analyze the tendency of one event to be followed by another. A definition of a Markov decision process (MDP) is given here, which provides the mathematical framework for modelling decision making in situations where outcomes are partly random and partly under the control of a decision [73].

A Markov process helps us to generate a new sequence of random but related events mathematically, which looks similar to the original. It is useful for analyzing dependent random events. In other words, the current event depends on what happened before (the previous event). For example, yesterday's weather has an influence on today's weather.

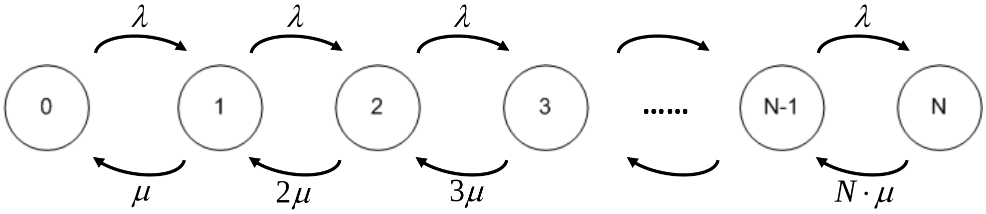

Figure 3.2 Transition Diagram of Erlang B Systems

Assume that we have a set of states, $S = \{s_1, s_2, \cdots, s_n\}$, where n is the total number of states in a Markov chain, as shown in Figure 3.2. The process starts in one of these states and moves successively from one state to another, or stays in its current state. Here, we define such a move as a transition. If the chain is in state s_i currently, and then it moves to state s_j

with a probability denoted by p_{ij}, this probability does not depend on which states the chain was in before the current state [74]. The probability p_{ij} is called the transition probability from state s_i to state s_j. If the process remains in the state is was in, the probability is shown as p_{ii}.

If we use a matrix M to present all the probabilities transferring from one state to another, the matrix M can be shown as:

$$M = \left\{ \begin{matrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{matrix} \right\}$$

The matrix M is called as the transition matrix in a Markov chain.

The Markov process is a useful mathematical method, and is widely used in different areas, such as statistics, queuing theory, information sciences, economics and etc. In wireless networks, researchers usually use a Markov process to generate analytical models or predict the system performance.

However, there is very limited number of papers focusing on how to apply Markov process to energy efficient topology management. A set of research works which apply Markov processes to a wireless environment is introduced here. These works will help us understand how to apply Markov process to energy efficient topology management in a wireless environment.

In [72], the authors propose a prediction technique with the aid of a Markov renewal process to compute the likelihoods of a user being in a specific state after N time transitions in mobile environments. Both the mobility model and prediction process are generated. This technique can be used to estimate the expected traffic load and the behaviour at each location in the service area. It can also provide an efficient network resource management and ensure a certain level of QoS for the mobile users.

The research in [75] presented the issues of location and request prediction in wireless networks in a homogeneous fashion, characterizing them as a discrete sequence prediction problem. An analytical model of high altitude platform (HAP) is discussed in [76], and the authors investigate the approaches to improve the Grade of Service (GoS) in a coexistence scenario with different user types in a HAP system. An analytical model is developed to describe the system activities with the aid of a two dimensional Markov process. A novel restriction mechanism is implemented in order to achieve a fair balance of GoS.

An energy efficient distributed relay selection in wireless cooperative networks is introduced in [77]. The authors consider finite state Markov channels in the relay selection problem, adaptive modulation and coding, as well as residual relay energy. The target of this work is to reduce error propagation, increase spectral efficiency and maximize network lifetime. The analytical and simulation results the proposed relay selection scheme are significantly better than the existing memoryless method and random selection.

In our thesis, the Markov process will be widely used as the analytical model to predict system performance and potential network energy reduction. Particularly, the multi-dimensional Markov chains will be developed in our scenario, because there are multiple-servers in our network (multi base stations).

3.3 Performance Measures

A set of parameters are chosen to estimate the system performance and potential energy reduction in the simulation. The Signal to Interference plus Noise Ratio (SINR) is used here to measure the quality of wireless connections in our Monte Carlo simulation. For example, it is used to determine whether a user can access the system or an existing user loses its current service. Blocking and dropping probabilities are measured to guarantee the system Quality of Service (QoS) which are used in both the analytical and simulation models. The data throughput, commonly used to decide the capacity of wireless services, is used to measure the system capacity of next generation mobile broadband systems. Energy Reduction, one of the most important parameters in our thesis, is used to measure how much energy consumption can be saved with the aid of our topology management scheme. The Cumulative Distribution Function (CDF) is used to process the initial data and to deliver the statistical behaviour of the simulation results. Error bars are plotted on some graphs because there usually are errors involved in the experiment due to impurity of the sample, limits on the accuracy of the scales and other equipment [78].

3.3.1 Signal to Interference plus Noise Ratio

Signal to Interference and Noise Ratio, which is also known as Carrier to interference and Noise Ratio, is one of the fundamental parameters to measure the performance of user and the system in wireless communication [79] . It is defined as the ratio of signal power to the combined noise and interference. The equation for calculating SINR is shown as:

$$SINR = \frac{P}{I+N} \tag{3.1}$$

where P is the received power at the receiver; I is the sum of the co-channel interference power from other devices, N is the noise power which is typically fixed if the bandwidth and frequency are given.

SINR will be used in our work to determine whether a new user or an existing user can receive reasonable service from the transmitter.

3.3.2 Blocking and Dropping Probabilities

Blocking and dropping probabilities are two very important measurements which are used to estimate the Quality of Service of the system. The blocking probability is defined as the statistical probability that a voice connection cannot be established due to insufficient transmission resources in the network [80], which occurs when new user arrives the network. Thus, we have:

$$P_B = \frac{N_b}{N_{total}} \tag{3.2}$$

where P_B is the system blocking probability, N_b is the total number of activations being blocked and N_{total} is the total number of activations in the network.

Similarly, dropping probability is defined as the probability that a connection is interrupted during transmission, which should occur after a connection had been built up. Thus, we have:

$$P_D = \frac{N_d}{N_{accept}} \tag{3.3}$$

where P_D is the system dropping probability, N_d is the total number of activations being dropped and N_{accept} is the number of accepted activations in the network.

3.3.3 Throughput

The network throughput in our thesis is defined as the average rate of successful data packet delivered over a communication channel [80]. Thus, we have:

$$Thr = \frac{N_r}{N_{total}} \tag{3.4}$$

In our thesis, the measurement of throughput is used to measure the capacity of the network and to discuss how specific schemes influence the capacity of the network.

3.3.4 Energy Reduction

Energy reduction is selected as one of the important measurements in our work. It is used to show the efficiency of our energy efficient schemes, which is defined as:

$$ER = (1 - \frac{E_{TM}}{E_{total}}) \cdot 100\% \tag{3.5}$$

where E_{TM} is the energy consumption of the network with topology management scheme, and E_{total} is the total energy consumption of the network without topology management scheme.

3.3.5 Cumulative Distribution Function

A group of Monte Carlo simulation results will be obtained from the experiments. In order to analyze the simulation results easily, the cumulative distribution function (CDF) is used here to describe the probability that a real valued random variable X with a given probability distribution will be found at a value equal to or less than X [81]. Thus, we have [81]:

$$CDF \equiv F(x) = \int_{-\infty}^{x} f(t)dt \tag{3.6}$$

where *f(x)* is the probability density function of *x*. The results of our simulation like blocking probability and dropping probability are mainly measured at regular points in the service area. The CDF of these results will clearly show the probability of a valued random variable with a given distribution.

3.3.6 Error Bars

Error bars have been plotted on some diagrams in our thesis (e.g. Figure 5.4), which are used to show the confidence intervals of data or the deviation along a curve. The type of confidence limit plotted shows the error in the sampled mean. It is used in plots of system blocking probability versus offered traffic when comparing the results of analytical model and Monte Carlo simulation.

The size of error bar is determined as [82]:

$$e = \mu \pm z_c \cdot \frac{\sigma}{\sqrt{N}} \tag{3.7}$$

where μ is the mean of sample, σ is the standard deviation, N is the number of trials, and z_c is related to the confidence interval. If $N > 30$, the confidence interval is considered as the normal distribution. $z_c = 2.56$ if a 99% confidence interval is assumed [82]. All the error bars are the same size above and below the mean of sample. For N<30, it should be considered as the t-distribution instead of a normal distribution. For the Monte Carlo simulation in our thesis, the number of trials is equal to or higher than 40 in order to obtain accurate results. Thus, the normal distribution should be applied for the plots of error bars.

3.4 Validation

Both analytical models and Monte Carlo simulations are used in our thesis. A set of analytical models are developed with the aid of multi-dimensional Markov processes in each chapter (chapter 5, 6 and 7) to discuss the behaviour of users and system performance in specified cases. Then, related Monte Carlo simulations are used to validate the analytical models. Mathematical analyses for predicting system performance and the influence of parameter values are available in chapter 5. A Monte Carlo simulation is used here under the same scenario in order to corroborate that the predicted results from the analytical model are correct. A more complex analytical model is developed in chapter 6 where the handover mechanism is combined with the topology management scheme to provide higher energy efficiency for the next generation mobile broadband networks. The theoretical and experimental results are compared in chapter 6 which verifies both the analytical model and the simulation. In chapter 7, a more comprehensive analytical model is designed to provide more flexibility for the analytical models in a large network. As with chapter 5 and chapter 6, the results from both the analytical model and the simulator are compared again.

3.5 Conclusions

This chapter described the approaches of system modelling tasks which may be applied in this thesis. We discussed the potential system modelling techniques, including simulation and analytical models. MATLAB is selected as the main simulation tool in our work, and Monte Carlo approach is used to general statistically simulation results in order to obtain accurate results. Markov process is chosen as the analytical model used in our thesis. Next, the key measurements are defined and given to describe the system performance, such as SINR, blocking and dropping probabilities, throughput, energy reduction, CDF and error bars. Finally, a discussion of validation is shown, the simulation and analytical models will be both applied in our work.

Chapter 4. Distributed Dynamic Energy Efficient Topology Management for Next Generation Mobile Broadband Systems

Contents

4.1 Introduction

In next generation mobile broadband systems (BuNGee), researchers are considering how to deliver high throughput densities or extend the coverage area at low cost. This requires a large number of fixed base stations in the service area. Currently, these kinds of base stations are designed for best performance, where energy efficiency is not primarily considered.

As we introduced in chapter 1, the BuNGee network is a two-hop system architecture. This is made of backhaul links between Hub Base Station (HBS) and Access Base Stations (ABSs), with the access links formed by the ABSs connected to Mobile Stations (MSs). We propose several distributed energy efficient topology management schemes for this kind of system, and introduce a sleep/wake up mechanism in our work. Whether an ABS should be on or off is fully determined by the local information an ABS receives itself, rather than being controlled by its HBS. An ABS will be switched off to save energy when the traffic load on its adjacent is at low level.

The system architecture will be introduced in section 4.2, where we use the typical architecture for BuNGee networks. Next, the distributed energy efficient topology management schemes will be presented in section 4.3. Then, the energy model of our work is shown in section 4.4. We focus on reducing the energy consumption of the ABSs. Sections 4.5 and 4.6 are the simulation scenarios and the results with analysis. The results present the potential energy reduction and the system blocking probabilities with/without topology management. A trade off between energy reduction and system performance will be discussed.

4.2 System Architecture

In this chapter, we choose the BuNGee architecture as the network which was briefly introduced in chapter 1. Figure 4.1 gives an example of such a BuNGee architecture with backhaul and access links. Large numbers of ABSs are located around HBS, every 300m below roof top height to enable dense frequency reuse, possibly installed on street lamps to provide coverage for users along a street or just inside buildings. The role of the ABS is to forward data between HBS and MS because they cannot communicate with each other directly.

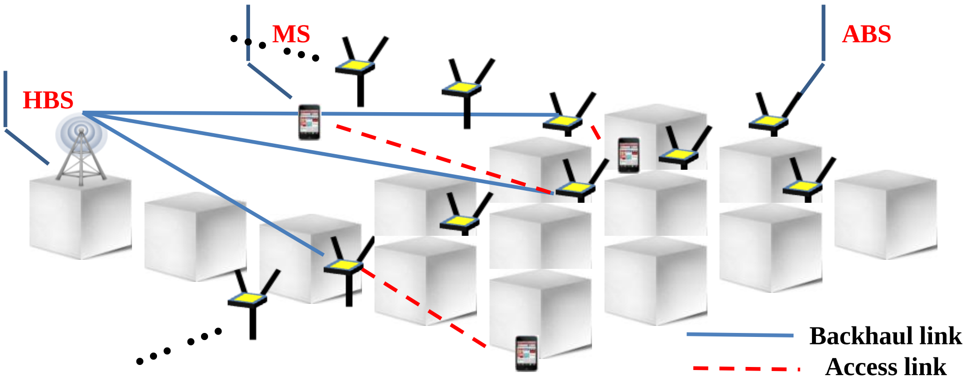

Figure 4.1 BuNGee Architecture with backhaul/access link

Here, we choose topology management (spatial domain) to reduce the network energy consumption because of the characteristics of the BuNGee architecture. It has a large number of ABSs, so the solutions of energy saving can be extended to the whole network. In ad-hoc and sensor networks, the dynamic routing problem is always a key issue to reduce energy cost because its routes usually have two or more hops. However, in this thesis we consider a two-hop system, where the backhaul link between HBS and ABS is fixed once they are deployed. Only the routes between ABSs and MSs can be determined depending on the routing strategy used. This is less flexible in terms of route options compared with more conventional ad-hoc networks, meaning that there is less to be gained in terms of energy efficiency.

When an ABS is in idle mode, the receiving part will reduce its power, to just listen to necessary information from its two or four adjacent nodes periodically (Most of the nodes have two neighbours, with some nodes in particular positions having four, which are shown in Figure 4.2). The purpose of leaving the receiver in the ABS on is to ensure that the main parts of the ABS can be woken-up in sufficient time to cope with significant changes to the local traffic load. The power required in this receiving mode is very limited, because these nodes are located close and within line of sight of each other.

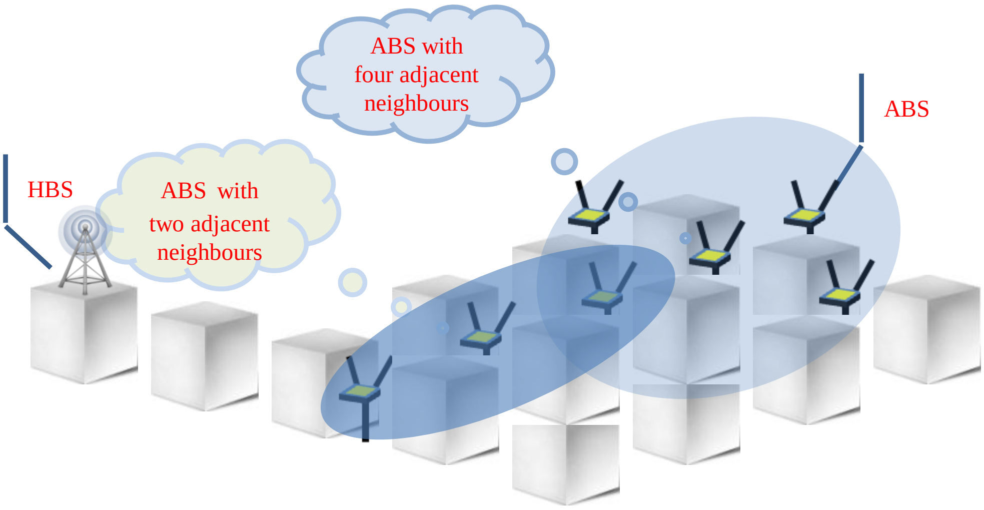

Figure 4.2 ABSs and its adjacent neighbours

The BuNGee architecture is based on a Manhattan grid environment. The deployment of this kind of network in a large network is shown in Figure 4.3, the blocks, stars located inside buildings and the large numbers of crosses represent buildings, HBSs and ABSs respectively. It is assumed that a MS always uses two-hops to obtain service from a HBS, with the data being forwarded by the ABS half way. An ABS has two (or four when they are located at street intersections) directional antennas pointing down the streets in order to improve coverage and control interference. Each ABS also has a special sub-system named the Hub Subscriber Station connected to a HBS which is used to connect to the HBS providing communication between an ABS and HBS. The HBS uses highly directional phased array antennas which produce up to 24 main beams if necessary, but only 20 are used in this configuration [3]. Every active ABS around HBS can obtain a main beam, increasing the link gain.

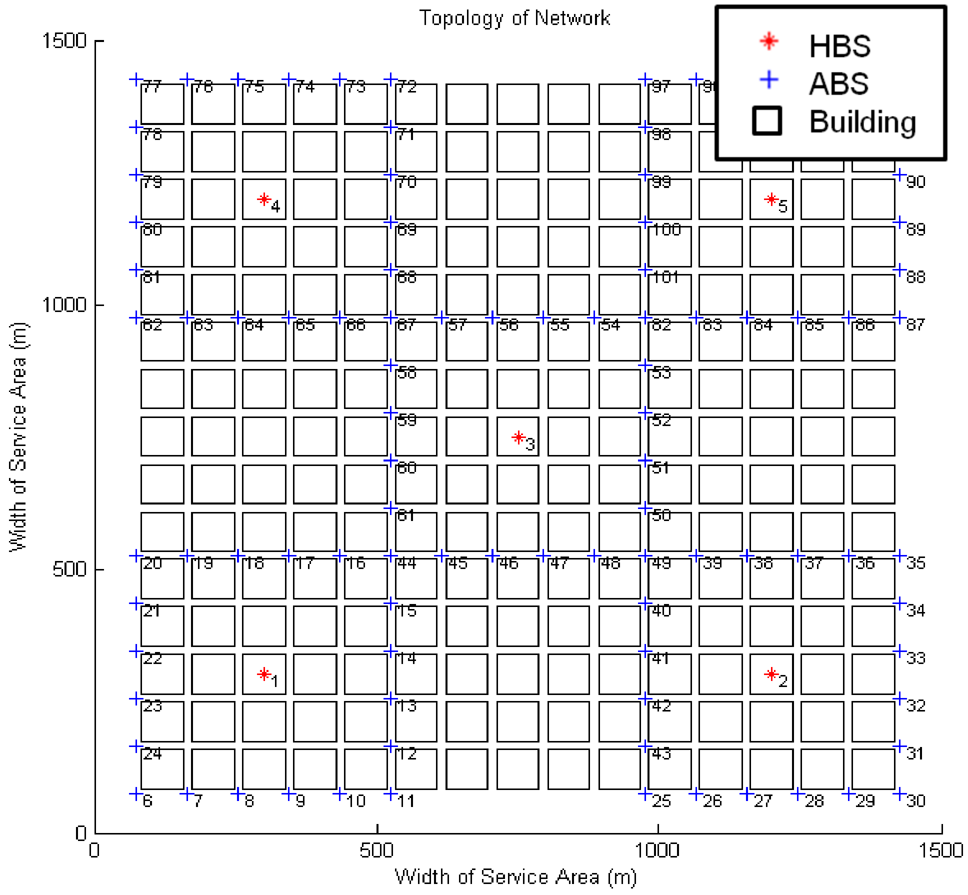

Figure 4.3 Topology of BuNGee Architecture

With the aid of this architecture, the overall system throughput can be significantly increased when system traffic is at a high level. However, it is not an effective strategy in terms of energy efficiency to keep all nodes on when considering the behaviour of users over a whole day. Figure 4.4 shows how the number of users varies throughout a typical day for a website. The highest peak occurs around 22:20 and the lowest point is around 05:30 in the morning [83]. Therefore, we should devise appropriate rules to switch off parts of ABSs in order to achieve energy saving in the overall network.

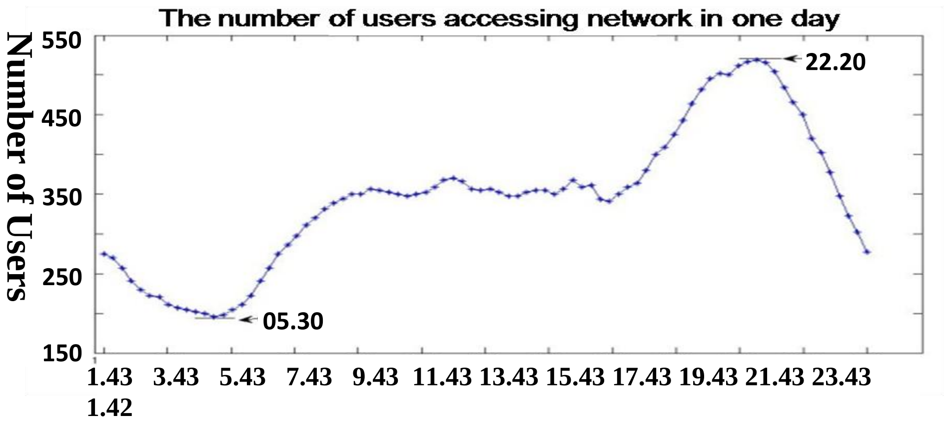

Figure 4.4 The number of users accessing network in one day [83]

4.3 Distributed Dynamic Energy Efficient Algorithms

In this chapter, use of distributed rules to control the behaviour of an ABS is investigated, with all the decisions being determined at the ABSs themselves. It is assumed that every ABS can be switched off. The key parameters we focus on at this stage are the traffic at an ABS, and the traffic and activity at its neighbours. Several rules are then designed to explore their influence on the system performance.

We choose instantaneous traffic and average traffic over a period in the past to best represent the density of a service area. This allows us to set a suitable threshold to control them. When the offered traffic is low in the network, the blocking due to bad positions of users will increase when the number of active ABSs decreases at the edge of the service area. If one ABS is switched off, some users at particular positions may be unable to find an alternative ABS to forward their data. In a central area, new users usually have more than one potential ABS to access, and that is the reason why we should exploit knowledge of the activity of neighbouring nodes. A possible set of rules is shown below:

Rule 1:

For switching from working mode to idle mode (on to off), all conditions below should be satisfied:

1. All its adjacent ABSs should be in working mode.
2. The capacity usage of an ABS at time $t < C_{self,ins}^{OFF} = 30\% \bullet C_{max}$ of the maximum capacity.
3. The average capacity usage of an ABS between time *t* and time *t'*$< C_{self,ave}^{OFF} = 30\% \bullet C_{max}$.
4. The capacity usage of all its neighbouring ABSs at time $t < C_{adj,ins}^{OFF} = 50\% \bullet C_{max}$of the max capacity.
5. The average capacity usage of its adjacent ABSs between time *t* and time *t'*$< C_{adj,ave}^{OFF} = 50\% \bullet C_{max}$. (This is used to ensure the data can be forwarded to its neighbours on the target ABS when the original ABS is put to sleep).

Here we assume *Δt = t'-t = 10* seconds.

For switching from idle mode to working mode (off to on):

1. The capacity usage of the ABS's adjacent nodes at time *t*: $C_{adj,ins}^{ON} \geq 90\% \bullet C_{max}$ of the max capacity.
2. The average capacity usage of its adjacent nodes between time *t* and *t'*: $C_{adj,ave}^{ON} \geq 90\% \bullet C_{max}$.

The values of threshold $C_{self,ins}^{OFF}$, $C_{adj,ins}^{OFF}$ and $C_{adj,ins}^{ON}$ used here are due for the capacity analysis after we switch off an ABS. Depending on *rule 1.1*, the ideal number of ABSs can be switched off is one in two. With this condition, the maximum traffic on an ABS in the ON mode includes the traffic on itself and the data forwarded from its two neighbours.

$$C_{adj,ins}^{OFF} + \frac{C_{self,ins}^{OFF}}{2} + \frac{C_{self,ins}^{OFF}}{2} = 50\% + \frac{30\%}{2} + \frac{30\%}{2} = 80\% < C_{adj,ins}^{ON} = 90\% \tag{4.1}$$

That means the active ABSs still work when they forward all the traffic from their neighbours, and there is another 10% extra capacity left for new arrivals.

We also examine the effect of changing some of the parameter values to explore how they affect the system performance.

Rule 2 & Rule 3 (changing the capacity usage threshold):

The capacity usage threshold is changed from 30% to 20% and 40% of the maximum capacity separately. Other parameters remain fixed.

