DEVELOPMENT OF A DATA RATE-BASED SLEEP MODE ALGORITHM FOR ENERGY SAVINGS IN AN LTE HETEROGENEOUS NETWORK FOR A PICO eNodeB CELL

BY

Abubakar Sadiq AHMED, B. ENG. (UNIMAID) 2010

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DECLARATION

I declare that the work in this dissertation entitled “Development of a Data Rate-based Sleep Mode Algorithm for Energy Savings in an LTE Heterogeneous Network for a Pico eNodeB Cell” has been carried out by me in the Department of Electrical and Computer Engineering. The information derived from literature has been duly acknowledgedin the text and a list of referencesprovided.No part of this dissertation has been previously presented for another degree or diploma at this or any other Institution.

Abubakar Sadiq AHMED _____ _____

(Student) Signature Date

CERTIFICATION

This dissertation entitled "**DEVELOPMENT OF A DATA RATE-BASED SLEEP MODE ALGORITHM FOR ENERGY SAVINGS IN AN LTEHETEROGENEOUS NETWORK FOR A PICO eNodeB CELL**" by AbubakarSadiqAHMED meets the regulations governing the award of degree of Master of Science (M.Sc.) in Telecommunications Engineering of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

(Dr. K. A. Abubilal) _____ _____

Chairman, Supervisory Committee Signature Date

(Dr. S. M. Sani) _____ _____

Member, Supervisory CommitteeSignature Date

(Dr. Y. Jibril) _____ _____

Head of Department Signature Date

(Prof. S. Z. Abubakar) _____ _____

Dean, School of Postgraduate Studies Signature Date

DEDICATION

This research work is dedicated to my beloved parents, Alh. Ahmed Mohammed Kabir and Mrs. MadinaAbdullahi.

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ABSTRACT

There are several energy saving algorithms proposed to save energy in heterogeneous networks, but most of these algorithms achieved energy savings at the expense of service provisioning. Base stations significantly contribute to power consumption in cellular networks. This research work presented a Data Rate-Based Sleep Mode Algorithm for energy savings for a pico evolved NodeB (eNodeB) cell in aLong Term Evolution (LTE) heterogeneous network (HetNet). The algorithm was able to track traffic situations and estimate user data rate and energy consumption in the heterogeneous network. The algorithm switched the operating state of some pico eNodeB cells to sleep mode (inactive state) at low (less than or equal to 10 user equipment per macro area coverage)and medium traffic (greater than 10 user equipment per macro area coverage) during which the users are offloaded to other pico eNodeB and macro eNodeB cells to save overall energy consumption in the network. As traffic increased (greater than 10) and the average user data rate of the overall network reduced (less than 2Mbps), the pico eNodeB cells woke up (active state) to ensure service delivery was not obstructed. The work considers temporal fluctuations of traffic with a view to achieving higher energy savings. The traffic model, data rate model, and a powerconsumption modelare developed to implement the sleep mode algorithm. The developed sleep mode algorithm is implemented in Matrix Laboratory (MATLAB) R2013a. The developed algorithm was compared with the relevant specification of the 3rdGeneration Partnership Project (3GPP) Always-on scheme. The results showthat the developed sleep mode algorithm achieved an improvement of up to 75% and 50% in terms of energy savings for the pico eNodeB cells at low and medium traffic, respectively. For the overall HetNet, the improvements of 9.28% and 6.19% were achieved for low and medium traffic, respectively. The improvements of 9.45% and 6.30% are achieved in terms of the energy efficiency in 3GPP HetNet Configuration 4b for low and medium traffic while the improvement of 9.45% and 6.22% are achieved in 3GPP HetNet Configuration 1while guaranteeing a good service delivery.

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LIST OF ABBREVIATIONS/ACRONYMS

Acronym	Definition
3GPP	3rd Generation Partnership Project
AC	Alternating Current
BLER	Block Error Rate
Conf1	Configuration 1
Conf4b	Configuration 4b
COMP	Coordinated multipoint transmission/reception
CQI	Channel Quality indicator
CSI	Channel State Indicator
DC	Direct Current
DL	Downlink
EE	Energy Efficiency
eNodeB	evolved NodeB
eNB	eNodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved Universal Terrestrial Access Network
FPGA	Field Programmable Gate Array
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate
GSM	Global System for Mobile communications
HetNet	Heterogeneous Network
HSPA	High Speed Packet Access
ICI	Inter Cell Interference
IMT-A	International Mobile Telecommunications-Advanced
ITU-R	International Telecommunication Union-Radio aspect
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced

LIST OF ABBREVIATIONS/ACRONYMS (CONT'D.)

LPN	Low Power Node
MATLAB	Matrix Laboratory
MBR	Maximum Bit Rate
MCS	Modulation and Coding Scheme
MeNB	Macro eNB
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
NRB	Number of Resource Blocks
PeNB	Pico eNB
Pci	Power Consumption
QoS	Quality of Service
R	Data Rate
RTotalUE	Data Rate all UE
RAT	Radio Access Technology
RB	Resource Block
RF	Radio Frequency
RMUE	Data Rate Macro UE
RPUE	Data Rate Pico UE
SAE	System Architecture Evolution
SINR	Signal to Interference and Noise Ratio
SON	Self Organizing Network
TBS	Transmission Block Size
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
WiFi	Wireless Fidelity
VoIP	Voice over Internet Protocol

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

During the last decade, there has been a tremendous growth in cellular networks market. The number of subscribers and the demand for cellular traffic has increased.Hence, the mobile operators find meeting these new demands in wireless cellular networks inevitable, while they save to keep their costs minimum (Hasan *et al.*, 2011).In a wireless network, base stations (BSs) consume about two-third of total network power consumption and are logically responsible for 70% of CO_2 emission from the entire network. For this reason, management of energy consumption of wireless base station has become an essential topic of discussion in the research society (Tun&Kunavut, 2014).

Figure 1.1 shows a chart of the power consumption of various components of a base station. The power supply consumes less with about 7.5%. The essence of the Air conditioning is to provide site cooling which takes up to 17.5% while signal processing

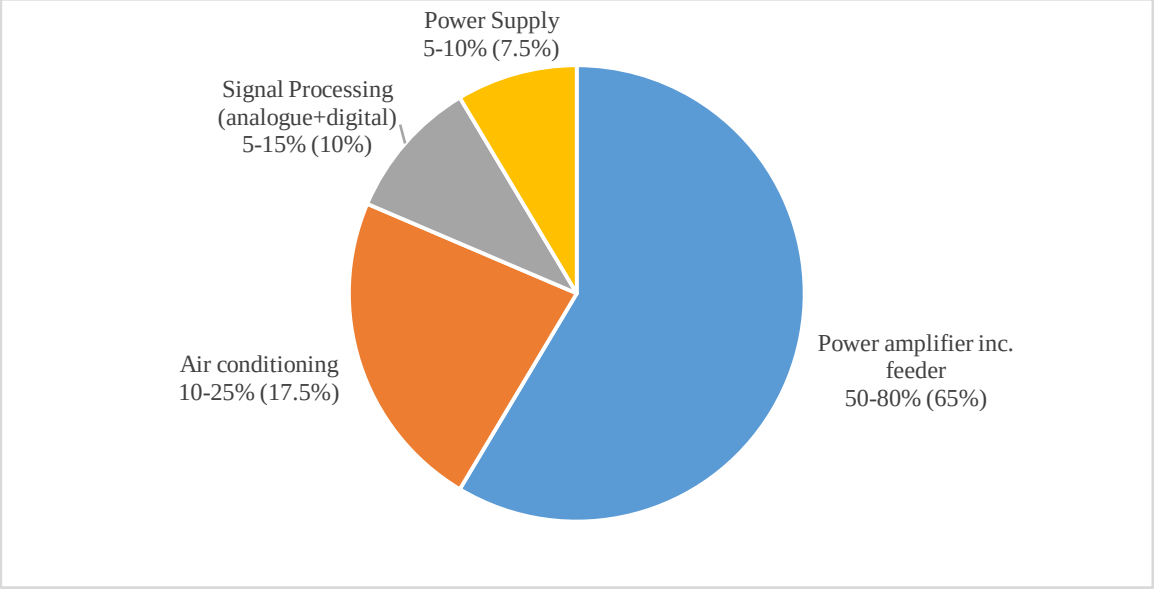


Figure 1.1:Power Consumption Distribution in Radio Base Stations (Correia*et al.,* 2010)

contributes about 10% of the power consumption. The power amplifier including feeder losses consumes about 65% which is highest amongst the components of the base station.

In each cell, the base station transmits common control signals and data signals to mobile users (MU), and the cell size is defined as the area in which the MUs can receive control signals from the BS. Cell size and capacity are generally static at the phase of network planning based on estimation of peak traffic load. Significant spatial and temporal fluctuations exist due to user mobility. To save energy of the whole network, the phenomenon of traffic load fluctuation implies that some base stations can be switched off when the traffic load is light (Zhinsheng *et al.*, 2010).

Figure 1.2 shows atypical load profile across one week, which clearly exhibits significant spatial and temporal fluctuations. During either low or no traffic periods i.e., early mornings or daytime in residential areas when loads are small, many base stations are underutilized, but still consume significant amount of energy.The base stations are underutilized at night and weekends. Thus, the traffic volume of the night time is much lower than that of the daytime (Alam *et al.,* 2012).