Rule 4 (changing the requirement of neighbour's activity):

If an ABS plans to switch off, at least one of its adjacent nodes must remain in working mode. Other parameters remain the same with *rule 1*. That means two out of three ABSs can be switched off in ideal condition.

Rule 5 (full self decision):

The decision is fully determined by the action of the ABS itself, ignoring the activity of its adjacent nodes. This rule is different from other rules; it is likely to deliver good energy saving when the local traffic is very low. In extreme situations, all the ABSs located in a local area may switch into the idle mode simultaneously. A newly arriving MS may not obtain service from any ABSs. The drawback is that this may deliver bad system performance for the users deployed in this area, meaning that the overall system wide quality of service thresholds may be breached.

4.4 *Energy Model*

Here, we discuss the uplink only. The total energy consumption in the system comes from the MS, ABS, and HBS. The power consumed at ABS and HBS will be different when varying from the working to idle state and based upon the number of users connected. The components of the ABS/HBS are divided into the following parts [84]: Radio Frequency (RF), Signal Processing, A/D Converter, Power Supply, Battery Backup and Cooling. Thus, the energy cost for the MS is computed while data is being transmitted, represented by following:

$$E_{MS} = \sum_{i=1}^{n_{MS}} t_{MS,i} P_{MX,Tx,i} \tag{4.2}$$

where n_{ms} is the number of MSs in system; $t_{MS,i}$ is the service time for MS *i*. $P_{MS,Tx,i}$ denotes the power for MS *j* in transmission.

The calculation of the energy consumption for the ABS is more complex than with the MS. We divide the energy consumption into the idle and working states. The extra 'wake-up' energy consumed when switching from idle to working mode is also considered here [85]. Next, the energy consumed while in working mode can be divided into three parts: energy for receiving the signal, energy for transmitting the signal, energy for the components in the ABS except for the RF part. The first two parts of energy are only consumed when nodes receive or transmit data; the third part always exists if an ABS is active. The energy consumption by the MS, ABS and HBS is represented by the following equations:

$$\begin{aligned} E_{ABS} &= \sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j} P_{ABS,idle,j} + t_{ABS,work,j} P_{ABS,work,j} + n_{idle,j} E_{wakeup})(\frac{1}{1-\mu_{sl}}) \\ &= \sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j} P_{ABS,idle,j} + t_{ABS,Rx,j} \frac{P_{ABS,Rx}}{\mu_{RF}} + t_{ABS,em,j} P_{ABS,em} \\ &\quad + t_{AP,Tx,j} \frac{P_{ABS,Tx,j}}{\mu_{RF}} + n_{idle,j} E_{wakeup})(\frac{1}{1-\mu_{sl}}) \end{aligned} \tag{4.3}$$

where n_{ABS} is the number of ABSs in service area; $t_{ABS,idle,j}$ /$t_{ABS,work,j}$ is the total time when this ABS is in idle/working mode; $P_{ABS,idle,j}/P_{ABS,work,j}$ denotes the power in idle/working mode respectively; $n_{idle,j}$ is the number of times ABS j switches from idle into working mode; E_{wakeup} shows the energy consumption in this process. The energy consumption in switching an ABS to the idle state is very limited, so it is ignored in our discussion. $t_{ABS,Rx,j}$ / $t_{ABS,em,j}$ / $t_{ABS,\boldsymbol{Tx},j}$ denotes the time this node is in the receiving/active/transmitting states. Similarly, $P_{ABS,idle,j}/P_{ABS,em}/P_{ABS,Tx,j}$ is the power consumption in the corresponding states. μ_{RF} is the efficiency of amplifier in the RF part; μ_{sl} is the loss in the power supply and battery backup. The energy consumption of the HBS is made up of the receiving part and the components in the HBS except the RF part. The cooling system is considered here because the HBS is much more powerful and complex than the ABS.

$$E_{HBS}=\sum_{i=1}^{n_{HBSs}}(t_{HBS,Rx,i}\frac{P_{HBS,Rx,i}}{\mu_{RF}}+t_{HBS,em,i}P_{HBS,em})(\frac{1}{1-\mu_{sl}-\mu_{cool}}) \tag{4.4}$$

where n_{HBS} is the number of HBSs in the service area; $t_{HBS,Rx,i}/t_{HBS,em,i}$ is the total time that this ABS is receiving or active; $P_{HBS,Rx,i}$ and $P_{HBS,em}$denote the power in receiving and active respectively; μ_{RF} is the efficiency of amplifier in the RF part; μ_{sl} is the loss in the power supply and battery backup and μ_{cool} is the ratio of energy spent on cooling system compared with the total energy consumption of the HBS. The transmit power of HBS is not considered because only uplink is discussed in the chapter. The details of parameters for energy model are shown Table 4.1.

Table 4.1 Parameters for Energy Model [3]

Parameter	Value
Power in receiving mode	5W (ABS)
Power in idle mode	250mW (assumed 5% of receiving mode)
Efficiency of RF	20%
Supply loss	10%
Efficiency of cooling system	50%
ABS max transmit power	5W
MS max transmit power	200mW

4.5 Simulation Scenario

In the simulation, MATLAB is used as the simulation tool. There are 5 HBSs and 96 ABSs deployed in a 1.5km by 1.5km service area and 6000 users are uniformly distributed throughout the streets or within 5 metres of the inside wall of buildings. The users arrive one-by-one in sequence, with the inter-arrival time being determined by exponential distribution, such that the offered traffic in general follows a Poisson traffic model. The WINNER II propagation model [86] is used in our simulation, which is introduced in detail in the appendix, 24 channels are available for communication. The related parameters are defined in Table 4.2.

Table 4.2 System Parameters [86]

Parameter	Value
HBS max antenna gain	17dBi
ABS max antenna gain	17dBi
Frequency	2.4GHz
SINR threshold	9dB
Noise Floor	-114dBm/MHz
Average transmit rate	2Mbps
Average size of a file	4MB

The performance of the strategies has been evaluated with and without topology management. Here we choose the blocking probability (BP) and the average percentage of ABS in working mode as a way of measuring the system performance. We try to find out which strategy has the best energy reduction while keeping the system blocking probability below 5% [87].

4.6 Results and Analysis

Figure 4.5 shows the blocking probability vs offered traffic in the system. In the legend, *s(xx%)* means the capacity threshold for switching the ABS from working to idle mode on each node is less than *xx%* capacity. Similarly, *n(xx%)* means the capacity threshold applied to its neighbours. *Self/1neigh..on* shows the minimum number of nodes that should be in working mode if the target ABS plans to switch off. *Self* means the strategy only depends on the prior knowledge of the node itself, i.e. it does not consider the state of its neighbours. *1neigb..on* means at least one of its adjacent node should be in ON mode. If no reference is made in the legend to the capacity of the neighbours, it means all neighbours of the ABS are active.

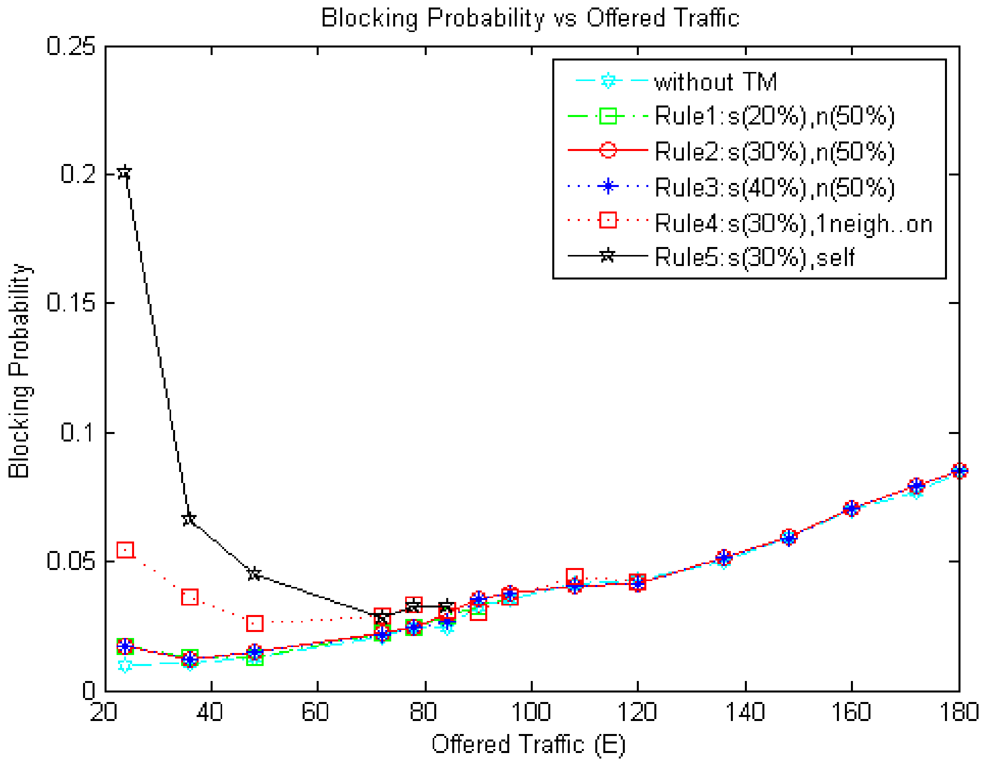

Figure 4.5 Blocking Probability vs Offered Traffic

We can see that the strategy without topology management has the best result compared to the other strategies. Meanwhile, the impact of changing *rules 1/2/3* is minimal compared them to the results without TM. The blocking probability of *rule 4* is higher than *rules 1/2/3* when the offered traffic is low, because a large number of ABSs are switched off and some MSs in bad locations are now out of coverage. *Rule 5* causes very bad performance when the offered traffic is low as expected, but blocking will drop sharply to an acceptable value after the traffic reaches 48 Erlangs, and merges with the results of other rules after 72 Erlangs.

Figure 4.6 describes the percentage of ABS in working mode vs offered traffic. Here the results for rule 4 and 5 (one neighbour on / does not consider its neighbours) are much lower than those rules with all adjacent nodes in ON mode when the offered traffic of the system is at a low level. Particularly, the value for rule 4 (one neighbour on) is about 36% when offered traffic equals to 24 Erlangs, and this result is close to the theoretical lower bound which we analysed in the previous section. The *rules 1/2/3* in which all adjacent nodes should be on can also benefit in terms of energy saving, but the percentages of ABSs in working mode are much higher than other rules.

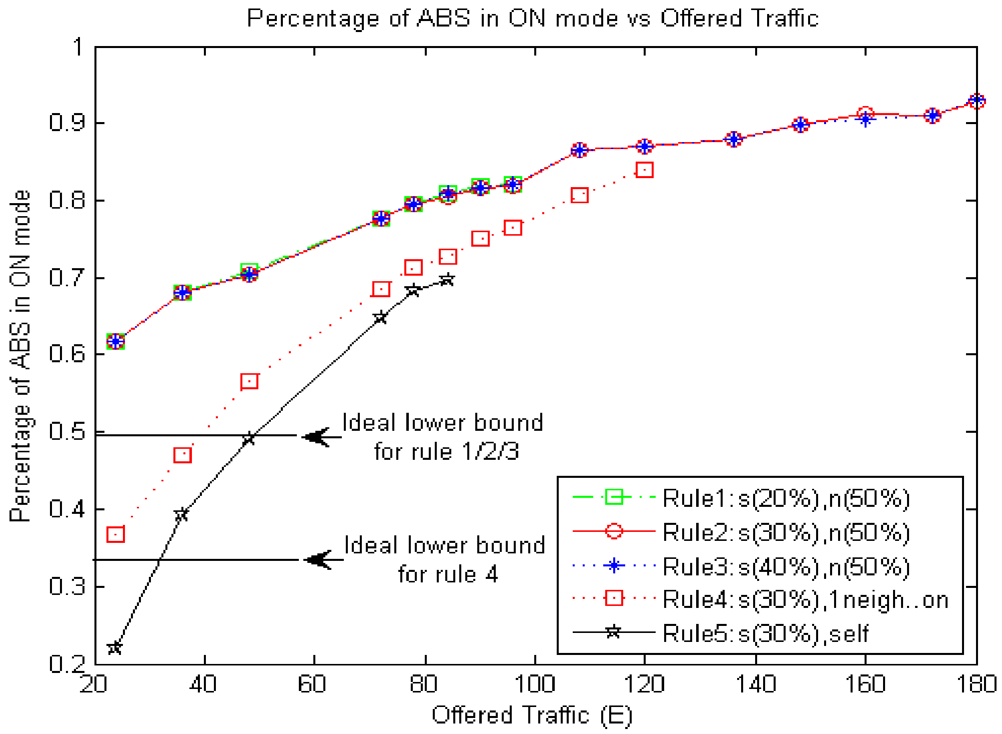

Figure 4.6 Percentage of ABS in ON mode vs Offered Traffic

It can be observed from Figure 4.5 and Figure 4.6 that the number of adjacent nodes in working mode is a more important factor affecting the energy saving compared with just changing the traffic threshold. Rule 4 (at least one adjacent node on) has very good performance in both blocking probability and energy saving at low traffic levels. *Rule 5* (fully determined by the node itself) has the best performance in energy saving but performs poorly in terms of blocking probability at low traffic levels. However, it can potentially be used at mid traffic levels (48E – 84E), since it saves more energy than *rule 4* and has a similar BP. It is possible to propose a mixed strategy with the previous two rules in order to obtain the best overall combined performance over all traffic levels. *Rules 1/2/3* (all adjacent nodes should be in ON mode) have the lowest performance among these rules, but their BP results are very close to the result without topology management. Meanwhile, it can also save energy, so it has good reliability.

Figure 4.7 and Figure 4.8 show the energy consumption per file vs offered traffic and energy reduction per file with/without topology management vs offered traffic respectively. The percentage of energy reduction in Figure 4.8 is slightly lower than the results in Figure 4.6, because although the energy consumption for keeping ABS active is reduced, the energy cost for transmitting and receiving the data still exists.

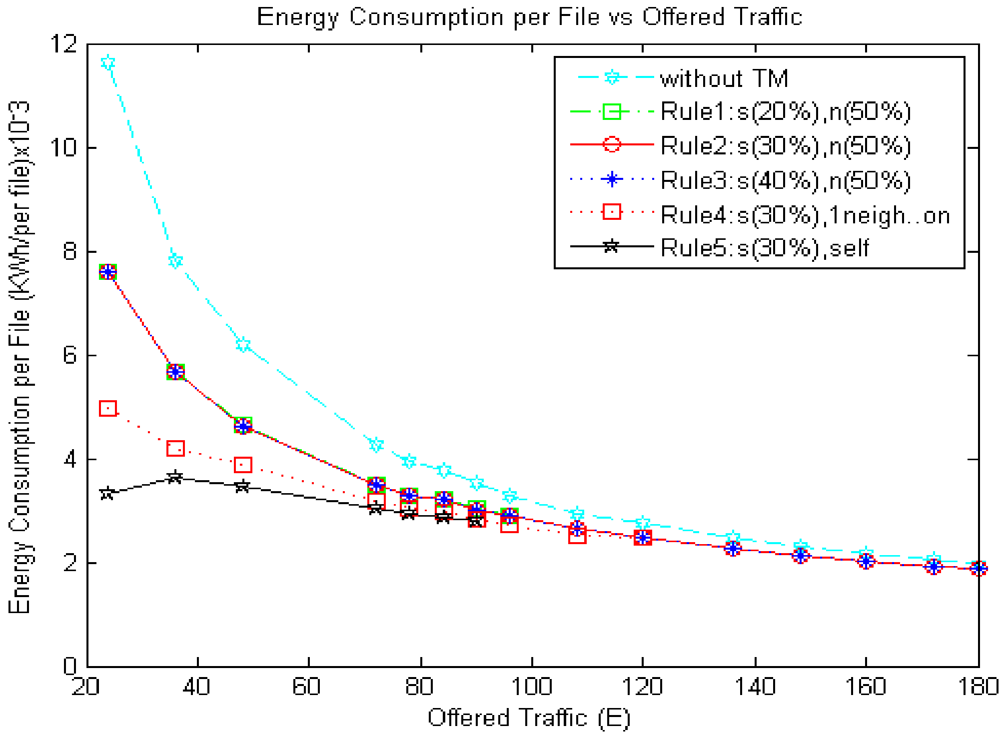

Figure 4.7 Energy Consumption per File vs Offered Traffic

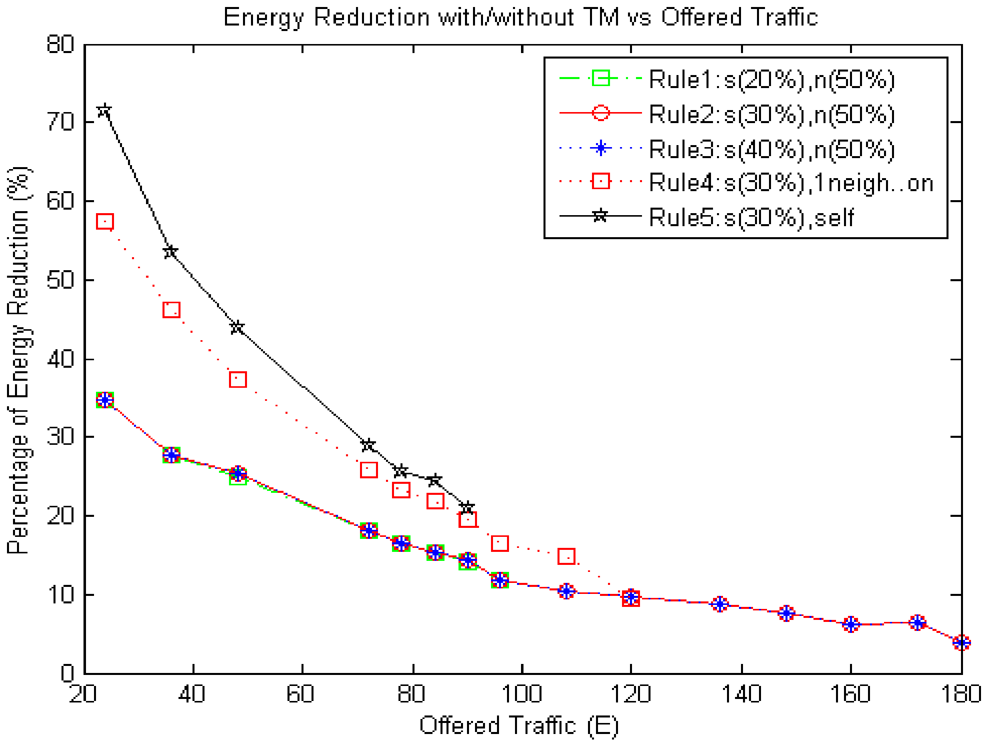

Figure 4.8 Energy Reduction with/without TM vs Offered Traffic

4.7 Conclusions

In this chapter, we have presented several traffic load based fully distributed topology management strategies for use with beyond next generation mobile broadband systems. The simulation results show all the strategies can reduce the energy consumption by 35% to 70% at low traffic levels. The rule that (at least one of adjacent ABS should be on) has the best performance when balancing system QoS and energy reduction. This saves up to 58% energy compared with the strategy without topology management. Meanwhile, the strategy 'full self decision at the ABS' does not work well at low traffic levels, but has the potential for use at the mid traffic levels as it provides more energy saving. It means that it is possible to propose a mixed strategy which has the advantage of the previous two rules to obtain good overall performance over all traffic levels. The algorithm introduced in this chapter will be used in the next three chapters.

Chapter 5. Theoretical Analysis for Energy Efficient Markov Process

Contents

5.1 Introduction

In this chapter, an energy efficient topology management scheme is proposed for Beyond Next Generation Mobile Broadband Systems (BuNGee), which employs an analytical model to describe the energy efficient strategy and predict the system performance. This analytical model is discussed with the aid of a multi-dimensional Markov process in a simple *three*-base station network, and then applied to a larger BuNGee network. The purpose of this work is to show how suitable parameters can be determined for the traffic load based topology management schemes to achieve a trade off between system performance and energy efficiency. The topology management scheme is developed based on the work in chapter 4. Here, the analytical model uses a simple scenario compared to the scenario used in chapter 4 in order to reduce the complexity of system modelling design. One of the main differences is that only some of ABSs are assumed to be switched off when necessary. The others should always keep working. In chapter 4, every ABS can be switched off. The details of this part will be discussed in the next section.

The remaining part of this chapter is structured as follows: Section 5.2 describes our proposed topology management scheme and the analytical model is then developed. The energy model and potential energy reduction performance are presented in section 5.3. In section 5.4, Simulation Scenarios, simulation results and analysis are set out. Finally, our conclusions are presented in section 5.5.

5.2 Analytical Model Design for three-ABS Networks

In this section, the system level behaviour of the scenario is analysed. There are *i*-ABSs in the service area and each ABS has n_i available channels. The energy efficient topology management analytical model can be described with the aid of a multi-dimensional Markov chain. Each state in the Markov chain is defined as the number of channels occupied on an ABS, with each ABS in the service area forming one dimension. An *n*-channel *three*-ABS network is discussed first in order to explore how the energy efficient topology management problem can be solved with a Markov process in a standard network. A general *n*-channel *i*-ABS system is analysed later based on this initial model.

Figure 5.1 depicts the *three*-ABS system architecture. Areas 1 and 2 represent the coverage areas of ABS1 and ABS3 respectively. Unlike the work in chapter 4, these are assumed to be always in the ‘ON’ mode. In dense deployment systems, there is often a high degree of overlapping coverage, so, here ABS2 is assumed to provide service for both of these two areas if in ‘ON’ mode. However, it is assumed to switch into a sleep (‘OFF’) mode in order to save energy when the local traffic level is low. There are many ways to determine the parameter values for switching a specific ABS on/off, such as traffic load, SINR and power. In this chapter, the key parameters we focus on are the traffic loads and activities on an ABS and its neighbours. The reason we have chosen traffic load is because it is clearly a relevant parameter in the decision making process. In the Markov chain we now derive, the state is defined as the number of channels occupied on each ABS.

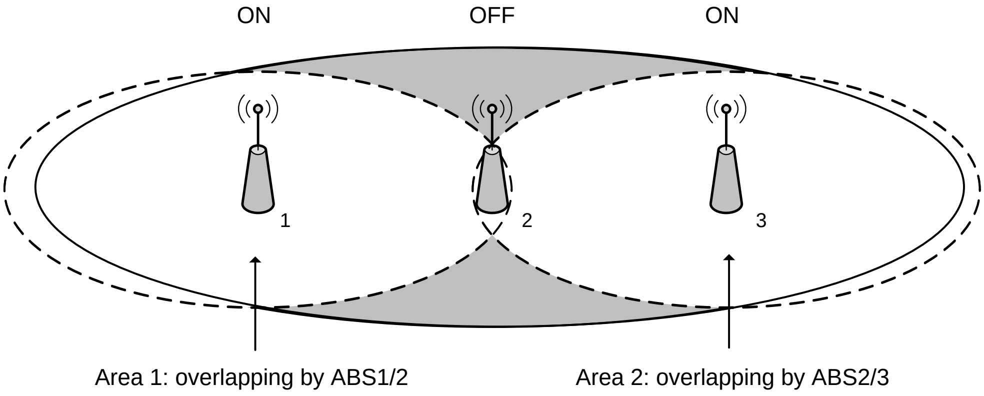

Figure 5.1 The architecture of a three-*ABS network*

In this *three*-ABS network, our proposed energy efficient topology management scheme is described as follows [88]:

To switch an ABS from working (ON) mode into sleep (OFF) mode, the following should be satisfied:

1) The capacity usage of an ABS at time *t* is smaller than a threshold capacity (n_{self}^{OFF}).
2) The capacity usages of all its neighbouring ABSs at time *t* are smaller than a threshold capacity (n_{adj}^{OFF}).

If both of above are satisfied, the ABS will prepare to switch into sleep mode. New users are not allowed to access the ABS at this stage.

To switch an ABS from sleep mode into working mode, the following should be satisfied:

The instantaneous capacity usage of one of its adjacent ABSs at time *t* is higher than a threshold capacity (n_{adj}^{ON}).