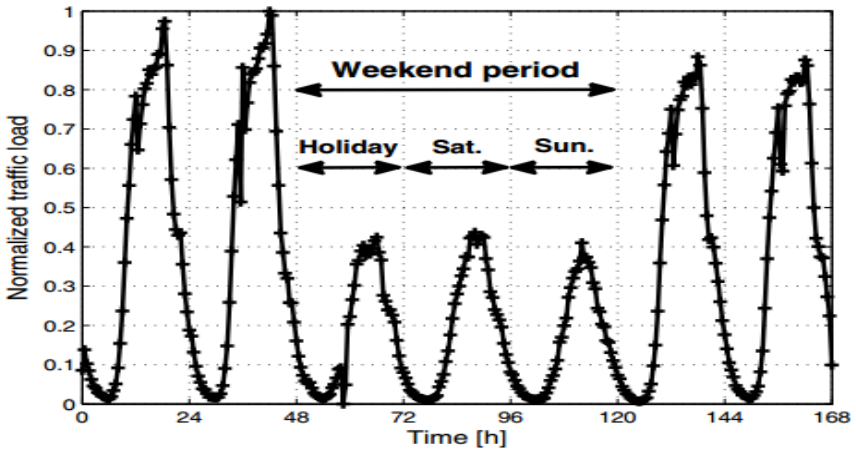


Figure1.2: Normalized Real Traffic Load during One Week Captured by a Cellular Operator(Oh *et al.*, 2010)

Heterogeneous network is one of the key technologies to reduce energy consumption in a cellular network where the cell size is diversified (Xu*et al.,* 2013).Heterogeneous Network (HetNet) could

mean a network comprising of different Radio Access Technologies (RATs) such as Wireless-Fidelity (WiFi), Global Systems for Mobile Communications (GSM), Universal Mobile Telecommunications System/High Speed Packet Access (UMTS/HSPA), Long Term Evolution (Advanced) (LTE/LTE-A) (Zhang, 2012). HetNets are multi-tier radio access networks in which micro and/or pico/femto cells are overlaying the macros as shown in Figure 1.3. Macro base stations are used as a baseline and provide uniform coverage of about 500m-35km and transmit power of 20W-40W (46dBm) (Zhang, 2012). Micro and pico/femto (often also referred to as small) cells are equipped with low power base stations which are deployed in hotspots to increase capacity, or in dead spots unreachable by macro base stations in order to increase coverage.The coverage area is about 40m and 20m for pico and femto cells respectively(Dini *et al.,* 2013).

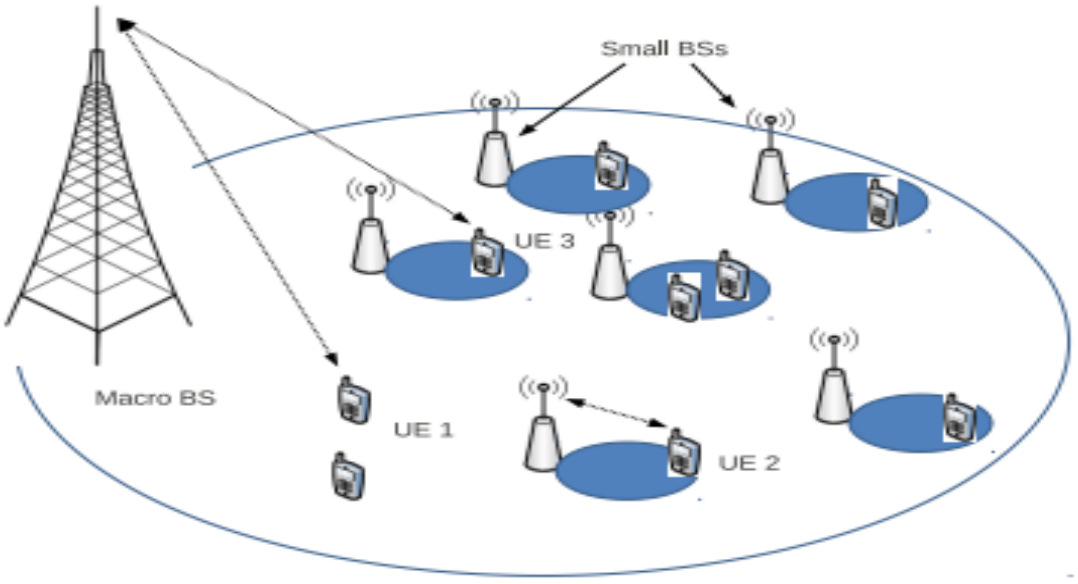


Figure1.3:HetNet Scenario with Macro Cell and Small Cells (Dini *et al.,* 2013)

HetNets are considered as an integral part of future generation wireless networks where multiple low power, low cost small cell (e.g. femtocells, picocell) base stations (SBSs) are deployed to complement the macrocell networks. HetNets are proposed to increase the data rates and capacity to the residential areas by reducing traffic from the macrocell network (Ekti *et al.,* 2013).