Considering individual users (MSs) accessing the system, the arrival and departure rates are assumed to follow an exponential distribution [89]. There is no queuing assumed in our scenario. Figure 5.2 is a graphical representation of this *three*-ABS network. The Markov process can be described as a cube with each node in the diagram represented a state $S(j_1, j_2, j_3)$. The numerical argument j_i in a state represents the number of channels being used on the *i*-th ABS. For example, $S(0,4,2)$ means that no channels on ABS1 are occupied, four channels are occupied on ABS2, and two channels are being used on ABS3. n_i is the maximum number of available channels on ABS_i. The *three*-ABS network is assumed to start from $S(0,0,0)$, and can stay in the current state, if at most one arrival or departure occurs, it can move in any of the three orthogonal directions defined by the axes representing a single state transition.

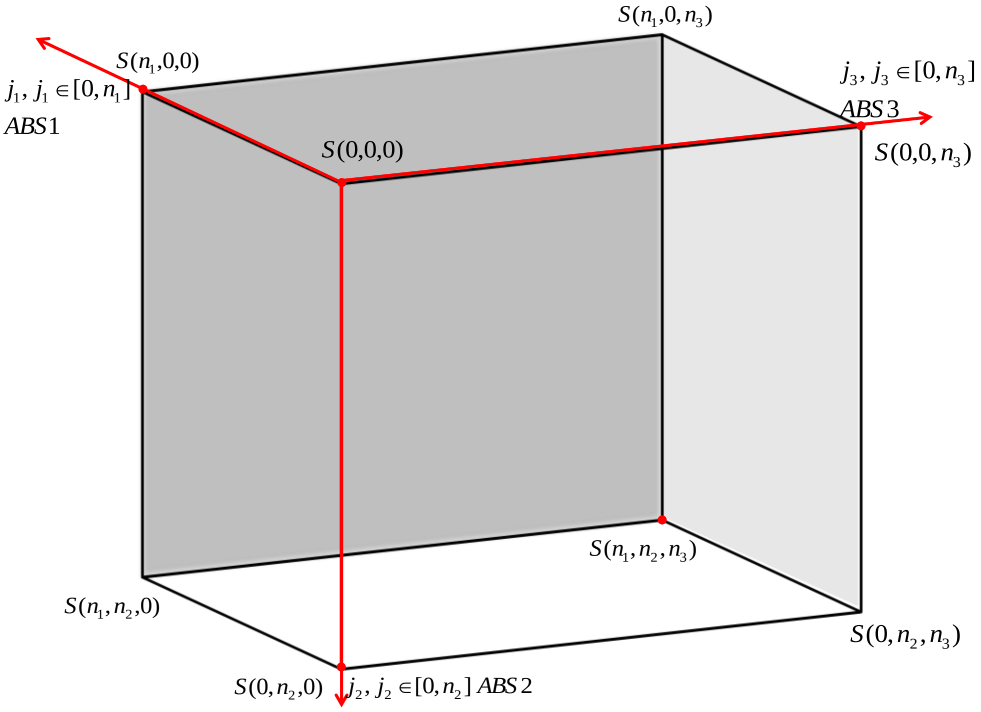

Figure 5.2 A graphical representation of the three dimensional Markov Mode of a three-*ABS network*

Figure 5.3 shows the state transition diagram when, for clarity, the number of channels occupied on ABS1 is always equal to zero. This is represented as the front surface in Figure 5.2.

The notation in use is defined as follows:

λ_2/λ_3: The arrival rate for ABS2/ABS3 when not fully occupied.

λ_{23}: The arrival rate for ABS2/ABS3 when one of them is fully occupied and the local traffic is all forwarded to the alternative ABS3/ABS2.

μ: The departure rate per channel.

n_i: The maximum available channels on ABS_i.

n_{adj}^{ON}: The threshold to switch on an ABS. If the number of channels occupied on the adjacent ABSs to an ABS in sleep mode is equal to or greater than this threshold, we turn the sleeping ABS on.

n_{adj}^{OFF}: The threshold to switch off an ABS. If the number of channels occupied on the adjacent ABSs to an ABS in working mode is smaller than this threshold, we prepare to turn off this ABS.

n_{self}^{OFF}: The threshold to switch off an ABS. If the number of channels occupied on an ABS itself is smaller than this threshold, we prepare to turn off this ABS.

α_{adj}^{ON} : The percentage of the total capacity used on the adjacent ABSs to ABS-i. So, $n_{adj}^{ON} = \lceil \alpha_{adj}^{ON} \bullet n_i \rceil$.

α_{adj}^{OFF} : The percentage of the total capacity used to on the adjacent ABSs of ABS-i. So, $n_{adj}^{OFF} = \lceil \alpha_{adj}^{OFF} \bullet n_i \rceil$.

α_{self}^{OFF} : The percentage of the total capacity used on ABS-i itself. So, $n_{self}^{OFF} = \lceil \alpha_{self}^{OFF} \bullet n_i \rceil$.

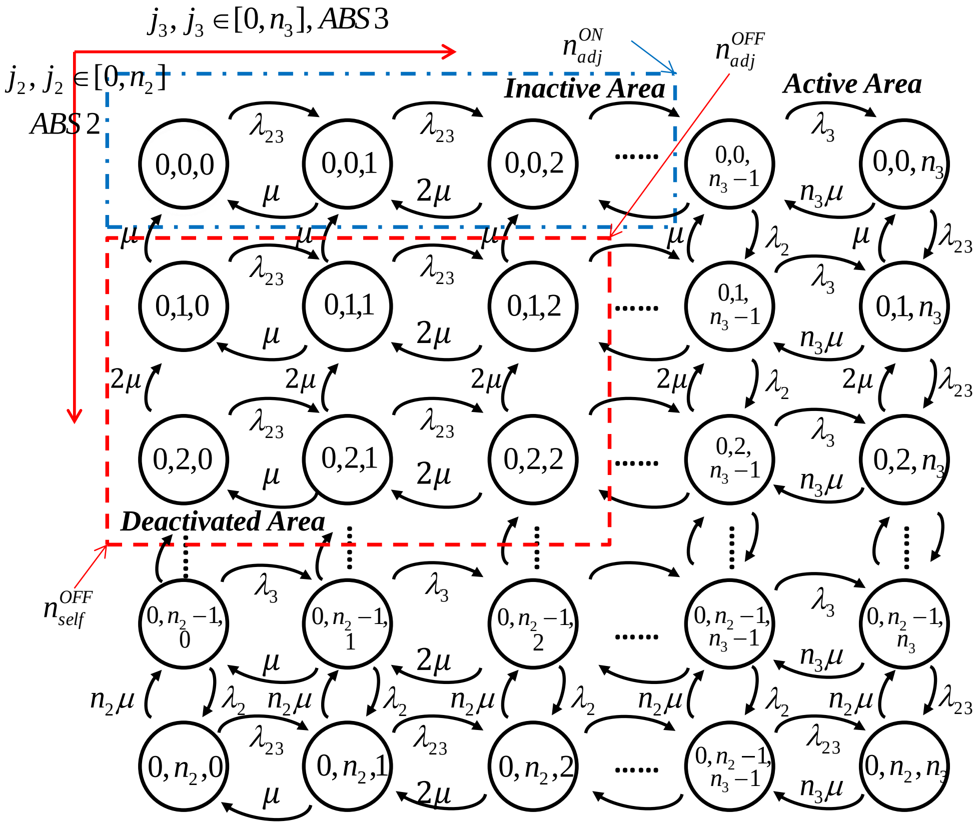

Figure 5.3 The state transition diagram of a three-*ABS network with topology management when the number of channels occupied on ABS1 is equal to zero*

Depending on the behaviour of ABS2 (which can switch into sleep mode), the state transition diagram can be divided into three parts: the Inactive Area (the area enclosed within dash dot lines), the Deactivated Area (the area enclosed within dashed lines) and the Active Area (the remaining area). In the Inactive Area, ABS2 is fully switched off, $S(0,0,j_3 < n_{adj}^{ON})$, so the potential energy reduction occurs in this area. In the Deactivated Area, any new comer MS is not allowed to access ABS2 because it is preparing to turn off in our scheme, $S(0,0 < j_2 \leq n_{self}^{OFF}, j_3 \leq n_{adj}^{OFF})$. The state can only transfer into the inactive area when all the users on ABS2 have ceased communicating. In the Active Area, all ABSs are active and the network achieves maximum capacity at this stage. Extrapolating to all three ABSs operating, the designated areas in Figure 5.3 would become volumes.

In order to introduce the state transition diagram clearly and to illustrate the concept, it is assumed that new comer MSs access ABS2/ABS3 only (reducing the problem to two dimensions) and the state transfers from $S(0,0,0)$. That means the system is fully empty, ABS3 is working but ABS2 is in the sleep mode. At this stage, the arrival rate on ABS3 is equal to λ_{23} . Since new users only have to access to ABS3, the state can only transfer along the Inactive Area in the horizontal direction until the threshold (n_{adj}^{ON}) of switching on ABS2 is attained, At this point, the system state transfers into the Active Area, and ABS2 is switched on to accept local traffic. Now, the arrival rate is equal to λ_3 on ABS3 in the horizontal direction and λ_2 on ABS2 in the vertical direction. When the channels on ABS2 are fully occupied, i.e. $j_2 = n_2$ (n_2 is the maximum number of available channels on ABS2), the arrival rate in the horizontal direction becomes λ_{23}. This is because new comers cannot find any available channel on ABS2; they have to access ABS3 in order to obtain service. Similarly, if the channels on ABS3 are fully occupied, i.e. $j_3 = n_3$, the arrival rate in the vertical direction becomes λ_{23} as well. If the number of channels occupied by both ABSs is smaller than the thresholds ($j_2 < n_{self}^{OFF}$ and $j_3 < n_{adj}^{OFF}$), the state transfers into the Deactivated Area. In this area, ABS2 prepares to switch off and will no longer provide service for any new users. All the traffic will be forwarded to ABS3. Therefore, the arrival rates do not exist for ABS2 while they equal λ_{23} for ABS3. In both directions, they have the same departure processes. The departure rates are represented as $j_i\mu$, where j_i is the number of busy channels on ABS2/3. If we were to extend to all three dimensions in the Markov model, a similar process would occur on ABS1.

A. *Equilibrium Analysis*

We now address the equilibrium analysis for the *three*-ABS system. When the system is in a steady state, the transition rate out of $S(j_1, j_2, j_3)$ should be equal to that into $S(j_1, j_2, j_3)$ for a *three*-ABS network. The probability that the system in $S(j_1, j_2, \cdots, j_i)$ is represented as $P(j_1, j_2, j_3)$. For a specific

$S(j_1, j_2, j_3)$ in the previous diagram, it has 2×3 adjacent states potentially suitable for transition. That is because there are *three*-ABSs in the network and two possible changes of the number of channels occupied on each ABS, a user arriving or departing. An extra situation is where no user arrives or leaves the system. The number of channels occupied on a specific ABS_i is between 0 and n_i (where n_i is the maximum number of available channels for ABS_i).

Therefore:

$$P(-1, j_2, j_3) = P(j_1, -1, j_3) = P(j_1, j_2, -1,) = 0 \tag{5.1}$$

Similarly:

$$P(n_1+1, j_2, j_3) = P(j_1, n_2+1, j_3) = P(j_1, j_2, n_3+1) = 0 \tag{5.2}$$

The general *statistical* equilibrium for an *n*-channel *three*-ABS network at $\mathrm{S}(j_1, j_2, j_3)$ is:

$$\begin{aligned}&(\lambda_{j_1} + j_1\mu + \lambda_{j_2} + j_2\mu + \lambda_{j_3} + j_3\mu)P(j_1, j_2, j_3)\\ &= (j_1+1)\mu P(j_1+1, j_2, j_3) + \lambda_{j_1-1}P(j_1-1, j_{2,} j_3)\\ &+ (j_2+1)\mu P(j_1, j_2+1, j_3) + \lambda_{j_2-1}P(j_1, j_2-1, j_3)\\ &+ (j_3+1)\mu P(j_1, j_2, j_3+1) + \lambda_{j_3-1}P(j_1, j_{2,} j_3-1)\end{aligned} \tag{5.3}$$

where $\lambda_{j1}, \lambda_{j2}, \lambda_{j3}$ are the arrival rates for each ABS transferring from the current state to the adjacent state if a new user arrives. If $j_i = n_i$, we define $\lambda_{j_i} = 0$ in order to obtain a general form of the equation. Meanwhile, $\lambda_{j1-1}, \lambda_{j2-1}, \lambda_{j3-1}$ represents the arrival rates from the previous state to the current state.

The arrival rate for a specific ABS-*i* in Area-*m* is determined by the service area, the user density of Area-*m* and the probability of a new user accessing ABS-*i* in this area.

The notations in use are presented as follows:

$A_{area,m}$:The size of Area-*m*.

ρ :The user density in the whole service area.

$\theta_{i,m}$:The probability of a new user accessing ABS-*i* in Sub-area-*m*.

$n_{adj.i}^{ON}$: The traffic load threshold for an ABS-*i* to switch on ABS2, $i\epsilon[1,3]$.

$n_{adj,i}^{OFF}$: The traffic load threshold for an ABS-*i* to switch off ABS2, $i\epsilon[1,3]$.

$n_{self,2}^{OFF}$: The traffic load threshold for ABS2 to switch off itself.

Depending on the activities and number of channels occupied on these three ABSs, $\lambda_{j1}, \lambda_{j2}, \lambda_{j3}$ can be described as follows:

Referring now to the full three-dimensional Markov model of Figure 5.2, the arrival rate at ABS1 is:

1. If both ABS1 and ABS2 are working,

$$\lambda_{j_1} = \theta_{1,1} \cdot A_{area,1}\rho; \theta_{1,1} = 0.5$$

$$((n_{adj,1}^{OFF} \leq j_1 < n_1 \parallel j_3 \geq n_{adj,3}^{OFF}) \,\&\, j_2 \neq 0) \parallel (j_2 = 0 \,\&\, (n_{adj,1}^{ON} \leq j_1 < n_1 \parallel j_3 \geq n_{adj,3}^{ON})$$

2. If ABS1 is working but ABS2 is switched off,

$$\lambda_{j_1} = \theta_{1,1} \cdot A_{area,1}\rho; \theta_{1,1} = 1$$

$$(j_1 < n_{adj,1}^{OFF} \,\&\, j_3 < n_{adj,3}^{OFF} \,\&\, 0 < j_2 < \alpha_{self,2}^{OFF}) \parallel (j_2 = 0 \,\&\, j_1 < j_1 < n_{adj,1}^{ON} \,\&\, j_3 < \alpha_{adj,3}^{ON})$$

3. If ABS1 is working but ABS2 is switched off,

$$\lambda_{j_1} = \theta_{1,1} \cdot A_{area1}\rho; \theta_{1,1} = 0$$

$$j_1 = n_1$$

where $\theta_{i,m}$=1 means all the new arrivals must access ABS-*i*, $\theta_{i,m}$= 0 means the new arrivals cannot served by ABS-*i* at all, $\theta_{i,m}$= 0.5 means the new arrivals have 50% chance of accessing ABS-*i*. Here, we assume a new user has equal probability of being served by two adjacent ABSs if both of them are available.

For the arrival rate on ABS2,

1. If ABS2 is switched off or full,

$$\lambda_{j_2} = \theta_{2,1} \cdot A_{area,1}\rho + \theta_{2,2} \cdot A_{area,2}\rho; \theta_{2,1} = 0, \theta_{2,2} = 0$$

$$(j_1 < n_{adj,1}^{OFF} \ \& \ j_3 < n_{adj,3}^{OFF} \ \& \ 0 < j_2 < n_{self,2}^{OFF}) \parallel (j_2 = 0 \ \& \ j_1 < n_{adj,1}^{ON} \ \& \ j_3 < n_{adj,3}^{ON}) \parallel j_2 = n_2$$

2. If all three ABSs are working,

$$\lambda_{j_2} = \theta_{2,1} \cdot A_{area,1}\rho + \theta_{2,2} \cdot A_{area,2}\rho; \theta_{2,1} = 0.5, \theta_{2,2} = 0.5$$

$$((n_{adj,1}^{OFF} \le j_1 < n_1 \parallel n_{adj,3}^{OFF} \le j_3 < n_3) \ \& \ j_2 \ne 0) \parallel (j_2 = 0 \ \& \ (n_{adj,1}^{ON} \le j_1 < n_1 \parallel n_{adj,3}^{ON} \le j_3 < n_3))$$

3. If ABS1 is full but ABS2/3 still have available channels,

$$\lambda_{j_2} = \theta_{2,1} \cdot A_{area,1}\rho + \theta_{2,2} \cdot A_{area,2}\rho; \theta_{2,1} = 1, \theta_{2,2} = 0.5$$

$$j_1 = n_1 \ \& \ ((n_{adj,3}^{OFF} \le j_3 < n_3 \ \& \ j_2 \ne 0) \parallel (j_2 = 0 \ \& \ n_{adj,3}^{ON} \le j_3 < n_3))$$

4. If ABS3 is fully occupied but ABS1/2 still have available channels,

$$\lambda_{j_2} = \theta_{2,1} \cdot A_{area,1}\rho + \theta_{2,2} \cdot A_{area,2}\rho; \theta_{2,1} = 0.5, \theta_{2,2} = 1$$

$$j_3 = n_3 \ \& \ ((n_{adj,1}^{OFF} \le j_1 < n_1 \ \& \ j_2 \ne 0) \parallel (j_2 = 0 \ \& \ n_{adj,1}^{ON} \le j_1 < n_1))$$

5. Both of ABS1 and ABS3 are fully occupied,

$$\lambda_{j_2} = \theta_{2,1} \cdot A_{area,1}\rho + \theta_{2,2} \cdot A_{area,2}\rho; \theta_{2,1} = 1, \theta_{2,2} = 1$$

$$j_1 = n_1 \ and \ j_3 = n_3 \ and \ j_2 \ne n_2$$

$\lambda_{j3}, \lambda_{j1-1}, \lambda_{j2-1}, \lambda_{j3-1}$ can be defined similarly.

In the previous $(n_1 + 1)(n_2 + 1)(n_3 + 1)$ general statistical equations (5.3), one of them is redundant. In a Markov process, the sum of all state occupancy probabilities must equal 1, i.e.:

$$\sum_{j_1=0}^{n_1} \sum_{j_2=0}^{n_2} \sum_{j_3=0}^{n_3} P(j_1, j_2, j_3) = 1 \tag{5.4}$$

where n_i is the number of maximum available channels for a specific ABS.

The normalization equation can be expressed as [76]:

$$\boldsymbol{AP=B} \tag{5.5}$$

where A is the $((n_1+1)(n_2+1)(n_3+1))^2$ coefficient matrix, P is the $(n_1+1)(n_2+1)(n_3+1)$ state probability vector, and B is an $(n_1+1)(n_2+1)(n_3+1)$ constant vector.

The state probability P can be solved as $0 \le j_i \le n_i$ [76]:

$$\boldsymbol{P} = \boldsymbol{A}^{-1}\boldsymbol{B} \tag{5.6}$$

B. Blocking Probability

System blocking can be defined as the situation where no service can be obtained by a newly arrived user. The total probability is calculated as the sum of blocking probabilities in each sub-area. Blocking occurs when all the ABSs which provide service for the same sub-area are full. In Figure 5.1, blocking occurs when the channels on both ABS1 and ABS2 are fully occupied. Therefore, the system blocking probability is expressed as:

$$BP_{system} = \frac{\lambda_{area,1}}{\lambda_{all}} \cdot \sum_{j_3=0}^{n_3} P(n_1, n_2, j_3) + \frac{\lambda_{area,2}}{\lambda_{all}} \cdot \sum_{j_1=0}^{n_1} P(j_1, n_2, n_3) \tag{5.7}$$

where $\boldsymbol{\frac{\lambda_{area,1}}{\lambda_{all}}, \frac{\lambda_{area,2}}{\lambda_{all}}}$ are the arrival rates in sub-area *1/2* over the system arrival rate. In other words, they are the probabilities of new users arriving in a specific sub-area.

C. Probabilities of ABS2 being in the OFF mode (Inactive Area)

The sum of probabilities of ABS2 in the OFF mode is described as the inactive area in Figure 5.4 and its general equation is:

$$P_{inactive,2} = \sum_{j_1=0}^{n_{adj,1}^{ON}-1} \sum_{j_3=0}^{n_{adj,3}^{ON}-1} P(j_1, 0, j_3) \tag{5.8}$$

D. Probabilities of ABS2 being in the deactivated OFF mode (Deactivated Area)

The sum of state probabilities in the deactivated OFF mode is represented as the deactivated area in Figure 5.3 and its equation is shown as below:

$$P_{deactivated,2} = \sum_{j_1=0}^{n_{adj,1}^{OFF}-1} \sum_{j_2=1}^{n_{self,2}^{OFF}-1} \sum_{j_3=0}^{n_{adj,3}^{OFF}-1} P(j_1, j_2, j_3) \tag{5.9}$$

If the number of channels occupied for these three ABSs is smaller than the corresponding thresholds, ABS2 will prepare to turn off and transfer to the deactivated mode.

5.3 Energy Model

In this section, we introduce an energy model, and then show how our proposed energy efficient topology management scheme can be optimised. The optimised scheme will be then used with the BuNGee architecture to reduce system energy consumption. Unlike the energy model in chapter 4, we did not calculate the power consumption on an ABS based on the power consumed on each component. Instead, we use the power consumed on an ABS at a specific mode to calculate the network energy consumption.

Here, only the access link is considered. The total energy consumption of the access link in a typical wireless communication system comes from MSs and the ABSs. However, we do not consider the energy cost from the MS here because their energy cost represents less than 20% of the overall system energy consumption in a wireless communication network [90]. Depending on the behaviour of ABS2, three different modes are assumed: working mode (fully on), idle/sleep mode (switched off) and deactivated mode (preparing to switch off). The details of the power consumed in the different modes are shown in Table 5.1.

Table 5.1 Parameter for Energy Consumption [91]

Parameter	Value
Power in active mode	10W
Power in deactivated mode	10W (The ABS is assumed to remain ON in this mode)
Power in sleep mode	5% of active mode

The energy consumption (E_{ABS}) and energy reduction (E_R_{ABS}) of ABS2 can be represented as [88]:

$$E_{ABS} = \sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j} Pt_{ABS,idle,j} + t_{ABS,work,j} Pt_{ABS,work,j}) \tag{5.10}$$

$$\begin{aligned} E\_R_{ABS} &= 1 - \frac{E_{ABS}}{E_{ABS\_withoutTM}} = 1 - \frac{\sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j} Pt_{ABS,idle,j} + (t_{all} - t_{ABS,idle,j}) Pt_{ABS,work,j})}{\sum_{j=1}^{n_{ABS}} t_{all} Pt_{ABS,work,j}} \\ &= \frac{\sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j}(Pt_{ABS,work,j} - Pt_{ABS,idle,j}))}{\sum_{j=1}^{n_{ABS}} t_{all} Pt_{ABS,work,j}} \end{aligned} \tag{5.11}$$

where n_{ABS} is the number of ABSs in the service area; $Pt_{ABS,idle,j}/Pt_{ABS,work,j}$ represent the power consumed when the j-th ABS is in idle/working mode; $t_{ABS,idle,j}/t_{ABS,work,j}$ represent the proportion of time the j-th ABS spends in idle/working mode; t_{all} is the system simulation time when the system is stable.

In the previous analytical model, the total time the j-th ABS spends in the idle mode over the simulation time when the system is in steady state ($\frac{\boldsymbol{t_{ABS,idle,j}}}{\boldsymbol{t_{all}}}$) can be expressed as the sum of the state probabilities that j-th ABS is switched off ($P_{idle,j}$). Thus, the potential for energy reduction in the system with topology management is:

$$E\_R_{ABS,Markov} = \frac{\sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j}(Pt_{ABS,work,j} - Pt_{ABS,idle,j}))}{\sum_{j=1}^{n_{ABS}} t_{all} Pt_{ABS,work,j}} \tag{5.12}$$

In this thesis, blocking probability (BP) is chosen as an important system performance guarantee that must be maintained. Our goal is to maximize the energy reduction while keeping the system QoS (blocking probability) at an acceptable level (below 5% [92]). We assume that the above three thresholds ($n_{adj}^{OFF}, n_{self}^{OFF}, n_{adj}^{ON}$) can vary from 0.1 to 1, but n_{adj}^{OFF} should be smaller or equal to n_{adj}^{ON} to avoid ABS2 being switched off immediately after it is switched on in practice. Thus, the blocking probability and energy reduction strategy with topology management when specific thresholds are given can be defined as:

$$BP(n_{adj}^{OFF}, n_{self}^{OFF}, n_{adj}^{ON})$$

$$E\_R(n_{adj}^{OFF}, n_{self}^{OFF}, n_{adj}^{ON})$$

The set of thresholds which satisfy the system performance threshold (*BP<=5%*), can be defined as ($n_{adj}^{OFF'}, n_{self}^{OFF'}, n_{adj}^{ON'}$). The most energy efficient thresholds can be obtained when:

$$E\_R_{\max} = \max(E\_R(n_{adj}^{OFF'}, n_{self}^{OFF'}, n_{adj}^{ON'})) \tag{5.13}$$

5.4 Simulation Scenarios, Results and Analysis

In this section, a set of Monte Carlo simulation experiments are described. Firstly, performance predictions from the analytical model are compared with Monte Carlo simulation for a *three*-ABS network in order to validate both approaches. Then, the architecture model is applied to a multi-hop beyond next generation network.

A. Multi-channel three-ABS networks

A set of simulations have been undertaken, where the analytical and Monte Carlo simulation results are compared for the *three*-ABS network scenario with 16 channels on each ABS, assuming the thresholds for switching on/off an ABS are varied. In this case, the traffic load is assumed to be the same in each sub-area. Two different system traffic loads (the sum of the traffic loads from all sub-areas) are used (*9* and *21* Erlangs) in order to analyze the system performance when the system traffic is at low and mid-levels. The system inter-arrival rate and service time follow exponential distributions, where the average service time is chosen to be *60s/call* and the average inter-arrival time is used to generate the system offered traffic. The arrival rates on each ABS follow the strategies in Section III. There is no queuing and dropping assumed in this scenario.

For the purpose of comparison, the Monte Carlo simulation comprises 20,000 users uniformly distributed in the service area. We use the same schemes with the analytical model to generate traffic model. The simulation results are measured when the system is stable, from 10%~95% of the total simulation time, and runs are repeated 40 times in order to obtain statistically significant results.

Figure 5.4 shows the blocking probabilities for the Markov Model with and without topology management (TM) and for the Monte Carlo simulation when system traffic load is increased. Error bars are used here to show the confidence intervals of the results from simulation. It can be seen that the results from the simulation are consistent with the results from the analytical model. The slight discrepancy between the analytical model and simulation is due to the traffic burstiness in simulation where an exponential distribution is assumed. The difference between the Markov Model results with and without TM is negligible. This is because in the *three*-ABS network scenario, if one of the ABSs is full, the local traffic can be forwarded to its adjacent neighbours. Therefore, the topology management scheme creates very limited reduction in performance in term of system blocking probability. This of course is highly desirable, as the TM scheme is used to save energy whilst guaranteeing QoS. Over the offered traffic range where blocking probability is less than 5%, the system works well. The offered traffic is less than 40 Erlangs compared to a total capacity of *3*x*16=48* channels.

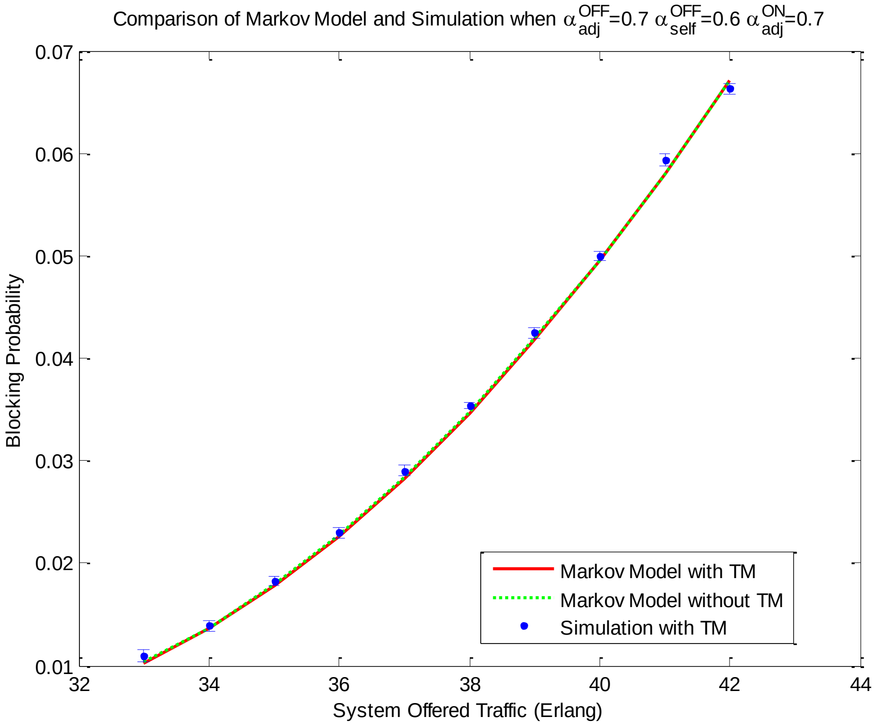

Figure 5.4 Comparison of Markov Model and Simulation when $\alpha_{adj}^{OFF} = 0.7$, $\alpha_{self}^{OFF} = 0.6$, $\alpha_{adj}^{ON} = 0.7$

Figure 5.5 shows the reduction in energy obtained through topology management. The results from the Markov model are consistent with those from Monte Carlo simulation. The curves produced from the analytical models are not smooth due to the increments used. For instance, α_{adj}^{OFF} grows from 60% to 80% in steps of 10%. However, the actual thresholds in corresponding points to the points are 10, 12 and 13 ($n_{adj}^{OFF} = \lceil \alpha_{adj}^{OFF} \bullet n_i \rceil$).

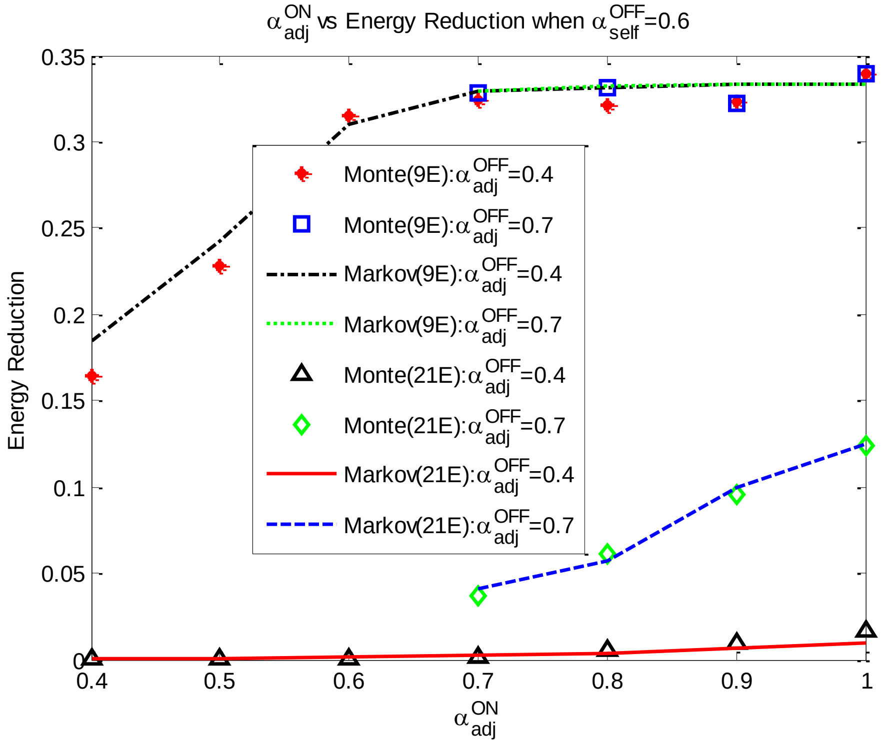

Figure 5.5 Comparison of analytical and simulation results of energy reduction when system offered traffic loads are equal to 9 Erlangs and 21 Erlangs ($\alpha_{self}^{OFF} = 0.6$)

In a *three*-ABS network, the maximum energy reduction occurs when ABS2 is always switched off (at low traffic level), with a reduction of 33% in the system energy consumption as compared to the case without topology management. If α_{self}^{OFF} is fixed, the potential energy reduction will increase while α_{adj}^{ON} and α_{adj}^{OFF} increase. It can be seen that α_{adj}^{OFF} (The threshold of switching off an ABS is based on the percentage of maximum traffic load on its adjacent ABS) almost does not affect the system energy reduction at low traffic load level, less than 1% changes in energy reduction when it increases from 0.4 to 0.7. Considering the state transition diagram introduced in Figure 5.3, which means most of the state probabilities are located in the Inactive Area, and only a few users can be influenced if the threshold to switch off an ABS is varied. However, if the system traffic load is at the mid-level, an increase in energy saving of at least 40% can be obtained when α_{adj}^{OFF} increases from 0.4 to 0.7.

It is noteworthy that the threshold to switch on an ABS (α_{adj}^{ON}) affects the performance more significantly when the traffic load is not very heavy, while the system does not reach the maximum energy reduction (around 33% in this case).

Figure 5.6 provides another example of how certain parameters influence the system performance. It shows the potential energy reduction when α_{self}^{OFF} and α_{adj}^{OFF} are varied while α_{adj}^{ON} is fixed. It indicates that when the traffic load is low, the impact of varying α_{self}^{OFF} and α_{adj}^{OFF} becomes negligible. In our case, when the traffic load is 9 Erlangs, the potential energy reduction is always around 33% irrespective of parameter changes. This is because ABS2 is in sleep mode for most of the simulation time, and only a small amount of users are affected by the parameters switching off an ABS.

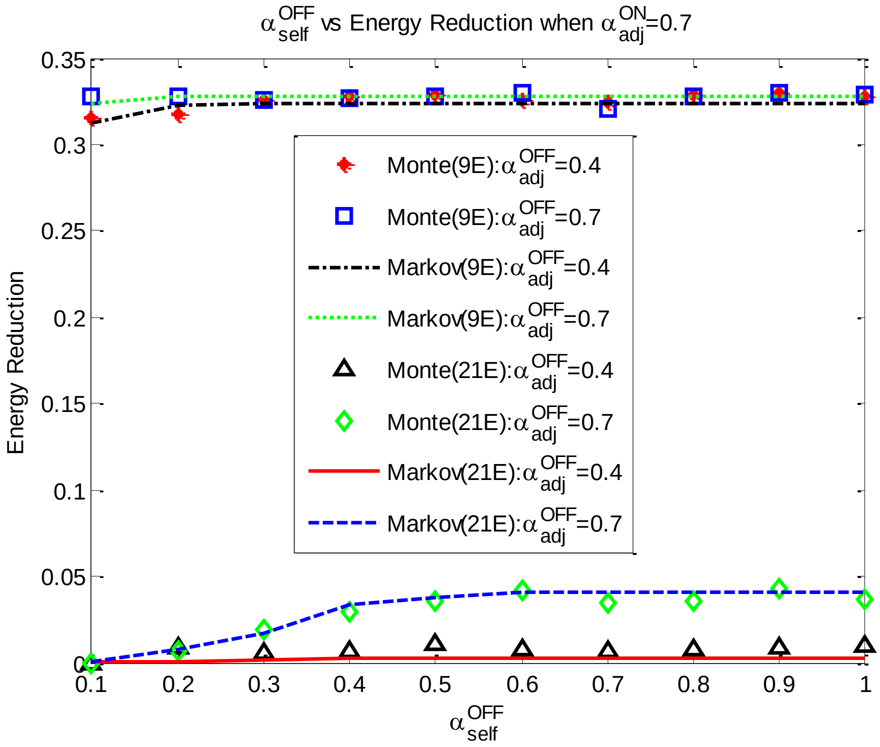

Figure 5.6 Comparison of analytical and simulation results of energy reduction when system offered traffic loads are equal to 9 Erlangs and 21 Erlangs (α_{adj}^{ON}=0.7)

In contrast, at the mid-traffic load (21 Erlangs in our case) it is noticed that α_{self}^{OFF} can improve the system performance smoothly but soon reaches an upper bound. This is because it is difficult to switch off an ABS if the threshold associated with switching off an ABS is too low. As expected, an improvement in terms of energy reduction is seen by varying the value of α_{adj}^{OFF}.

Comparing the results of fixing α_{self}^{OFF} with the results of fixing α_{adj}^{ON}, there is a significant improvement in performance by varying parameter α_{adj}^{ON} rather than α_{self}^{OFF} (13% vs 3.8%) in the mid-level traffic load condition. This is explained as the higher the value of α_{adj}^{ON}, the more difficult it is for users to transfer from the Inactive Area to the Active Area. α_{self}^{OFF} can provide some benefit to system performance when the system traffic load is at a mid or heavy level. However, the potential energy reduction will be quite limited due to the heavy traffic conditions.

B. Multi-channel multi-ABS networks

We now move to the case of applying the analytical model to a large service area. Here, a typical BuNGee architecture is considered which was briefly introduced in Section I, Chapter 5 as the scenario we discussed. Figure 5.7 shows the deployment of a typical BuNGee architecture. A powerful HBS is located on the roof and a few ABSs are deployed along streets to guarantee the system QoS. A certain degree of overlapping exists in order to provide good coverage for users. We assume that half of these ABSs can be switched off to save energy when the local traffic is at a low level. Figure 5.8 illustrates how to apply the previous *three*-ABS network into a larger network. The whole network can be divided into several *three*-ABS networks, which are presented with shadows in the diagram. The overall system performance can be analysed to some extent based on the behaviours of ABSs in each sub-network. The boundaries of each sub-network are made up of the ‘always ON ABSs’, which means the service area for an ‘always ON ABS’ is divided into two adjacent *three*-ABS networks.

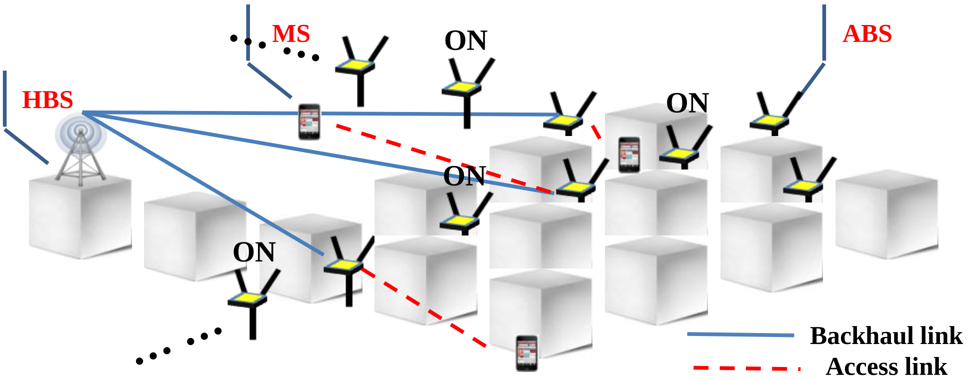

Figure 5.7 Typical BuNGee Architecture

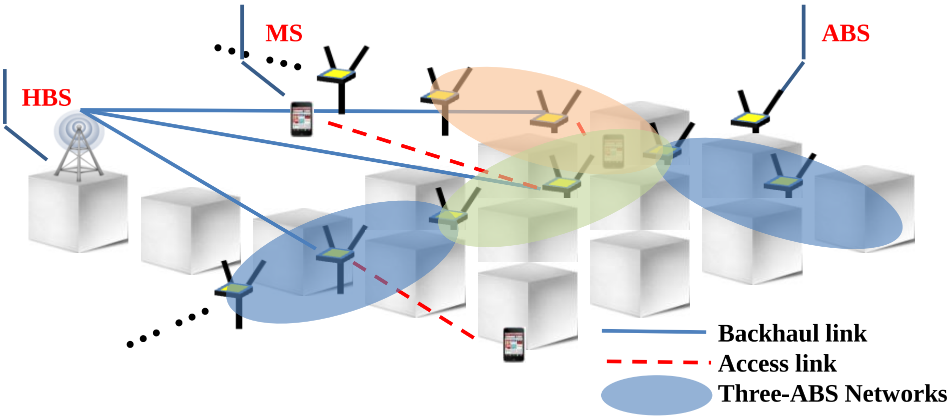

Figure 5.8 Three-*ABS networks in a larger network*

It is assumed that the service area includes a typical BuNGee cell with 1 HBS and 20 ABSs [3], and 20,000 users are uniformly distributed in the service area. The inter-arrival time and service time of users are again determined by an exponential distribution, such that the traffic model in general follows a Poisson distribution. A coverage area based channel assignment scheme is used here which is exactly the same with the relevant schemes assumed in *three*-ABS network.

Figure 5.9 shows the system blocking probability when the offered traffic increases. It can be seen that the system blocking probability can be predicted by the analytical model very well if the system traffic load is at low level (lower than 175 Erlangs). However, the approximation becomes increasingly less accurate when the system traffic loads are high, even before the system blocking probability reaching the 5% threshold at around 250 Erlangs. This is because the traffic load on an ABS which is located at the boundary of a *three*-ABS network ('always ON ABS' in our case) can be affected by its adjacent *three*-ABS network as well. Thus, it is difficult to predict the arrival rates for these 'always ON ABSs'. However, the impact is very limited when the traffic load is low. Thus, we do not use the analytical model to predict the system performance when traffic loads are at a mid/high level in this chapter, which in any case are of much less interest, given that maximal energy savings are achieved through topology management at low traffic levels.

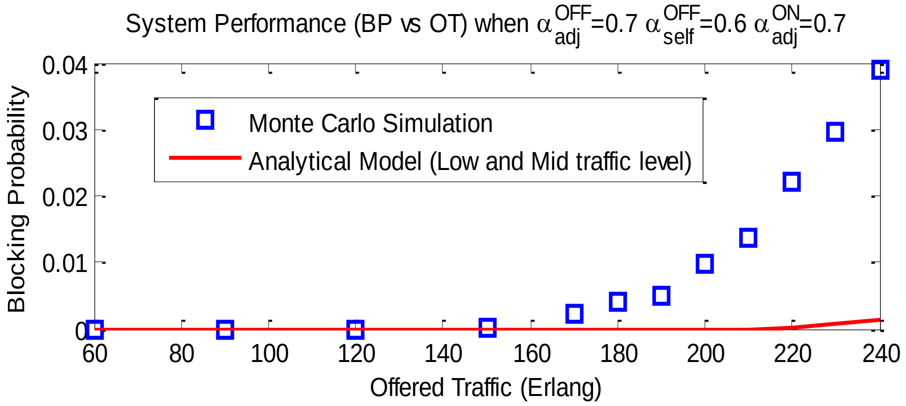

Figure 5.9 Comparison of Markov Model and Simulation when $\alpha^{OFF}_{adj} = 0.7$, $\alpha^{OFF}_{self} = 0.6$, $\alpha^{ON}_{adj} = 0.7$

Figure 5.10 shows the comparison between the analytical and simulation results in a typical BuNGee cell when the system offered traffic is equal to 60 Erlangs. It should be noted that in a *three*-ABS network, the arrival rates of the two 'always ON ABSs' are only influenced by the middle ABS which can be switched off. However, in a practical network like BuNGee, the arrival rate of an 'always ON' ABS can be affected by both of its adjacent three-ABS networks. Similar with the blocking probability, it is difficult to obtain an accurate result if the *three*-ABS model is applied to the multi-ABS model directly. However, when the system offered traffic is low, the influence from adjacent sub-networks is limited because they are always kept in the sleep mode for most of the time.

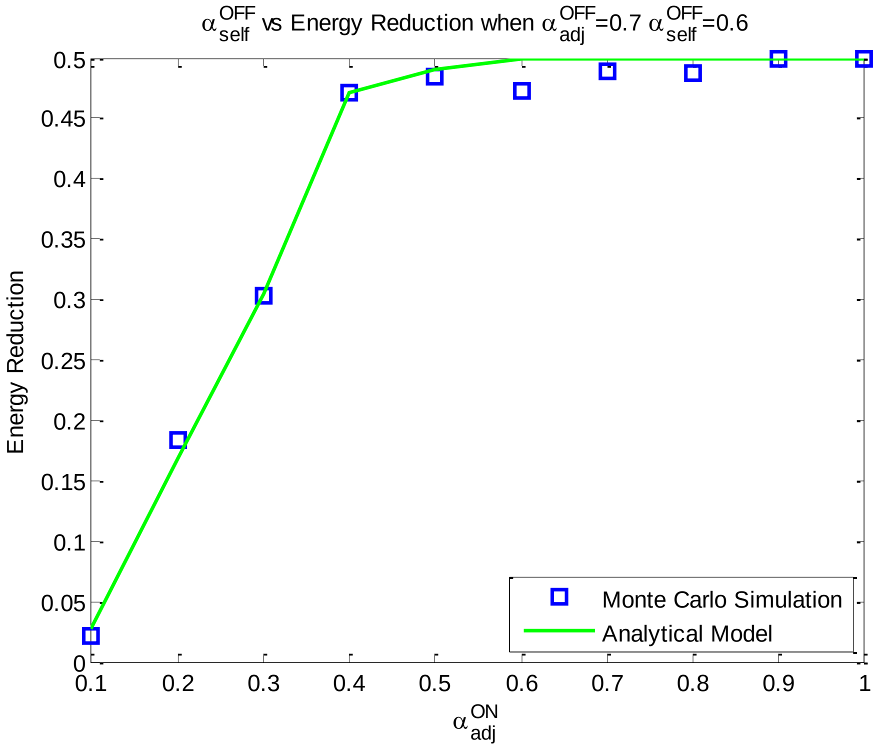

Figure 5.10 Comparison of analytical and simulation results of energy reduction when system offered traffic is equal to 60 Erlangs (α^{OFF}_{adj}=0.7, α^{OFF}_{self}=0.6)

It is clear that more accurate analytical models could be developed for multi-ABS networks, but is it useful to see the potential of the simpler model applied to the more complex multi-ABS network. Figure 5.9 and Figure 5.10 show that the model can be used to predict performance (blocking probability and energy reduction) with reasonable accuracy under appropriate conditions (the traffic load is at low level).

5.5 Conclusions

In this chapter, a traffic load based energy efficient topology management scheme has been developed and an analytical model has been designed with the aid of multi-dimensional Markov process to characterise the energy efficiency performance of wireless networks when sleep modes are used to deactivate base stations at locally low traffic load levels. The aim is to reduce the system energy consumption of wireless networks whilst guaranteeing the system QoS. The scenario is firstly studied as a simple three base station model and then applied into a BuNGee architecture which can be deployed in dense urban areas to provide high throughput density and ensure the QoS and coverage for users.

It can be seen that the results from the simulation are consistent with the results from the analytical model. The traffic load based thresholds to switch on/off base stations which are measured from its adjacent base stations have higher impact than the threshold on this base station itself. The latter threshold has very limited influence for the system energy reduction. The slight discrepancy between the analytical model and simulation is due to the traffic burstiness in simulation where an exponential distribution assumed.

Chapter 6. Analytical Model for Energy Efficient Topology Management with Handover Mechanism

Contents

6.1 Introduction

The main contribution of this chapter is to develop an analytical model combined with the energy efficient scheme and handover in order to reduce the system energy consumption and discuss how certain parameters influence the system performance for wireless networks. We analyse the traffic load based topology management scheme by a multi-dimensional Markov Process and discuss how the handover mechanism provide further benefit for the system energy efficiency. The work in this chapter is based on the ideas and results from chapter 5, and the system scenario and energy model are almost the same as for chapter 5.

The remainder of this chapter is organised as follows. In section 6.2, we present the system scenario and topology management scheme based on the work in chapter 4 and 5. The analytical model is deeply discussed in Section 6.3. Results are shown and discussed in section 6.4. Finally, we conclude the chapter in section 6.5.

6.2 System Scenario and Energy Efficient Schemes

6.2.1 System Model

In this chapter, we still consider the BuNGee architecture which was introduced in previous chapters as the scenario under discussion. A certain degree of potential overlapping coverage is assumed in Figure 6.1. If a new user arrives and it is within the range of more than one ABS, it is connected to the one offering the best Signal to Interference plus Noise Ratio (SINR).

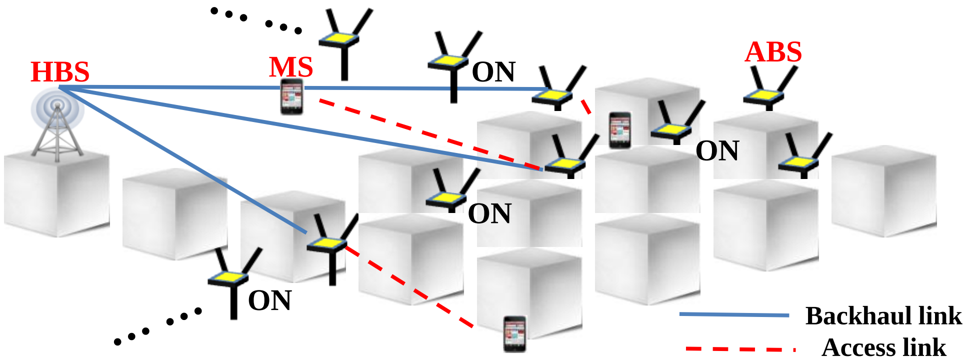

Figure 6.1 A typical BuNGee architecture

High capacity density is assured by having many ABSs, each ABSs providing small cell coverage. The overlapping coverage provides flexibility when traffic loads are lower to turn off some of the ABSs when they are not in use. In this context, we study the following sleep/wake up mechanism [93]: the ABSs are divided into two groups: one should always be kept in working mode to guarantee the system QoS and provide full coverage, while the other group can be switched off. Their traffic loads can be served instead by neighbours when the local traffic is low (lower than a threshold). When the traffic increases (higher than a threshold), one or more ABSs have to wake up depending on the traffic load and location. As shown in Figure

6.1, the ‘always ON ABSs’ are marked with ‘ON’, and are deployed every three ABSs. The detail of the energy efficient topology management scheme is shown as follows:

6.2.2 Energy Efficient Scheme

The energy efficient topology management scheme is developed based on the work in Chapter 4 and 5. However, in this chapter, we use a handover mechanism in our work, which will be detailed in this section.

To switch an ABS from working mode into sleep mode, the following should be satisfied:

1) The Capacity usage of an ABS at time *t* is smaller than a threshold (n_{self}^{OFF}) of the maximum capacity $C_{self}^{ABS_i} < n_{self}^{OFF}$.
2) The Capacity usage of all its adjacent ‘always ON ABSs’ at time *t* is smaller than a threshold (n_{adj}^{OFF}) of the maximum capacity $C_{adj}^{ABS_i} < n_{adj}^{OFF}$.

If both of above are satisfied, this ABS prepares to switch into sleep mode; new users are not allowed to access this ABS at this stage. Meanwhile, the traffic on this ABS can be handed over to adjacent ABSs if necessary, which will be introduced later.

To switch an ABS from sleep mode into working mode, the following should be satisfied:

The instantaneous capacity usage of its ‘always ON ABSs’ at time *t* is equal to or higher than a threshold n_{adj}^{ON} of the maximum capacity $C_{adj}^{ABS_i} \geq n_{adj}^{ON}$.

This topology management scheme is fully distributed controlled by ABSs themselves. The information about traffic loads should be exchanged between adjacent ABSs.

A new parameter n_h is defined here as the threshold to hand over the traffic load on ABS2 to adjacent ABSs.

Thus, the handover scheme is shown as the follows:

1) The Capacity usage of an ABS at time *t* is equal to or larger than 1 ($C_{self}^{ABS_i} \geq 1$). In other words, this ABS should be used by at least a user.
2) The sum of capacity usage on this ABS itself and either of its adjacent 'always ON ABSs' at time *t* is equal to or smaller than a threshold (n_h), $C_{self}^{ABS_i} + C_{adj,q}^{ABS_i} \leq n_h$, where $n_h \leq n_{self}^{OFF}$ and $n_h \leq n_{adj}^{ON}$, q is defined as the set of adjacent ABSs for a specific ABS_i

Especially, n_h is limited because we assume that the ABS should prepare to switch off firstly and then hand over its traffic loads to adjacent ABSs.

6.3 Analytical Model Solutions

In this section, we design and formulate the energy efficient handover topology management problem with the aid of a multi-dimensional Markov process. This analytical model is developed based on our previous work in [93]. Here, we will discuss how the handover mechanism impact on the system performance and the energy consumption. The setup of the scenario is the same as in Chapter 5, where an *n*-channel *m*-ABS system is considered. However, the details about the transition diagram are new, and we will also describe how to apply the handover scheme to the analytical model.

The notation in use is defined as follows:

λ_2/λ_3: The arrival rate for ABS2/ABS3 when both of them are not fully occupied.

λ_{23}: The arrival rate for ABS2/ABS3 when one of them is fully occupied and the local traffic in Area2 is all forwarded to the alternative ABS.

μ: The departure rate per channel.

n_i: The maximum available channels on ABS_i.

n_{adj}^{ON}: The threshold to switch on an ABS. If the number of channels occupied on the adjacent ABSs of an ABS in sleep mode is equal to or greater than this threshold, we turn on the sleeping ABS.

n_{adj}^{OFF}: The threshold to switch off an ABS. If the number of channels occupied on the adjacent ABSs of an ABS in working mode is smaller than this threshold, we prepare to turn off this ABS.

n_{self}^{OFF}: The threshold to switch off an ABS. If the number of channels occupied on an ABS itself is smaller than this threshold, we prepare to turn off this ABS.

n_h: The threshold to hand over the traffic load on ABS2 to adjacent ABSs.

In order to introduce the analytical model clearly, we assume that new arrivals access ABS2/ABS3 only (reducing the problem to two dimensions), and then explain the analytical model with handover mechanism using the cube model. Figure 6.2 shows the state transition diagram when the number of channels occupied on ABS1 is equal to 0, and how the energy efficient handover scheme can be applied to the analytical model, which is described as the front surface in the previous cube diagram. The details of how the handover mechanism works will be introduced later.

Depending on the sleep mode and handover mechanism, the state transition diagram can be divided into five aspects: the Inactive Area (area enclosed with dash dot lines), the Deactivated Area (area enclosed with dashed lines), the Handover Area (area enclosed with dotted lines), the Invisible Area (the states with dotted boundaries) and the Active Area (the remaining area). In the Inactive Area, ABS2 is in sleep mode, which means the potential energy reduction of the system occurs in this area. In the Deactivated Area, ABS2 is preparing to switch off, and new arrivals are not allowed to access ABS2. In the Handover Area, the traffic loads on ABS2 will forward to other ABSs, which is also part of the Deactivated Area. The Invisible Area means that the states which are located in this area cannot occur with the topology management scheme used here. In the Active Area, all three ABSs are active and the whole network achieves the maximum capacity at this stage.

Now, more details are shown to explain how it works. We assume that the state transfers from $S(0,0,0)$, which means the system is fully empty and ABS2 is in sleep mode. At this stage, the arrival rate on ABS3 is equal to λ_{23}. The state can only transfer along the Inactive Area in the horizontal direction until the threshold n_{adj}^{ON}. That is due to the fact that new arrivals are only allowed to access ABS3. If the traffic load on ABS3 is equal to or higher than threshold n_{adj}^{ON}, ABS2 will be switched on to forward the local traffic. Meanwhile, the state transfers into the Active Area can move toward both the horizontal and vertical directions (obtaining service from either ABS2 or ABS3). Next, if the number of channels occupied on both ABS2 and ABS3 are smaller than the threshold ($j_2 < n_{self}^{OFF}$ and $j_3 < n_{adj,3}^{OFF}$), the state transfers into the Deactivated Area, which means the system traffic load is reducing and the network prepares to switch off ABS2. In this area, ABS2 is still working but does not provide service for new arrivals. If the system traffic load decreases persistently, the state may transfer into the Handover Area, which means the traffic on ABS2 should hand over to ABS1 and ABS3 immediately depending on the topology management scheme used. The state cannot transfer into the Invisible Area because all the traffic load has been forwarded into the Inactive Area before the state enters the Invisible Area. In other words, the states in the Invisible Area cannot occur at all in our scenario.

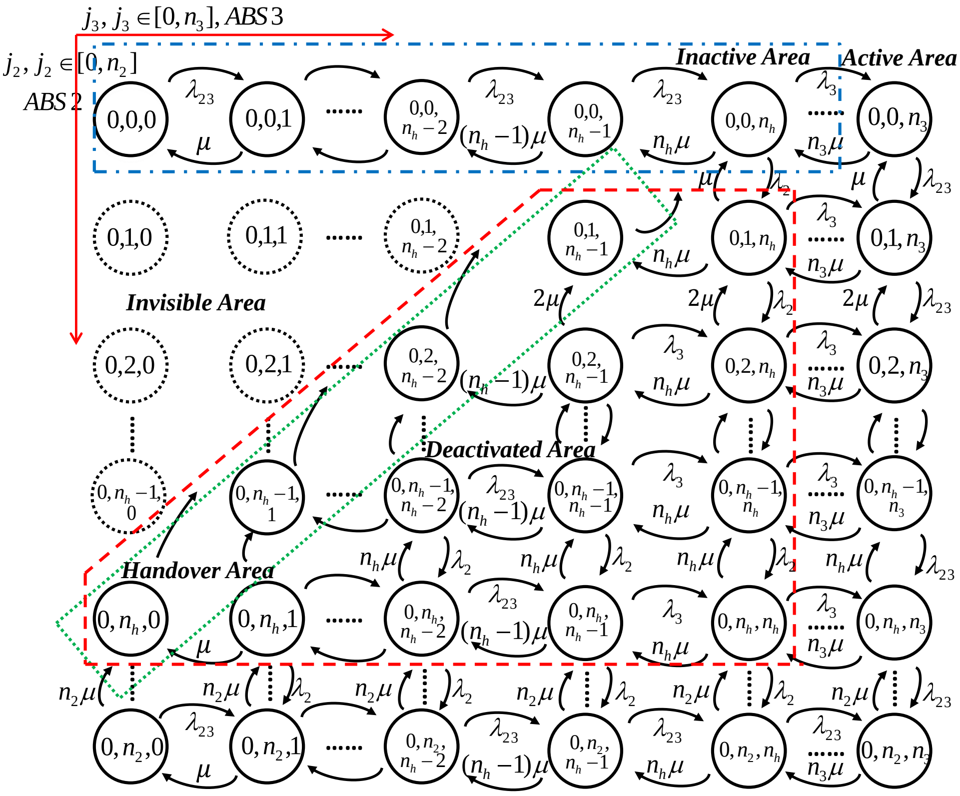

Figure 6.2 State transition diagram when ABS 1 and 2 are empty with topology management

The details of how the handover mechanism operates in the network are shown in Figure 6.3, which include the Handover Area and the Inactive Area of the state transition diagram. It is possible that some of the traffic load on ABS2 has to forward to ABS1 and the others to ABS3 depending on the positions of mobile devices because ABS2 can provide service for both Aera1 and Aera2. That is why the state with a large number of channels being occupied on ABS2 has more potential states to transfer in the diagram. For example, $\mathrm{S}(0, n_h, 0)$ means that there are no channels on ABS1 and ABS3, and n_h channels occupied on ABS2. We assume that $n_h^{ABS1}(n_h^{ABS1} \epsilon [0, n_h], n_h^{ABS1}$is an integer) users can be handed over to ABS1 and n_h^{ABS3} $(n_h^{ABS3} = n_h - n_h^{ABS1})$ users can be forwarded to ABS3 in this case. The probability of handing over from $\mathrm{S}(0, n_h, 0)$ to a specific state in the Inactive Area will be introduced later. It is noticed that the threshold of handover (n_h) should be equal to or smaller than the threshold of switching on ABS2 (n_{adj}^{ON}) in order to avoid ABS2 being switched on immediately after the handover process. Here, we define that n_{PC} is the difference between n_{adj}^{ON} and n_h which the protection channels (PC) for the energy efficient scheme and handover scheme. It can be expected that the smaller the value of n_{PC}, the easier it is for the sleeping ABS to be switched on after the process of handover.

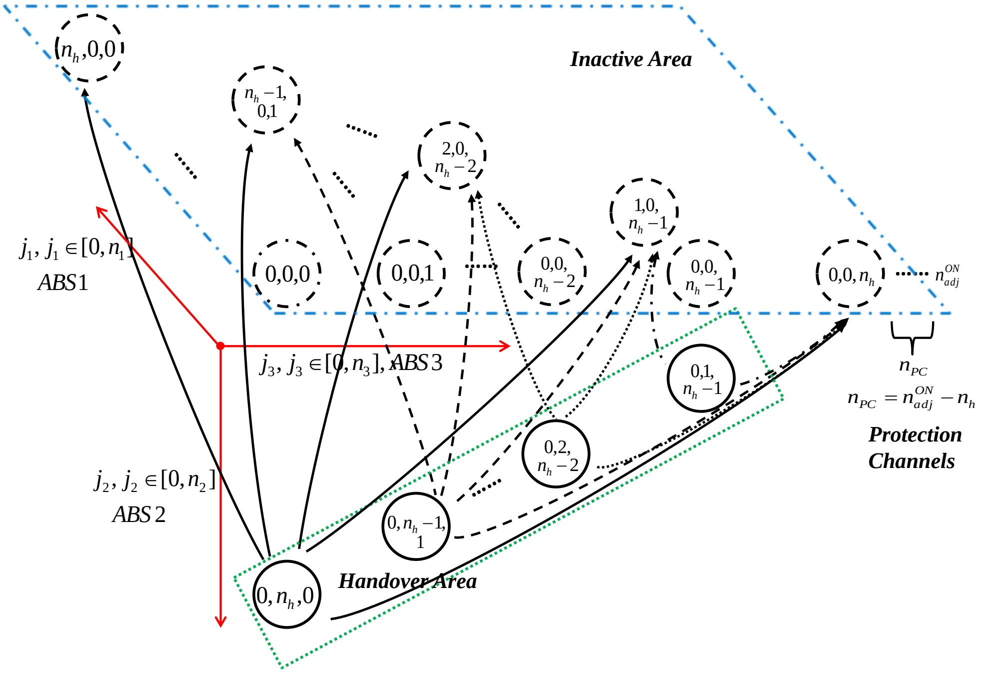

Figure 6.3 Handover Mechanism for three-*ABS networks*

Figure 6.4 shows the representation of the *three*-ABS network as a cube model. The energy efficient topology management scheme with handover mechanism can be described in this cube model. The previous two-dimensional state transition diagram is considered as the front face of the large cube. Based on the behaviour of the network, this cube model can be divided into four aspects: the large cube, the small square on the top surface, the small cube inside the large cube and the missing volume near $S(0,0,0)$. The top small square shows that ABS2 is in sleep mode (Inactive Area). The small cube in the middle represents the Deactivated Area and the Handover Area. The missing volume near $S(0,0,0)$ shows the Invisible Area, where a state cannot transfer into this area and the rest of large cube describes the Active Area.

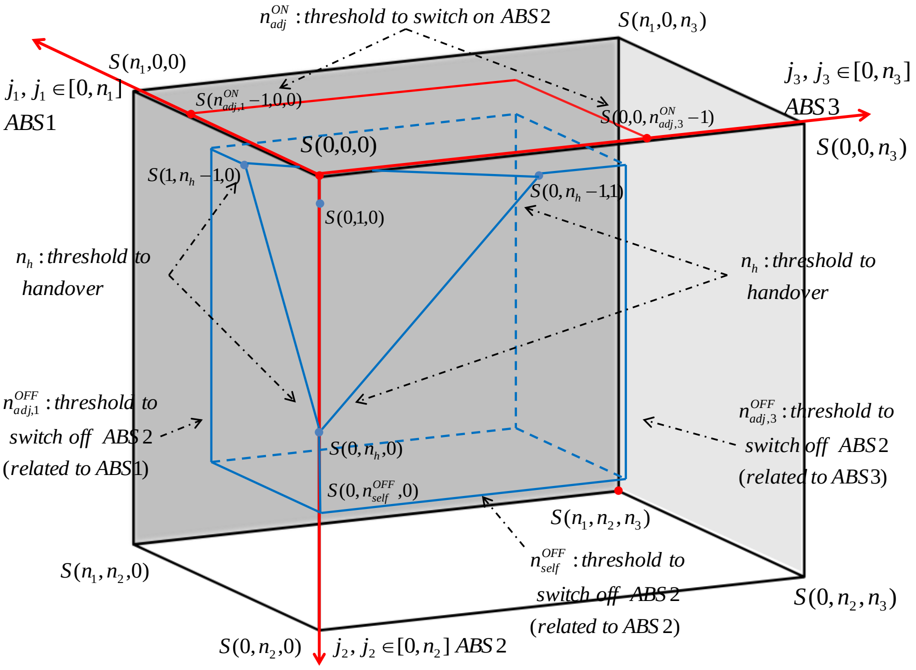

Figure 6.4 A representation of the three dimensional of the three-ABS network with energy efficient topology management scheme and handover mechanism

Using the state transition diagram works methodology seen in the equilibrium analysis of the *three*-ABS network, the flux out of $S(j_1,j_2,j_3)$ should be equal to that into $S(j_1,j_2,j_3)$ [76]. For a specific state $S(j_1,j_2,j_3)$ in the previous diagrams, there are 2x3 adjacent states potentially suitable for transition except the states located at the Handover Area or the boundary. That is because there are three ABSs in the network and two possible changes of the number of channels occupied on each ABS, with a new user arriving or an old user departing. For the states which are located at the boundaries of the diagram, at least one of its 2x3 adjacent states does not exist. The number of channels occupied on a specific ABS_i is between 0 and n_i (n_i is the maximum number of available channels on ABS_i). Thus, when $j_i = -1, i\epsilon[1,2,3]$ we have the probabilities:

$$P(-1, j_2, j_3) = P(j_1, -1, j_3) = P(j_1, j_2, -1,) = 0 \qquad (6.1)$$

Similarly, if $j_i > n_i, i\epsilon[1,2,3]$, we have:

$$P(n_1+1, j_2, j_3) = P(j_1, n_2+1, j_3) = P(j_1, j_2, n_3+1) = 0 \qquad (6.2)$$

For the states which are in the Invisible Area:

$$\sum_{j_1=0}^{n_h-j_2-1} \sum_{j_2=1}^{n_h-1} \sum_{j_3=0}^{n_h-j_2-1} P(j_1, j_2, j_3) = 0 \qquad (6.3)$$

The general statistical equilibrium for an *n*-channel *three*-ABS network at state $S(j_1, j_2, j_3)$ can be expressed as (except the states in the Handover Area and parts of states in the Inactive Area):

$$\begin{aligned}
&(\lambda_{j_1} + j_1\mu + \lambda_{j_2} + j_2\mu + \lambda_{j_3} + j_3\mu)P(j_1, j_2, j_3) \\
&= (j_1+1)\mu P(j_1+1, j_2, j_3) + \lambda_{j_1-1}P(j_1-1, j_{2,} j_3) \\
&+ (j_2+1)\mu P(j_1, j_2+1, j_3) + \lambda_{j_2-1}P(j_1, j_2-1, j_3) \\
&+ (j_3+1)\mu P(j_1, j_2, j_3+1) + \lambda_{j_3-1}P(j_1, j_{2,} j_3-1)
\end{aligned} \qquad (6.4)$$

where $\lambda_{j1}, \lambda_{j2}, \lambda_{j3}$ are the arrival rates for each ABS transferring from the current state to the adjacent states when a new user arrives. In other words, the number of channels occupied on an ABS changes. If $j_i = n_i$, λ_{j_i} does not exist because this ABS is full, it cannot provide service for new arrivals. However, we assume that λ_{j_i} is equal to 0 here in order to obtain a general form of the equation. Meanwhile, $\lambda_{j1-1}, \lambda_{j2-1}, \lambda_{j3-1}$ represents the arrival rates from adjacent states to current state. μ is the departure rate when a user leaves current state.

For the states $S(j_1, j_2, j_3)$ which are located at the Handover Area ($\sum_{j_1=0}^{n_h-j_2} \sum_{j_2=1}^{n_h} \sum_{j_3}^{n_h-j_2} S(j_1, j_2, j_3)$), they have:

$$\begin{aligned}
&(j_2+1)\cdot\frac{1}{j_2+1}P(j_1, j_2, j_3) = (j_1+1)\mu P(j_1+1, j_2, j_3) \\
&+ (j_2+1)\mu P(j_1, j_2+1, j_3) + (j_3+1)\mu P(j_1, j_2, j_3+1)
\end{aligned} \qquad (6.5)$$

As in Chapter 5, there are $(n_1+1)(n_2+1)(n_3+1)$ states in this three-dimensional Markov chain. Thus, we can obtain $(n_1+1)(n_2+1)(n_3+1)$ general statistical equations, but one of them is redundant. However, in a Markov process, we know that the sum of the overall state probabilities is equal to 1, thus we have:

$$\sum_{j_1=0}^{n_1}\sum_{j_2=0}^{n_2}\sum_{j_3=0}^{n_3} P(j_1, j_2, j_3) = 1 \tag{6.6}$$

The normalization equation can be expressed as:

$$\boldsymbol{AP=B}$$

where A is the $((n_1+1)(n_2+1)(n_3+1))^2$ coefficient matrix, P is the $(n_1+1)(n_2+1)(n_3+1)$ state probability vector, and B is the $(n_1+1)(n_2+1)(n_3+1)$ constant vector.

The state probability P can be solved as $j_i \epsilon [0, n_i]$:

$$\boldsymbol{P = A^{-1}B} \tag{6.7}$$

Blocking Probability

The calculation of blocking probability is discussed in detail in Chapter 5, and is shown as:

$$BP_{system} = \frac{\lambda_{area,1}}{\lambda_{all}} \cdot \sum_{j_3=0}^{n_3} P(n_1, n_2, j_3) + \frac{\lambda_{area,2}}{\lambda_{all}} \cdot \sum_{j_1=0}^{n_1} P(j_1, n_2, n_3) \tag{6.8}$$

where $\lambda_{\text{area,i}}$ $i \epsilon [1,2]$ is the arrival rate in sub-area i, λ_{all} is the overall arrival rate in the service area.

Potential Energy Reduction

Similarly, the potential energy reduction of the system with topology management with handover scheme is shown as:

$$E\_R = \frac{\sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j} (Pt_{ABS,work,j} - Pt_{ABS,idle,j}))}{\sum_{j=1}^{n_{ABS}} t_{all} Pt_{ABS,work,j}} \tag{6.9}$$

where $\mathrm{Pt}_{\mathrm{ABS,work,j}}$ is the transmit power when ABS_j is in working mode, $\mathrm{Pt}_{\mathrm{ABS,idle,j}}$ is the transmit power when ABS_j is in sleep mode.

6.4 Results and Analysis

In this section, whether the handover mechanism provides further benefit to the energy efficiency and how certain parameter values influence the network energy consumption for next generation mobile broadband systems is studied.

A) Benefit from handover mechanism

For the purposes of comparison, the Monte Carlo simulation scenario comprises 20,000 users uniformly distributed throughout the service area. There are 16 available channels on each ABS. n_h (the threshold to handover the users on ABS2 to its neighbour) is assumed as $n_h = n_{adj}^{ON} - 2$, where 2 is the number of protection channels introduced in Figure 6.3. In other words, the maximum number of channels occupied on ABS2 after handover is equal to $n_{adj}^{ON} - 2$. The simulation results are measured when the system is stable, from 10%-95% of the total simulation time, and is repeated 100 times in order to obtain statistically significant results. All the related parameter values in Markov process are the same with that of the Monte Carlo simulation.

Figure 6.5 shows the potential energy reduction for the system with/without the handover mechanism while α_{adj}^{ON} increases when the offered traffic is equal to 21 Erlangs. It can be seen that the scheme with handover mechanism improves the energy efficiency, where up to twice the energy reduction can be achieved compared to the scheme with TM only in some cases. This may occur when α_{adj}^{ON} is at a high value. That is because some of the states in the Deactivated Area handover to the Inactive Area directly. The base station with handover mechanism is more easily to be switched off compared to BS with TM scheme only. Meanwhile, the potential energy reduction is limited by the selection of certain parameters.

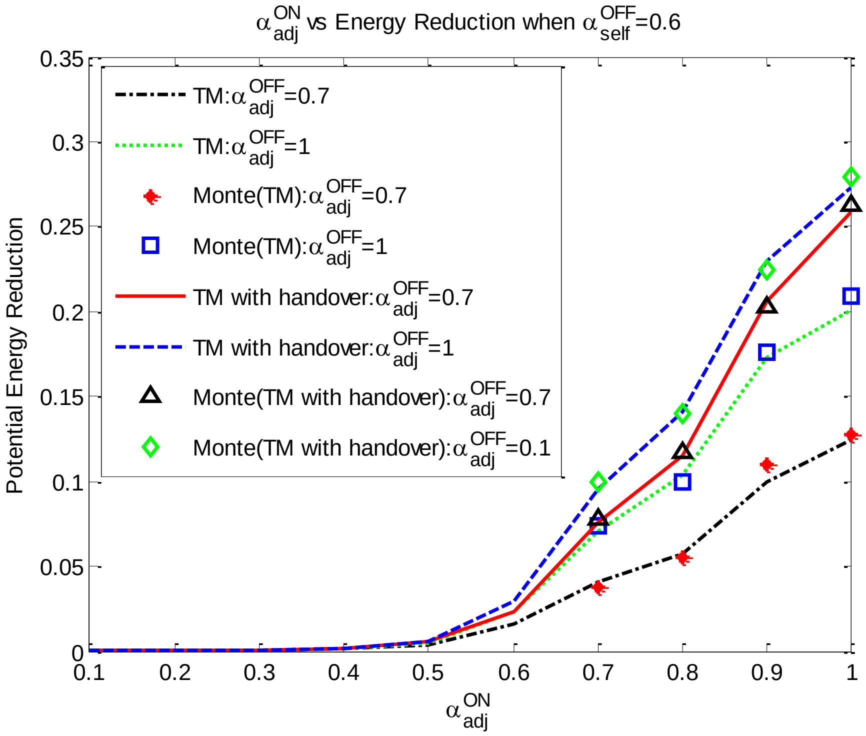

Figure 6.5 Comparison of results with/without handover mechanism when the system traffic load is equal to 21 Erlangs ($\alpha_{self}^{OFF} = 0.6$)

B) Threshold of handover users to adjacent base stations

This sub-section examines how n_h affects the potential energy reduction in our topology management schemes with handover. Here, n_h is a parameter to describe how easily a base station can be switched off. A small value of n_h means it is difficult to handoff the traffic loads to its adjacent BSs if a BS intends to switch off. A large value of n_h means that it is easy to handoff the traffic loads to its adjacent BSs. However, the base station suffers a risk of switching on again immediately after being switched off. The value of

n_h should not be equal to or greater than n_{adj}^{ON} because the number of users occupied on adjacent ABSs should be less the threshold n_{adj}^{ON} to keep the switched off ABS in sleep mode.

Figure 6.6 provides an example of how n_h influence the potential energy reduction. Here, $n_{adj}^{ON} = 0.7x16 = 11$, n_h varies from 4 to 10 (the number of users occupied on ABS 2 before handover). It can be seen that when traffic load is at low-mid level (21E), the potential energy consumption can be significantly saved while n_h increase compared to the results with TM scheme only. However, changes of n_h provide very limited improvement in energy efficiency when traffic load is low. This is because the network has achieved the maximum potential energy reduction with the TM scheme.

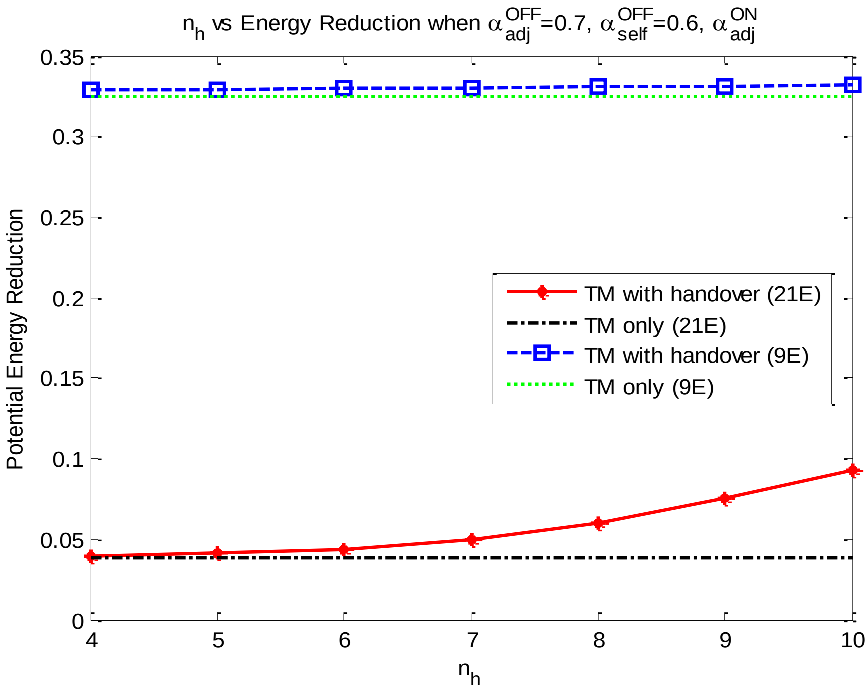

Figure 6.6 Potential energy reduction when the threshold of handover traffic load to adjacent BSs varies ($\alpha_{adj}^{OFF} = 0.7, \alpha_{self}^{OFF} = 0.6, \alpha_{adj}^{ON} = 0.7$)

6.5 Conclusions

In this chapter, we have developed a traffic load based topology management scheme with handover mechanism for next generation mobile broadband systems, which provides further benefits with the aid of handover mechanism for improving system energy efficiency. An analytical model has been introduced which incorporates the effects of overlapping coverage through the aid of a multi-dimensional Markov chain. The handover mechanism is embedded into this analytical model based on the work in Chapter 5. The results show that the handover schemes can improve the energy efficiency significantly, where up to twice energy reduction can be achieved if the certain parameters are selected. The results also show that the threshold to handover traffic load adjacent ABSs influence the system potential energy reduction when the system traffic load is at low-mid level. However, it provides very limited energy efficieny benefit when traffic is low.

Chapter 7. Multi-dimensional Markov Process for Multi Base Station Systems

Contents

7.1 Introduction

In this chapter, an analytical model is developed for a four base station network. It has the flexibility of specifying a greater degree of overlapping coverage over a larger number of base stations in dense urban environments. It is then applied to a large network using three different topology management approaches in order to understand the impact of the model approximation problems when the system traffic load is at medium/high levels in chapter 5 and chapter 6. It aims to provide a much more accurate prediction when the system traffic load is at medium/high level than the work in Chapter 5. What is more, base station modes are divided into three levels depending on their behaviour and we show how to combine an energy efficient scheme with a multi-dimensional Markov process, which will be clearly shown in our analytical model.

The remainder of this chapter is organized as follows. In Section 7.2, the system scenario and energy efficient schemes are described. Section 7.3 presents the detailed solutions for increasing the accuracy of results when the system traffic is at middle/high levels based on the work in Chapter 5 and 6. Results are presented and discussed in Section 7.4. Finally, the findings of the study are concluded in Section 7.5.

7.2 System Scenario and Energy Efficient Schemes

A. System Model

As with previous chapters, we still use the BuNGee architecture as the scenario under discussion, which is shown in Figure 7.1, but new the degree over overlapping coverage assumed by each ABS is increased. If a new user arrives and is within the range of more than one ABS, it is connected to the one offering the best Signal to Interference plus Noise Ratio (SINR).

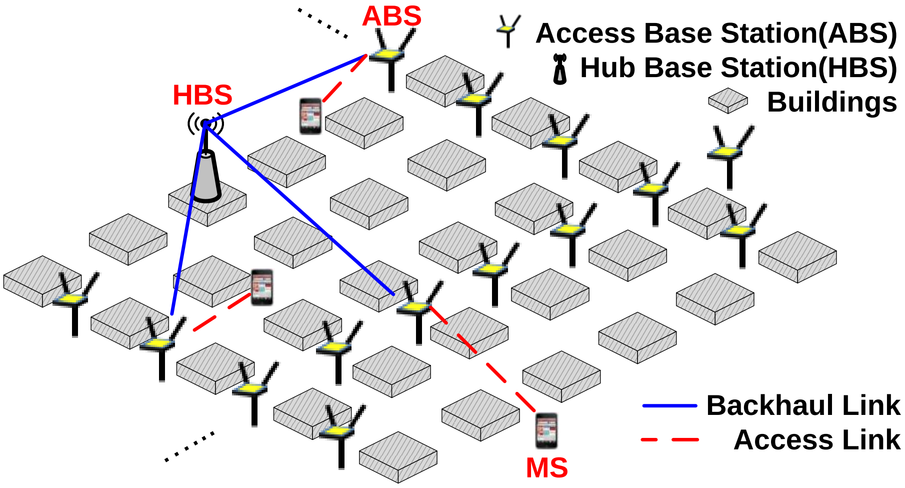

Figure 7.1 An example of typical BuNGee architecture

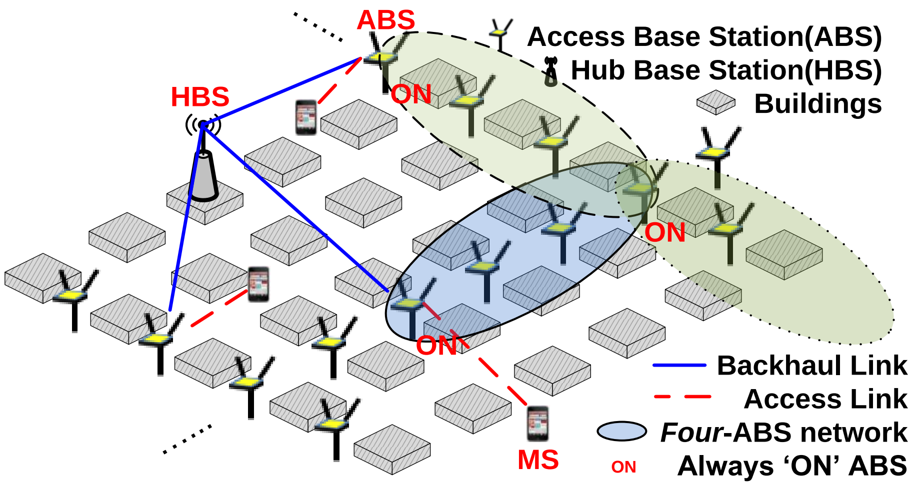

Figure 7.2 A typical BuNGee architecture with four-*ABS sub-networks*

The detailed operation of the energy efficient topology management scheme is similar with the schemes in previous chapters. However, the ABSs located at the boundaries in a sub-network are assumed to be always ON in this chapter, which will be introduced later. The topology management scheme can be described as follows:

To switch an ABS from working mode into sleep mode, the following should be satisfied:

1) The capacity usage of an ABS at time *t* is smaller than a threshold (n_{self}^{OFF}) of the maximum capacity $C_{self}^{ABS_i} < n_{self}^{OFF}$;
2) The capacity usage of all adjacent 'always ON ABSs' at time *t* is smaller than a threshold (n_{adj}^{OFF}) of the maximum capacity $C_{adj}^{ABS_i} < n_{adj}^{OFF}$;

If both conditions above are satisfied, this ABS prepares to switch into sleep mode; new users are not allowed to access this ABS at this stage. It will be fully switched off when all the traffic it is currently serving departs.

To switch an ABS from sleep mode into working mode, the following should be satisfied:

The instantaneous capacity usage of its neighbouring 'always ON ABSs' at time t is equal to or higher than a threshold n_{adj}^{ON} of the maximum capacity $C_{adj}^{ABS_i} \geq n_{adj}^{ON}$.

This topology management scheme is fully distributed and controlled by the ABSs themselves. The information about traffic load should be exchanged between adjacent ABSs.

B. Problem Formulation

In this subsection, we introduce and formulate the energy efficient topology management problem with the aid of a multi-dimensional Markov process. This substantially extended analytical model is developed based on our previous work in chapter 5 [93]. Here, we afford significantly greater flexibility allowing much more overlapping coverage (typical in small cell systems) and better potential for system energy reduction. The scenario, here, can be considered as an n-channel m-ABS system. In other words, there are i-ABSs ($\mathrm{i}\epsilon[1,\mathrm{m}]$) with n_i available channels on each ABS. Let $\mathrm{S}(j_1, j_2, \dots, j_i)$ be a state in the Markov chain, which is defined as the number of channels occupied on an ABS, with each ABS in the service area forming one dimension. Here, we assume that $j_i \epsilon [0, n_i]$ is an integer, where n_i is the maximum number of available channels on ABS_i . We denote by $\mathrm{P}(j_1, j_2, \dots, j_i)$, the vector describing the probabilities on $\mathrm{S}(j_1, j_2, \dots, j_i)$ when the system is in steady state.

The notations in use are defined as follows:

λ_3/λ_4: The arrival rate for ABS3/4 when both of them are not fully occupied.

λ_{34}: The arrival rate for ABS3/4 when one of them is fully occupied, with the local traffic forwarded by the alternative ABS.

μ: The departure rate per channel.

n_i: The total number of available channels on ABS_i.

n_{adj}^{ON}: The threshold to switch on an ABS. If the number of channels occupied on the adjacent ABSs of an ABS in sleep mode is equal to or greater than this threshold, the sleeping ABS is turned on.

n_{adj}^{OFF}: The threshold to switch off an ABS. If the number of channels occupied on the adjacent ABSs of an ABS in working mode is smaller than this threshold, we prepare to turn off this ABS.

n_{self}^{OFF}: The threshold to switch off an ABS. If the number of channels occupied on an ABS itself is smaller than this threshold, we prepare to turn off this ABS.

In order to facilitate understanding and reduce the complexity of the multi-dimensional Markov process, an *n*-channel *four*-ABS network is discussed firstly. This *four*-ABS network represents a part of a typical BuNGee cell depicted in Figure 7.2. Figure 7.3 gives an example of a *four*-ABS network architecture, where ABS 1 and 4 are always ON. ABS 2 and 3 can be switched off to save energy when the local traffic load is low. The coverage radius (R) for an ABS is assumed to be one and half times the distance (d) between two adjacent ABSs. This provides a degree of overlapping coverage, such that there are now three ABSs potentially suitable for access if a new user arrives in the system. For instance, Area 2, shown in Figure 7.3 can be overlapped by ABSs 1, 2 and 3. Area 1 and 4 can only be overlapped by two ABSs in this *four*-ABS model. However, if we apply this model to a large network, these two sub-areas can be overlapped by adjacent ABSs creating concatenated, overlapping sequences of *four*-ABS networks as well.

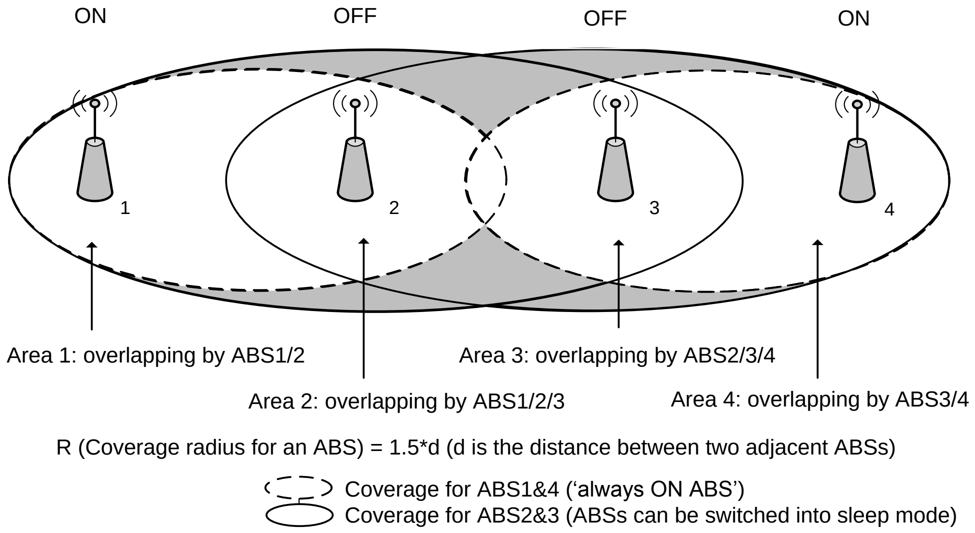

Figure 7.3 The coverage and overlapping area for four-*ABS network*

Considering individual users accessing the system, arrival and departure rates are assumed to follow an exponential distribution [94]. Based on the definition of state above, the behaviour of a *four*-ABS network can be described by a *four*-dimensional Markov chain, with each dimension representing the varying of number of channels occupied on a particular ABS. For a specific state $S(j_1, j_2, j_3, j_4)$, the network may remain in the same state or move to any adjacent state ($j_i \rightarrow j_i, j_i + 1 \ or \ j_i - 1$). Figure 7.4 shows a segment of the state transition diagram for the energy efficient topology management scheme. For clarity, the number of channels occupied on ABSs 1 and 2 equals zero. We assume that all new arrivals are located in the regions covered by ABSs 3 and 4. The reason for this is that it is difficult to depict a full four-dimensional chain on paper.

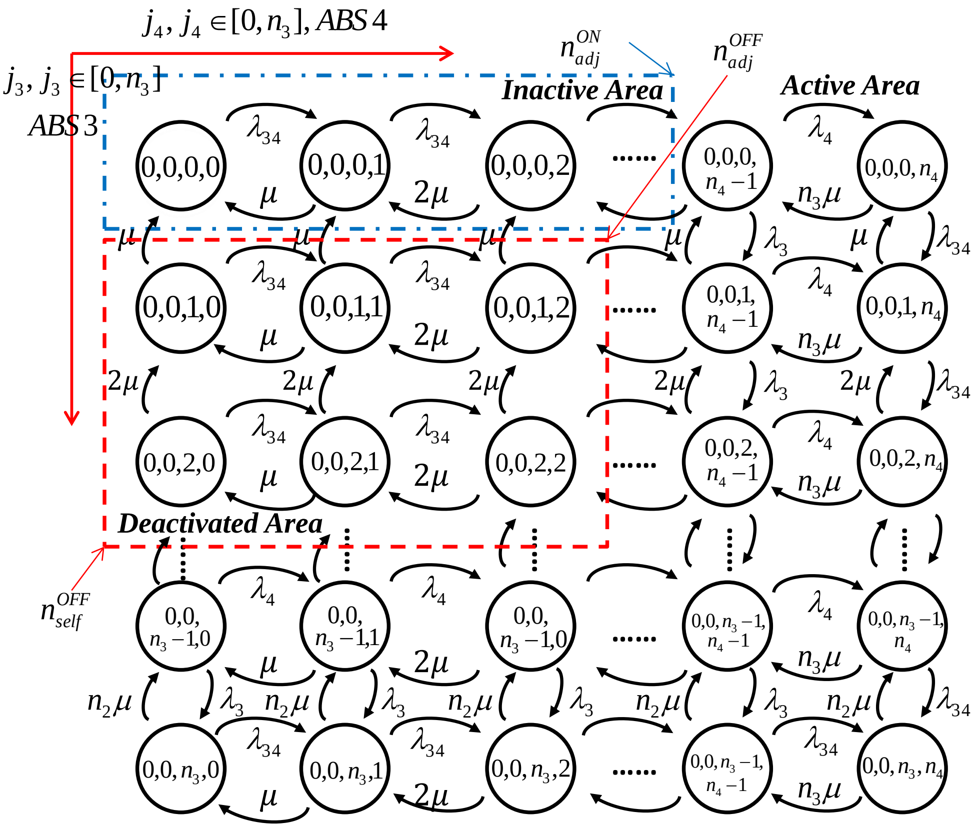

Figure 7.4 State transition diagram when ABS 1 and 2 are empty with topology management

The state diagram can be divided into three areas depending on the energy efficient topology management scheme used:

- Inactive Area (area enclosed with dash dot lines), where ABS3 is switched off (potential energy reduction occurs in this area).
- Deactivated Area (area enclosed with dash lines), where ABS3 prepares to turn off, new arrivals are not allowed access to ABS3.
- Active Area (the remaining area), where both of ABS 3 and ABS 4 are in working mode.

In detail, we assume $S(0,0,0,0)$ means the system is fully empty and ABS3 is in sleep mode. At this stage, the state can only transfer along the inactive area in the horizontal direction until the threshold (n_{adj}^{ON}) is reached because new arrivals are only allowed to access ABS 4. When the traffic load on ABS4 is equal to or higher than (n_{adj}^{ON}), ABS3 is switched on to forward local traffic. The system state transfers into the Active Area and can move along both horizontal and vertical directions if both ABS 3 and 4 have available channels. When the number of channels occupied on both ABSs is smaller than the threshold ($j_3 < n_{self}^{OFF}$ and $j_4 < n_{adj}^{OFF}$), the state then transfers into the Deactivated Area. In this area, ABS3 remains in working mode until all users leave. New arrivals are not allowed to access ABS3 because it is preparing to switch off. A similar process occurs when new arrivals are allowed to be located in the regions covered by ABS 1 and 2.

Knowing how the state transition diagram works, the equilibrium analysis for the *four*-ABS network requires that the flux out of $S(j_1, j_2, j_3, j_4)$ should be equal to that into $S(j_1, j_2, j_3, j_4)$. For a specific state $S(j_1, j_2, j_3, j_4)$ in the previous diagram, there are 2x4 adjacent states potentially suitable for transition. This is because there are four ABSs in the network and two possible changes in the number of channels occupied on each ABS, with a new user arriving or an old user departing. An additional situation occurs when no user arrives or leaves the system. The number of channels occupied on a specific ABS_i is between 0 and n_i. It is not possible to use a negative number of channels in the system. Therefore, we have:

$$P(-1, j_2, j_3, j_4) = P(j_1, -1, j_3, j_4) = P(j_1, j_2, -1, j_4) = P(j_1, j_2, j_3, -1) = 0 \quad (7.1)$$

Similarly, states with $j_i > n_i$ cannot exist:

$$\begin{aligned} &P(n_1+1, j_2, j_3, j_4) = P(j_1, n_2+1, j_3, j_4) \\ &= P(j_1, j_2, n_3+1, j_4) = P(j_1, j_2, j_3, n_4+1) = 0 \end{aligned} \quad (7.2)$$

The general statistical equilibrium for an *n*-channel *four*-ABS network at state $S(j_1, j_2, j_3, j_4)$ can be expressed as:

$$\begin{aligned}&(\lambda_{j_1}+\lambda_{j_2}+\cdots+\lambda_{j_4}+j_1\mu+j_2\mu+\cdots+j_4\mu)P(j_1,j_2,j_3,j_4)\\&=(j_1+1)\mu P(j_1+1,j_2,j_3,j_4)+\lambda_{j_1-1}P(j_1-1,j_{2,}j_3,j_4)\\&+(j_2+1)\mu P(j_1,j_2+1,j_3,j_4)+\lambda_{j_2-1}P(j_1,j_2-1,j_3,j_4)\\&+\cdots+(j_4+1)\mu P(j_1,j_2,j_3,j_4+1)+\lambda_{j_4-1}P(j_1,j_{2,}j_3,j_4-1)\end{aligned} \tag{7.3}$$

where $\{\lambda_{ji}\}$are the arrival rates for each ABS transferring from the current state to the adjacent state when a new user arrives or an old user leaves. If $j_i = n_i$, λ_{j_i} does not exist because this ABS is full; it cannot provide service for new arrivals. However, we define $\lambda_{j_i} = 0$ here in order to obtain a general form of the equation. Meanwhile, $\{\lambda_{ji-1}\}$ represent the arrival rates from adjacent states to the current state.

There are $(n_1+1)(n_2+1)(n_3+1)(n_4+1)$ states in this four-dimensional Markov chain. Therefore, we can obtain $(n_1+1)(n_2+1)(n_3+1)(n_4+1)$ general statistical equations, but one of them is redundant. However, in a Markov process, we know that the sum of all state probabilities is equal to 1, so we have:

$$\sum_{j_1=0}^{n_1}\sum_{j_2=0}^{n_2}\sum_{j_3=0}^{n_3}\sum_{j_4=0}^{n_4}P(j_1,j_2,j_3,j_4)=1$$

As we introduced in Chapter 5, the normalization equation can be expressed as:

$$\boldsymbol{AP=B}$$

where A is the$((n_1+1)(n_2+1)(n_3+1)(n_4+1))^2$coefficient matrix, P is the $(n_1+1)(n_2+1)(n_3+1)(n_4+1)$ state probability vector, and B is the $(n_1+1)(n_2+1)(n_3+1)(n_4+1)$ constant vector.

The state probability P can be solved as $j_i \epsilon [0, n_i]$:

$$\boldsymbol{P = A^{-1}B}$$

7.3 Multi-dimensional Markov Process for multi-ABS Networks

In this section, we use the state probabilities obtained in the previous section to show and optimise the system performance and the potential energy reduction for a *four*-ABS network first. This four-ABS energy efficient analytical model is then applied to a large network.

A. System Performance and Energy Reduction

Blocking Probability

Here, we use blocking probability to measure the system performance and QoS guarantee. Blocking occurs when no service is obtained by a newly arriving user from any ABS. It can be calculated as the sum of the state probabilities when all the ABSs providing service for a specific area are full. Thus, the system blocking probability is:

$$\begin{aligned} BP_{system} &= BP_{Area,1} + BP_{Area,2} + BP_{Area,3} + BP_{Area,4} \\ &= \frac{\lambda_{area,1}}{\lambda_{all}} \cdot \sum_{j_3=0}^{n_3} \sum_{j_4=0}^{n_4} P(n_1, n_2, j_3, j_4) + \frac{\lambda_{area,2}}{\lambda_{all}} \cdot \sum_{j_4=0}^{n_4} P(n_1, n_2, n_3, j_4) \\ &+ \frac{\lambda_{area,3}}{\lambda_{all}} \cdot \sum_{j_1=0}^{n_1} P(j_1, n_2, n_3, n_4) + \frac{\lambda_{area,4}}{\lambda_{all}} \cdot \sum_{j_1=0}^{n_1} \sum_{j_2=0}^{n_2} P(j_1, j_2, n_3, n_4) \end{aligned} \tag{7.4}$$

where $\lambda_{\text{area,i}}$ $i \in [1,4]$ is the arrival rate in sub-area *i*, and λ_{all} is the overall arrival rate in the service area.

Potential Energy Reduction

The potential energy reduction of the system with topology management is calculated, as in Chapters 5 and 6, as:

$$E\_R = \frac{\sum_{j=1}^{n_{ABS}} (t_{ABS,idle,j} (Pt_{ABS,work,j} - Pt_{ABS,idle,j}))}{\sum_{j=1}^{n_{ABS}} t_{all} Pt_{ABS,work,j}}$$

where $\mathrm{Pt}_{\mathrm{ABS,work,j}}$ is the power consumed when $\mathrm{ABS}_{\mathrm{j}}$ is in working mode, $\mathrm{Pt}_{\mathrm{ABS,idle,j}}$ is the power consumed when $\mathrm{ABS}_{\mathrm{j}}$ is in sleep mode.

B. Application of model to a multi-ABS network

The multi-dimensional Markov chain can be solved when the system is in the steady state as outlined in the previous section. However, when the number of dimensions is high and number of states is large, solving the matrix of probabilities can be computationally difficult. For example, if there are only two dimensions and six available states on each dimension, the total number of the elements in the matrix equals 6^{2^2}. However, this value increases to 12^{4^2} if we double the dimensions and the number of states on each dimension. Therefore, it becomes necessary to reduce the complexity of the multi-dimensional Markov chain. A possible approach is to use a single or low dimensional Markov chain instead of the high dimensional Markov process. This is one of the reasons why the analytical model is initially presented as a *four*-ABS network. However, this approximation becomes less accurate if we apply the *four*-ABS network to the full BuNGee system directly. This is because the traffic loads on the two 'always ON ABSs' can be influenced by the ABSs which are located adjacent to the *four*-ABS networks (They provide the coverage for the same sub-area). Hence, we next develop three approaches to improve the accuracy of our analytical model depending on the specific deployment of our scenario.

Half Channel Model with four-ABSs for multi-ABS System

In a typical BuNGee cell, a large number of ABSs are deployed with one third of them always kept ON. It is possible to divide the whole network into several *four*-ABS networks. Each *four*-ABS network is made up of two 'always ON ABSs' and two ABSs which can be switched off between them. These two 'always ON ABSs' are also components of adjacent *four*-ABS networks. Thus, we assume that they inherit only half of the maximum number of available channels compared with the original ABSs, as shown in Figure 7.5.

For a specific state $S(j_1, j_2, j_3, j_4)$ we have:

$$j_2, j_3 \in [0, n_i]$$

$$j_1, j_4 \in [0, \frac{n_i}{2}]$$

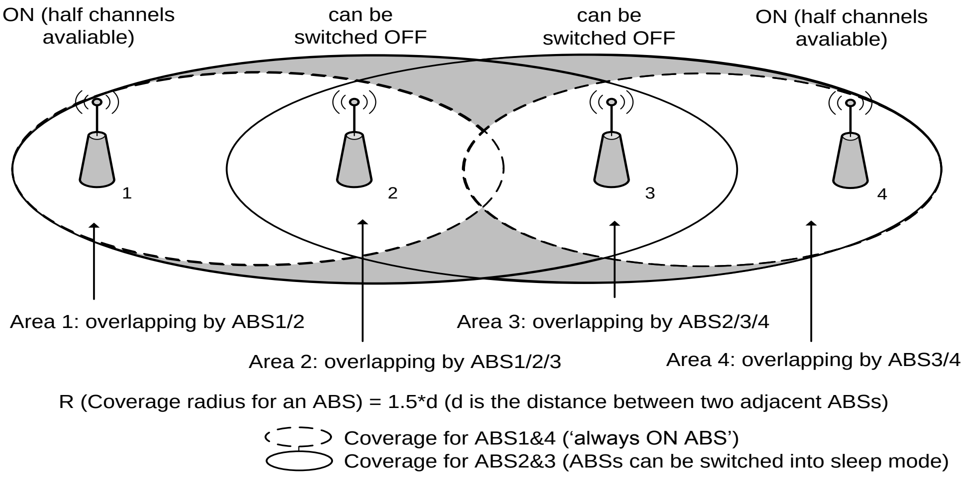

Figure 7.5 Architecture of the Half Channel Model

The advantage of this model is that it is flexible and easy to apply to a larger network. However, it is still not accurate enough under some conditions. It is similar to the 'faster server or two servers' problem [95] in computer science. We use two servers with half channels to provide service for the different regions instead of one good server with full channels which can provide service for the whole area. The one server case suffers experiences lower system blocking probability compared to the two server case. Therefore, this model potentially works well when the system traffic is low and the maximum number of available channels is large (e.g. more than 10). This is because the blocking probability is extremely low and the error is limited by the low traffic conditions. Some important functions are:

$$P(\frac{n_1}{2}+1, j_2, j_3, j_4) = P(j_1, n_2+1, j_3, j_4) = P(j_1, j_2, n_3+1, j_4) = P(j_1, j_2, j_3, \frac{n_4}{2}+1) = 0$$

Neighbour OFF Model with four-ABS for multi-ABS System

In order to obtain a more accurate model, it is possible to define upper and lower bounds on the performance for *four*-ABS networks. In the previous model, an ‘always ON ABS’ was divided into two components each with half of the channels. The error occurs when one of the components is full (being blocked here, and the other cannot forward its data even if it has available channels. However, this will not happen in a multi-ABS system because the original ABS can provide service for all the users in its coverage area.

In a large network, there are least two adjacent ABSs for an ‘always ON ABS’, one being located within the *four*-ABS network. Here, the worst situation is considered for the *four*-ABS network, another ABS which is located outside the *four*-ABS network should always remain in sleep mode, which is shown in Figure 7.6. This means that the ‘always ON ABS’ has to forward all the traffic for the ABS which is in the sleep mode; we define this model as the lower bound model of the *four*-ABS network.

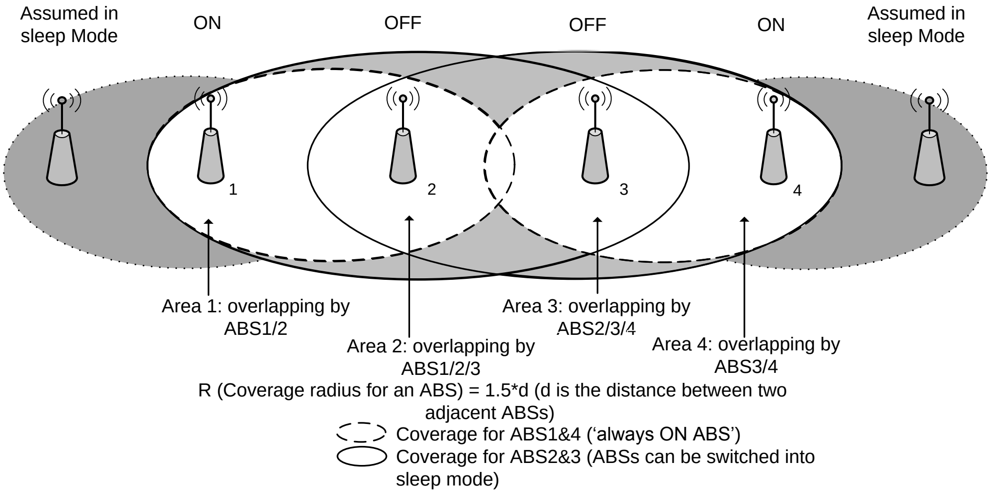

Figure 7.6 Architecture of Neighbours OFF Model

The advantage of this model is that the results are more accurate than the previous half channel model when the system traffic loads are at a low level, as most of the ABSs are switched into the sleep mode to save energy. The remainder of the 'always ON ABSs' can guarantee QoS and provide full coverage for the service area. However, this model will be less accurate when the system traffic load increases.

Neighbours considered Model with four-ABS for multi-ABS System

In contrast to the previous model, here the decision as to whether or not to switch an ABS ON/OFF is determined by the traffic load on its adjacent 'always ON ABS' depending on our energy efficient topology management scheme, which is shown in Figure 7.7.. This means the behaviour of ABS *left* and 2 are both affected by ABS 1. They will be switched ON/OFF simultaneously when the traffic load on ABS 1 reaches a threshold. In other words, the activities of ABS *left* and *right* can be predicted depending on the behaviours of ABSs 2 and 3.

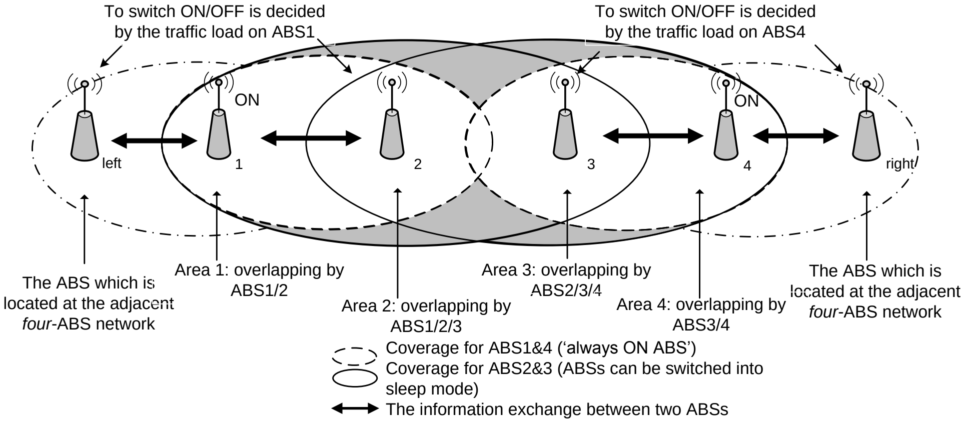

Figure 7.7 Architecture of Neighbours considered Model

This model is considered the most accurate of the three models introduced. However, considering that the degree of overlap is equal to three in our scenario, the traffic loads on a specific 'always ON ABS' are affected by its four adjacent ABSs (two in the same sub-network with the ABS, and the others located at the adjacent sub-networks). The disadvantage of this model is that the activity of one of these four ABSs which is controlled by another ‘always ON ABS’ is difficult to predict.

7.4 Results and Analysis

In this section, some important observations obtained from the analytical model. In considering the results, first of all, the analytical model is compared with Monte Carlo simulation for a *four*-ABS network. Secondly, three different approaches to applying the architecture model to a multi-hop next generation network with three different approaches are presented.

A. Multi-channel three-ABS networks

Consider the analytical model and a corresponding simulation with six channels on each ABS, assuming the thresholds for switching an ABS on/off are varied. In this case, the traffic load is assumed to be the same in each sub-area. Two different system traffic loads (the overall traffic loads in the *four*-ABS network) are used (3 Erlangs and 12 Erlangs) in order to analyze the system performance when the system traffic is at low and mid-levels respectively. The system inter-arrival rate and service time follow exponential distributions, where the average service time is chosen to be *60s/call*. The average inter-arrival rate is determined by both the system offered traffic and the average service time. The blocking occurs when there is no available channel for new arrivals.

For the purposes of comparison, the Monte Carlo simulation scenario comprises 20,000 users uniformly distributed throughout the service area. All the related parameters are the same as the Markov Model. The simulation results are measured when the system is stable, from 10%-95% of the total simulation time, and is repeated 100 times in order to obtain statistically significant results. Some of parameter values are summarised in Table 7.1.

Table 7.1 Parameters for Analytical Model and Simulation

Parameters	Value
Number of Channels	6
Degree of Overlap	3
Average service time per user	60s
Number of total users	20000
Repeat times	100

Figure 7.8 shows the system blocking probabilities of the Markov Model with topology management and of the Monte Carlo simulation when α_{adj}^{ON} increases. The results from simulation are closely consistent with the results from the analytical model. Slight discrepancies between the two are due to the burstiness of the traffic in the simulation where an exponential distribution is assumed, noting that α_{adj}^{ON} should be always equal to or larger than α_{adj}^{OFF}. This is because it is difficult to switch off an ABS immediately after switching it on in practice. The curves in the diagram are not smooth because there are only six channels on each ABS. The parameter α_{adj}^{ON} is varied in steps of 10% of the maximum number of channels on a specific ABS in this case.

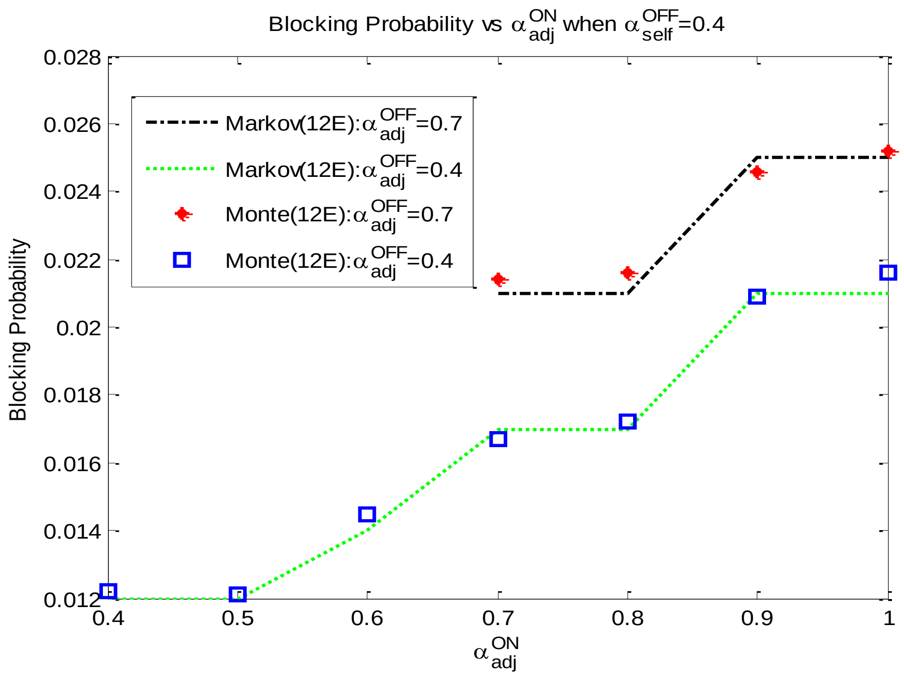

Figure 7.8 Comparison of analytical and simulation results of system Blocking Probability when the system traffic loads are equal to 12 Erlangs ($\alpha_{self}^{OFF} = 0.4$)

Figure 7.9 illustrates the potential energy reduction obtained through topology management. In a four-ABS network, the maximum energy reduction occurs when both ABS2 and ABS3 are always switched off (potentially occurring at low traffic level), with a reduction of 50% of the system energy consumption relative to the non-topology management case. If α_{self}^{OFF} is fixed, the potential energy reduction increase with α_{adj}^{ON} and α_{adj}^{OFF} increase. The parameter α_{adj}^{OFF} has very limited influence on system energy reduction at low traffic load levels, less than 1%, but increases when the traffic load increases from 0.4 to 0.7. Few users are affected when the threshold to switch off an ABS is varied. If we consider the state transition diagram introduced in Section 7.2, this means most of the state probabilities are located in the Inactive Area. However, if the system traffic load is at the mid-level, an increase in energy reduction of around 20% can be achieved when α_{adj}^{OFF} increases from 0.4 to 0.7. Notably, the threshold to switch on an ABS (α_{adj}^{ON}) affects performance much more significantly when the system traffic load is high.

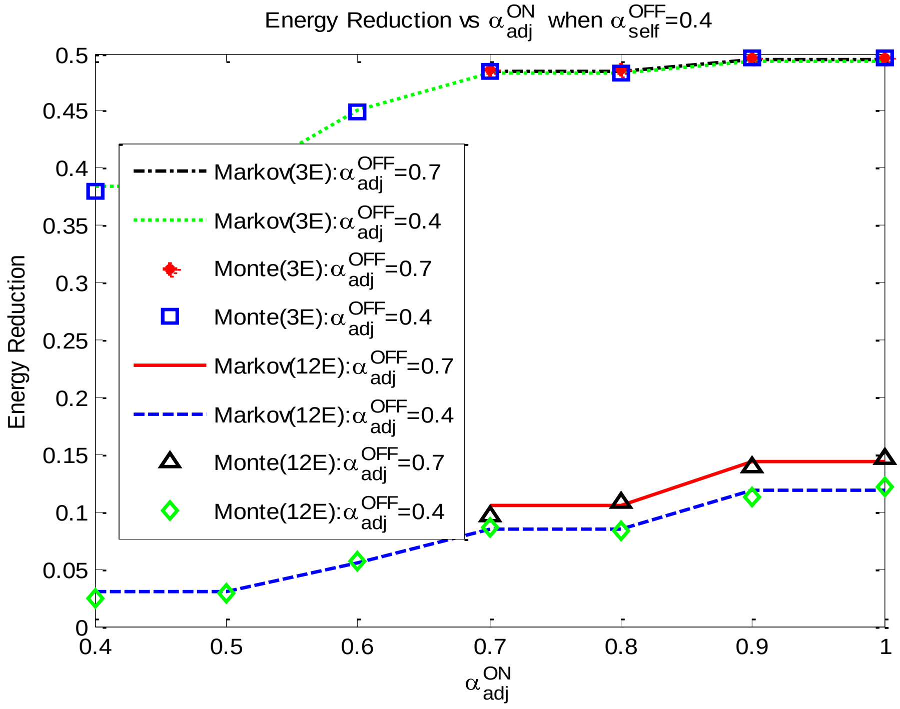

Figure 7.9 Comparison of analytical and simulation results of potential Energy Reduction when the system traffic loads are equal to 3 Erlangs and 12 Erlangs ($\alpha_{self}^{OFF} = 0.4$)

If α_{adj}^{ON} is fixed, the analytical and simulation results show that the impact of varying α_{self}^{OFF} and α_{adj}^{OFF} becomes unnoticeable. This is because only a small number of users that can be affected by the parameters switching off an ABS.

B. Application to a larger BuNGee network

We now move to the case of applying the *four*-ABS analytical model to a large service area. The scenario of the BuNGee architecture in a larger service area was introduced in Section 7.2. We assume that the whole network to include one HBS and 20 ABSs. 20,000 users are uniformly distributed over the service area. The inter-arrival time and service time of users are determined by an exponential distribution, such that the traffic model follows a Poisson distribution. A coverage area based channel assignment scheme is used here. The degree of overlapping coverage is three, meaning there are three ABSs potentially suitable for access if a new user arrives.

Here, the behaviour of the optimal strategies for the following three cases is illustrated and discussed:

1) Half Channel Model.
2) Neighbour OFF Model.
3) Neighbour Considered Model.

Figure 7.10 illustrates the system blocking probability as a function of increasing offered traffic for both analytical and simulation models. The Half Channel Model has the worst performance in terms of blocking probability. This is due to two of the four ABSs in the sub network having only half the number of channels compared to the other ABSs. The blocking probabilities of the Neighbour Considered Model and the Neighbour OFF Model are almost the same when the system traffic loads are at low and mid-levels. When the system traffic is at a high level, the Neighbour Considered Model is more easily being blocked. The Neighbour Considered model has the closest result with the simulation result, especially when the system traffic is at low/medium level. That is because the behaviours of adjacent *four*-base stations are considered here.

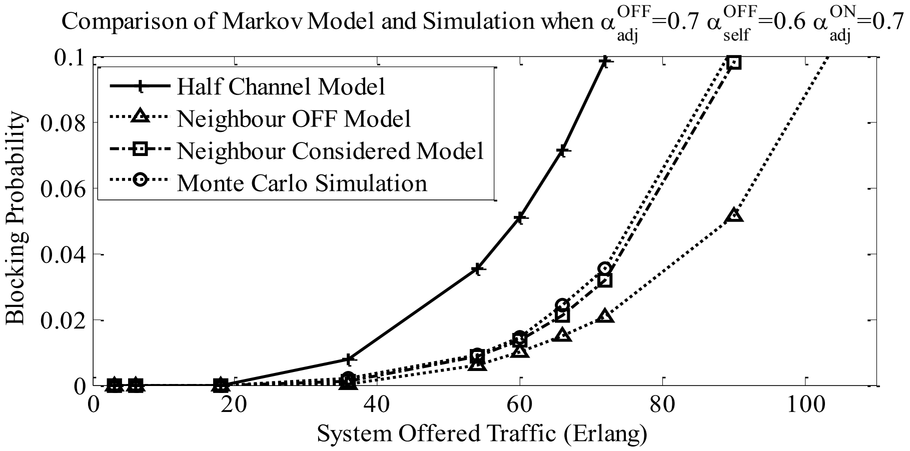

Figure 7.10 Comparison of three models and of System Blocking Probability when the system traffic load increases

Figure 7.11 shows the comparison between the three models in terms of system energy reduction when the system traffic increases. The Neighbour OFF model has the best performance among these models. This is because it assumes all the neighbours are always switched off; there is no traffic from neighbours at all. However, the simulation results are closer to the Neighbour Considered and Half Channel model, especially when the system traffic load is at extremely-low and at medium/high levels. The predictions are slightly less accurate when the traffic is at medium-low level (20 to 50 Erlangs). This is because of the high degree of overlapping in our scenario. With the Neighbour Considered model it is difficult to predict the behaviours from its adjacent 'always ON ABSs'. If we consider the results in terms of both blocking probability and system energy reduction, the Neighbour Considered model givers the most accurate results compared to the other two models.

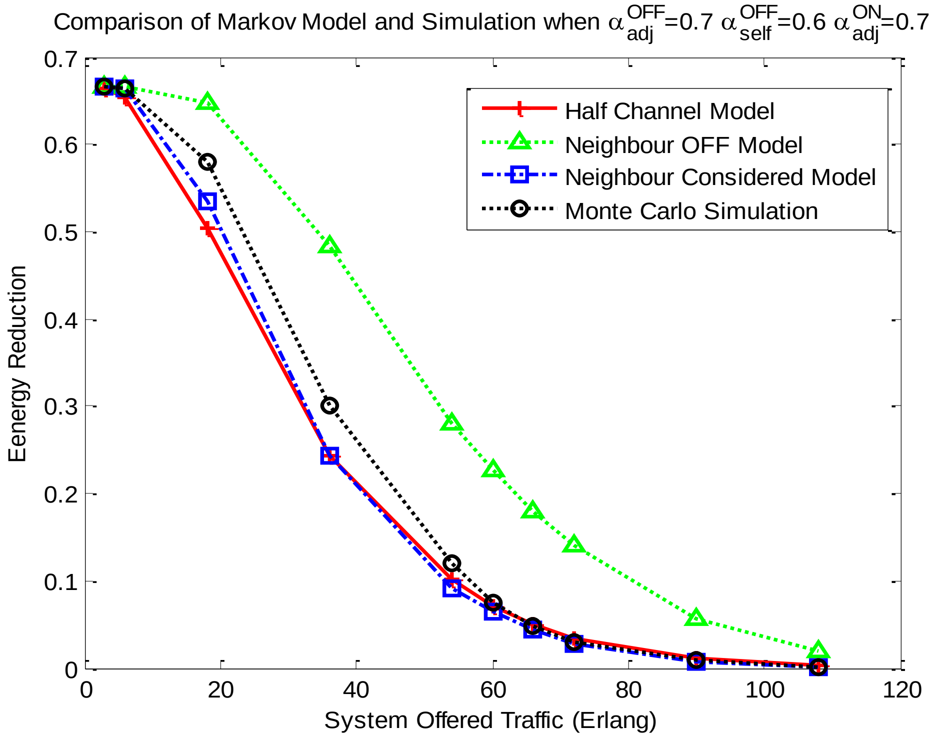

Figure 7.11 Comparison of three models of System Energy Reduction when the system traffic load increases

7.5 Conclusions

In this chapter, we have developed and optimised a traffic load based topology management scheme for next generation mobile broadband systems. The target is to find a trade off between energy efficiency and system QoS. An analytical model has been introduced which incorporates the effects of overlapping coverage through the aid of a multi-dimensional Markov chain. This model has then been applied to a larger service area using three different approaches. The analytical results are compared with and validated by a Monte Carlo simulation. We show the results of the analytical model to be consistent with the simulation in a large network. The Neighbour Considered model provides the best approach to mapping the analytical Markov chain model on to a large network.

Chapter 8. Further work

Contents

8.1 Dynamic Traffic Load Threshold Control Techniques

The energy efficient topology management techniques with sleep mode studied in this thesis use traffic load based thresholds to switch on/off base stations. These thresholds are fixed values in our scenario. However, the surrounding environment of the wireless system over the whole network is constantly changing. For instance, the local traffic load is influenced by user location, user density, time, etc. Thus, a fixed threshold topology management scheme may not provide the best system performance. Dynamic threshold control algorithms should be considered to be able to adapt the changes of the wireless environment.

A few aspects of the topology management scheme in our work have the potential to be optimized. The traffic load thresholds for switching on/off a base station can be optimized depending on the changes of the local environment. In chapter 4, these thresholds are determined as fixed values on every base station. The system performance is possible to improve further if the thresholds change dynamically on each base station in response to the environment.

8.2 Cognitive Radio for Green Communications

Cognitive radio (CR) is defined as “a wireless radio device that can adapt to its operating environment via sensing in order to facilitate efficient communications [96].” CR can plan and decide on its actions considering its targets, priorities and constraints, learn from past experience in the wireless environment, and then select the best strategy [97]. This technique enables efficient share of the spectrum, avoids interference between users, and has the potentially to bring significant improvement in energy efficiency of wireless networks.

One possible cognitive green communications scheme related to this thesis is the reinforcement learning based cluster energy efficient topology management scheme for next generation mobile broadband systems. The network will try to learn the minimum number of ABSs required in service area to guarantee system QoS depending on traffic load and past experience.

8.3 Docitive Network and Transfer Leaning for Green Communications

Docitive networks, developed from cognitive network, encourages nodes more expert to share their experience or policies with newcomers or less expert nodes [98]. In other words, nodes can teach adjacent nodes thereby aiming to reduce cognitive complexity, and provide a faster learning process and perform better and more reliable decisions [99]. It is considered as a ‘thinking’ or ‘teaching’ technology. As shown in Figure 8.1, the brief process of docition is shown as: acquisition, intelligent decision, action and docition [100].

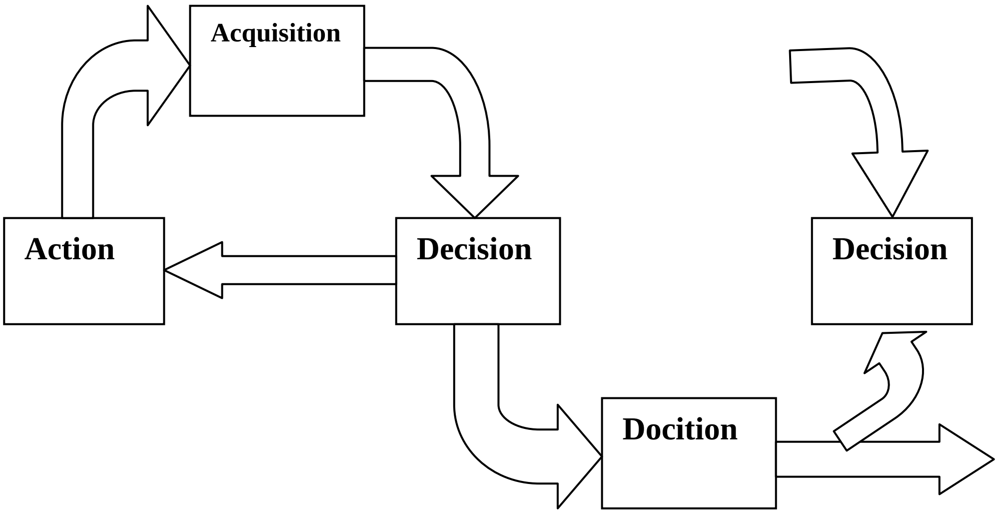

Figure 8.1 Docitive System Cycle, directly reproduced from [98]

In our previous work, the docitive decisions may occur when the switched off ABS is turning on. The adjacent working ABSs can 'teach' this ABS about the knowledge of network in order to improve system performance.

Transfer learning, attempts to develop methods to transfer knowledge learned in one or more source task and use it to improve learning in a related target task [101]. In our thesis, the exchange of information between adjacent bases stations exists in transmission. This information is potential available for transfer learning in the system. It helps the network to decide which base stations are more suitable to be switched off to improve energy efficiency. It also provides a potential solution for the dynamic traffic load threshold techniques which was introduced in section 8.1.

8.4 Low Complexity Analytical Model

The analytical tool we used in our work is the multi-dimensional Markov chain. The complexity of the Markov chain depends on the total number of states in the chain. For example, there are *n* dimensions and *m* states in each dimension, the total number of states can be calculated as m^n. It can be seen that the value of m^n grows sharply when both m and n increase, that is why we only use three/four dimensions in our thesis.

The complexity of the computation for the Markov chain can be reduced if the total number of states is limited. One of the potential solutions for this problem is to find a new definition of the state. For instance, the definition of state in our work is "the number of channels occupied on a base station, with each base station in the area of interest forming one dimension." Here, there are 16 available channels in our *three*-base station scenario (17 states in total in one dimension, with the state there is no channel being occupied). If we define the state as the working stage for a specific base station, the possible states in one dimension can be reduced from 17 to 2 (working mode/sleep mode), much smaller than 17. However, the disadvantage of this new definition is that it is very difficult for us to apply our energy efficient schemes into a Markov process, because it is hard to define how one state transfers to another mathematically.

Chapter 9. Conclusions

Contents

9.1 Summary and Conclusions

This thesis has examined how sleep modes can be used where there is a high level of overlap in next generation mobile broadband systems to improve system energy efficiency. Dynamic distributed topology management schemes are used here to switch off the small cells at low traffic load levels. It shows how by limited exchange of information between neighbouring base stations it is possible to maintain QoS, at a range of traffic loads, while enabling inactive base stations to sleep. A novel analytical model is designed using multi-dimensional Markov processes and is used to predict the theoretical system performance and potential energy reduction for BuNGee networks. A set of parameters are discussed to achieve the maximum energy efficiency. It is shown how some of the parameters have a higher impact than the others. In this thesis, the threshold from adjacent

ABSs to switch off an ABS plays more important role on energy efficiency. An energy efficient handover topology management is investigated for the BuNGee network as a way of providing further improvements to energy efficiency, up to twice potential energy reduction achieved compared to the scheme with topology management only. Several approaches to apply analytical models to large networks are discussed, which improved the accuracy of the analytical mode when the system traffic is at middle/high level. The detailed conclusions in each chapter are now explained.

Chapter 1 provides a brief introduction of this thesis and the purpose of our work. Chapter 2 presents a literature review on the research related to green communication. This focuses mainly on the energy efficient techniques in communication systems, especially for the works with energy efficient topology schemes and sleep modes. The green communication/energy efficiency related projects and researches around the world are also introduced.

Chapter 3 describes the research methodologies, simulation techniques, analytical models and the key measurements used in this thesis. The Monte Carlo simulation is widely used in our work, where MATLAB is selected as the simulation tool to evaluate performance. A Markov based analytical modelling technique is also explained which is used to predict the performance of the energy efficient topology management schemes developed in this thesis. The blocking, dropping probabilities, throughput and energy reduction are mainly used to evaluate the system performance for next generation mobile broadband systems.

In Chapter 4 we firstly introduced the dynamic distributed topology management schemes for BuNGee systems. A sleep/wake up mechanism is used here; a base station can be switched off to save energy consumption when the local traffic load is low. Whether an ABS should keep working or switched off is fully decided by the exchanged information between adjacent base stations, rather than being controlled by its higher tier Hub base stations.

It is shown that the topology management schemes can reduce the system energy consumption sufficiently from 35% to 70% compared to the network without topology management for next generation mobile broadband systems, while maintaining the quality of service.

In Chapter 5, a traffic load based energy efficient topology management scheme has been developed and an analytical model has been designed with the aid of multi-dimensional Markov process to describe energy efficient strategies and characterise the performance of BuNGee systems when sleep modes are used to deactivate base stations at locally low traffic load levels. The scenario is firstly studied as a simple three base station model and then applied into a BuNGee architecture which can be deployed in dense urban areas to provide high throughput densities and ensure the QoS and coverage for users.

It can be seen that the results from the simulation are consistent with the results from the analytical model. The traffic load based thresholds to switch on/off base stations which are measured from its adjacent base stations have higher impact than the threshold on this base station itself. The latter threshold has very limited influence for the system energy reduction. The slight discrepancy between the analytical model and simulation is due to the traffic burstiness in the simulation where an exponential distribution assumed.

An energy efficient topology management scheme employing combined sleep modes with handover for a BuNGee system is investigated as a way of providing further improvements to energy efficiency in Chapter 6. The foundations of the analytical model in chapter 5 are explained to describe the combined scheme and predict system performance. Here, the handover mechanism is considered as one of the important approaches to reduce energy consumption.

The results show that the handover mechanism can provide additional energy efficient benefit for BuNGee systems, where up to twice potential energy reduction can be achieved compared to the scheme with sleep mode only depending on what parameters selected when the system traffic is low-middle level.

In Chapter 7, we aim to increase the accuracy of the analytical models when the system traffic load is at medium/high levels over a large service area. We model such a system using a four base station network firstly with the aid of a four-dimensional Markov chain, and then optimise the sleep/wake up strategies assuming a degree of overlapping based on the information about the traffic loads. Three approaches (Half Channel Model, Neighbour OFF Model and Neighbour Considered Model) are used to apply this analytical model in order to closely predict system energy reduction and QoS performance in both four base station network and large network scenarios when system traffic load is at low/medium/high level.

It can be shown that the results of the analytical model are consistent with the simulation in a large network. The Neighbour Considered model provides the best approach to mapping the analytical Markov chain model on to a large network.

9.2 Summary of Novel Contributions

This thesis concentrates on how to apply traffic load based topology management schemes with sleep modes for next generation mobile broadband systems from both an analytical and simulation based perspectives. Very limited work had been carried out on improving energy efficiency for BuNGee networks and designing analytical models to predict system performance before the starting point of this work. The novel contributions of this thesis are highlighted in this section.

9.2.1 Distributed Energy Efficient Topology Management Schemes for Next Generation Mobile Broadband Systems

The energy efficiency - system performance trade off has been discussed in many publications for cellular networks. However, it is the first time this has been fully applied to an energy efficient topology management schemes for a BuNGee network to improve the system energy efficiency while guaranteeing QoS. Different with traditional cellular networks, the BuNGee network employs a high degree of overlapping small cells to deliver high throughput densities. These contributions have been published in [88] by *the Ninth International Symposium on Wireless Communication Systems (ISWCS 2012).*

9.2.2 Analytical Models to Describe Energy Efficient Schemes and Predict System Performance for BuNGee Systems when the System Traffic Load is Low

Many publications have been used to apply Markov processes to predict system performance in wireless communications. Some of them have focused on developing energy efficient schemes to predict system performance in cellular networks. However, it is the first time that an analytical model is designed where there is a high degree of overlapping small cells (BuNGee) to describe the traffic load based energy efficient strategies, to predict the system performance and select reasonable parameters for improving the system energy efficiency. In chapter 5, this analytical model is discussed with the aid of a multi-dimensional Markov process in a *three*-base station network, and then applied into a larger BuNGee network. The results show how reasonable parameters can be determined for the traffic load based topology management schemes to achieve a trade off between system performance and energy efficiency. It is observed that the results from the simulation are consistent with the results from the analytical model.

The related contributions have submitted in [93] *IEEE Transactions on Wireless Communications* in May 2013.

9.2.3 Impact of Parameters to Improve Energy Efficiency

Some publications introduced traffic load based energy efficient schemes in wireless environments [37, 38, 88]. Many of them only refer the value of thresholds from industry or based on the results from simulation. In chapter 5 and 6, the impact of parameters to influence system performance has been investigated based on an analytical model. This helps us to understand which parameters play more important roles than others for improving energy efficiency, and enable them to select the suitable values to achieve the maximum energy reduction. The parameters we discussed include the threshold from adjacent BS to switch off an ABS, the threshold to switch off an ABS itself, the threshold to switch on an ABS and the number of protection channels for a network combined sleep mode and handover. It is clearly shown that the use of an adjacent base station traffic load based threshold to switch on/off a base station of interest has a higher impact on performance than a load based threshold on the base station of interest itself in energy efficiency. The results have also shown that the number of protection channels can influence the system energy consumption when the traffic load is at low-mid level.

The contributions have been submitted to the journal *IEEE Transactions on Wireless Communications* [93] and are being prepared for submitting to the journal *IEEE Transactions on Mobile Computing* [102].

9.2.4 Energy Efficient Schemes combined Sleep Modes with Handover

Some works have focused on developing energy efficient handover for macro/femto cells network, like WiMAX-WiFi [48]. Chapter 6 develops energy efficient topology management schemes which merged sleep mode and handover to provide further energy reduction compared to the strategies with sleep mode only for BuNGee networks (small cells networks). An analytical model is developed to show how handover influences the system performance which is again characterised with the aid of a multi-dimensional Markov process. Results in this chapter show the proposed schemes are able to reduce extra energy consumption than the strategies introduced in previous chapters.

The contributions in this chapter are being prepared for submitting to the journal *IEEE Transactions on Mobile Computing* in Dec. 2013 or Jan. 2014 (draft completed in [102]).

9.2.5 Approaches to Apply Analytical Models to Large Networks

One of the limitations in chapter 5 and 6 is that the analytical models are less accurate when the system traffic load is high. The works in chapter 7 introduce three approaches to apply these analytical models to a large service area: Half Channel Model, Neighbour OFF Model and Neighbour Considered Model. It provides a potential solution applying analytical models to a large wireless networks. Results show the Neighbour Considered Model provides the most accurate results of all three models.

The ideas and the novel contributions in this chapter have been submitted in [103] by *IEEE Transactions on Vehicular Technology* – Special Issue on Green Mobile Multimedia Communications in July 2013**.**

Appendix A: WINNER II Propagation Models

WINNER II model provides a comprehensive set of channel models that are capable of covering the propagation environment of the access network of BuNGee. In our work, the WINNER II B1 model is used to calculate the pass loss between ABS and MS that is located outside of a building block. The path loss between ABS and MS inside of a building block is estimated by using WINNER II B4.

1) **WINNER II – Urban micro cell**

The propagation environment investigated by WINNER II in an urban micro-cell scenario is quite similar to BuNGee access networks' propagation environment. A Manhattan-grid layout is considered and all BS and MS antennas are assumed well below the rooftops of the surrounding buildings. All ABS and MS are assumed to be outdoor as illustrated in Figure 2-3. Both Line of Sight (LOS) and Non-Line of Sight (NLOS) cases have been considered, allowing for temporary blockage of the LOS, for example by large vehicles. The LOS and NLOS path loss are calculated as follows:

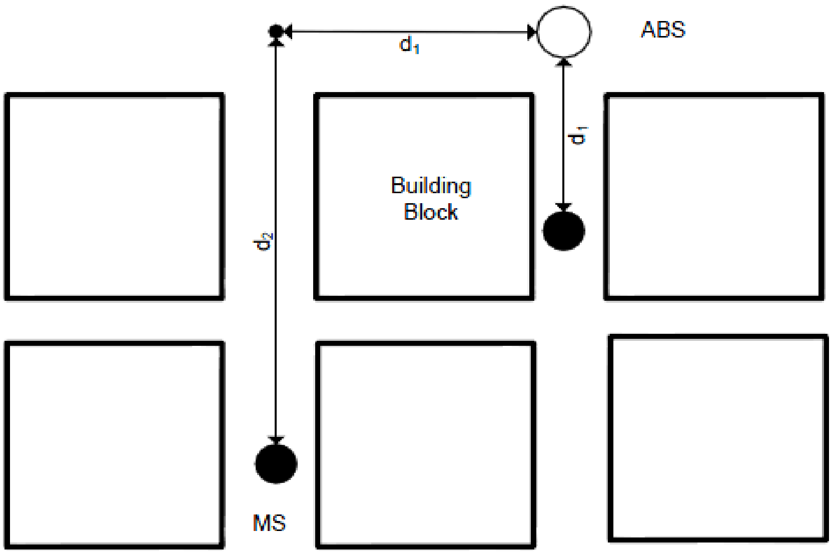

Figure A.1. WINNER II B1 Path Loss Calculation

LOS

If the MS and ABS are on the same street, the path loss can be calculated by:

$$PL = 40.0\log_{10}(d_1) + 9.45 - 17.3\log_{10}(h'_{BS}) - 17.3\log_{10}(h'_{MS}) \\ + 2.7\log_{10}(f_c/5.0)$$

Where

$$h'_{BS} = h_{BS} - 1$$

and

$$h'_{MS} = h_{MS} - 1$$

d_1 is the distance between ABS and the LOS MS, h_{BS} is the ABS antenna height and h_{MS} is the MS antenna height.

NLOS

If the MS and ABS are not on the same street, then the path loss can be shown as:

$$PL = \min(PL(d_1, d_2), PL(d_2, d_1))$$

where

$$PL(d_k, d_l) = PL_{LOS}(d_k) + 20012.5n_j + 10n_j \log_{10}(d_l) + 3\log_{10}(f_c/5.0)$$

and

$$n_j = \max(2.8) - 0.0024d_k, 1.84$$

PL_{LOS} is the path loss of B1 LOS and $k, l \in (1,2)$, d_1 and d_2 are distance between the entities along the street.

2) **WINNER II B4 – Outdoor to indoor**

The layout that is considered in WINNER II B4 is also an urban micro-cell. The only difference is that WINNER II B4 only considers the path loss between on-street BSs and in-building MSs. Therefore, in the interim simulation the path loss between ABS and in-building MS is obtained by using the WINNER II B4 propagation model. The scenario is shown in the next figure.

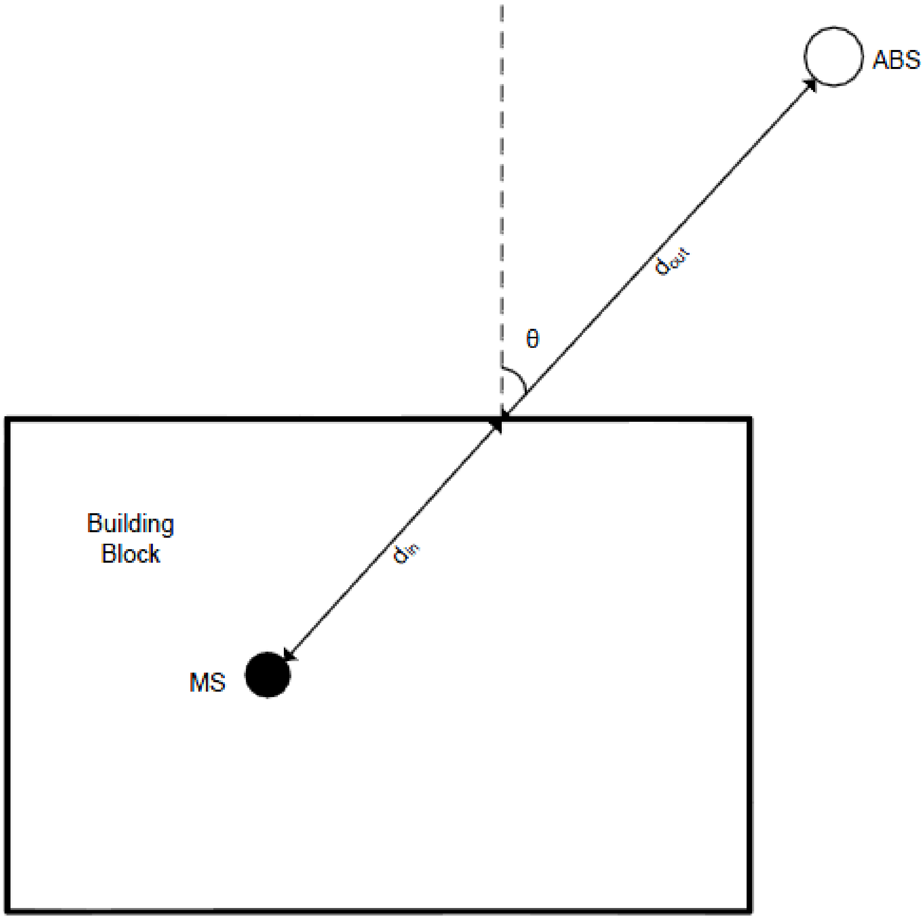

Figure A.2. WINNER II B4 Path Loss Calculation

The path loss in this case can be calculated by:

$$PL = PL_b + PL_{tw} + PL_{in}$$

$$PL_b = PL_{B1}(d_{out} + d_{in})$$

$$PL_{tw} = 14 + 15(1 - \cos(\theta))^2$$

$$PL_{in} = 0.5d_{in}$$

where PL_{B1} is the B1 path loss, d_{out} is the distance from the ABS to the penetration point on the wall, and d_{in} is the distance from that point to the mobile terminal. θ is the angle between the wall and the wireless link.

Glossary

ABS	Access Base Station
BMWi	Federal Ministry of Economics and Technology
BP	Blocking Probability
BuNGee	Beyond Next Generation Mobile Broadband Systems
CDF	Cumulative Distribution Function
COMGREEN	Communicate Green
CR	Cognitive Radio
CROSSFIRE	UnCooRdinated network StrategieS for enhanced interference, mobility, radio Resource, and Energy saving management in LTE-Advanced networks
CQ-CCR	Controllable Quality Clustering Capability Rating
DAS	Distributed Antenna Systems
DC	Direct Current
DPD	Digital Predistortion
EARTH	Energy Aware Radio and Network Technologies
ECONET	Low Energy Consumption NETworks
EPSEC	Engineering and Physical Sciences Research Council
EU	European Union
GHG	Greenhouse gas
GSM	Global System for Mobile Communications
GoS	Grade of Service
HAP	High Altitude Platform
HBS	Hub Base Station

ICT	Information and Communication Technology
ITN	Initial Training Network
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MITN	Multi-Partner Initial Training Network
MDP	Markov Decision Process
MS	Mobile Subscriber
NCCR	Normalized Clustering Capability Rating
Ofcom	Office of Communications
OPERA-Net	Optimizing Power Efficient in mobile Radio Networks
OPEX	Operational Expenditure
PA	Power Amplifier
PANAMA	Power Amplifiers aNd Antennas for Mobile Applications
PC	Protection Channel
PSD	Power Spectral Density
PSR	Power Spectrum Reuse
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
SINR	Signal to Interference plus Noise Ratio
TANGO	Traffic Aware Network planning and Green Operation
TM	Topology Management
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

WWAN	Wireless Wide Area Network

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