A picocell is a cell in a mobile phone network served by a low power (250mW(24dBm)-1W(30dBm)transmit powerand total power consumption of about 43 Watts) cellular base station that covers a small area (40m – 200m radius) with dense traffic such as a shopping mall, residential areas, a hotel or a train station. Femtocells are designed to serve much smaller areas (less than 40m) such as private homes or indoor areas (Hasan *et al.,* 2011).

Macro BSs are deployed outdoor, normally above the rooftop level. On the other hand, small base stations are normally deployed below the rooftop level; i.e. for outdoor, they are often placed over lampposts or street furniture, and for indoor they are typically installed by the end-users in residential or enterprise settings. HetNets are more energy efficient than macro-only deployment of the same capacity, due to low power consumption of the small cells. Hence, the use of HetNets instead of macro BSs alone will achieve some energy savings (Dini *et al.,* 2013).

Figure 1.4 shows HetNets with different deployment scenarios comprising macro-femtocell, macro-picocell, and macro-microcell with their coverage areas. The femtocells are deployed indoors.

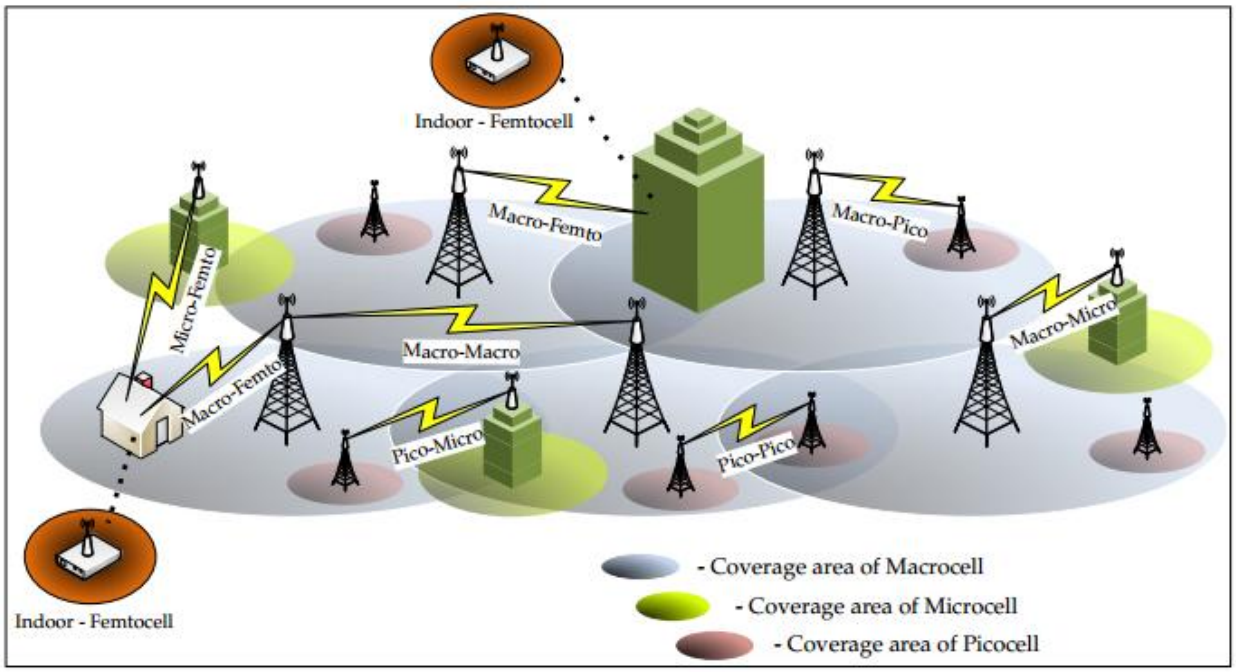


Figure 1.4: Heterogeneous Networks (HetNets) (Hasan *et al.,* 2011)

Small cell base stations that form an overlay layer on the existing macrocell network offer tremendous potential in terms of satisfying high data rate traffic requirements. However, small cell deployments can pose negative energy-efficiency implications if not equipped with advanced power saving mechanisms (Ashraf *et al.*, 2010).

1.2 STATEMENT OF RESEARCH PROBLEM

There has been poor energy savings in pico eNodeB HetNets which has resulted to poor service delivery in such networks. Base station sleep mode is an indispensable part of green network technology providing significant energy savings in the overall network. Most existing sleep mode algorithms achieved energy savings without considering average user data rate and this may bring about poor service delivery. The developed algorithm will introduce a more realistic energy saving scheme through the development of a data rate-based sleep mode algorithm. The developed scheme will adopt the realisticaverage user/subscriber data rate of 2Mbps (Motorola White Paper,

2009) as a metric for pico eNodeB sleep mode to improve energy savings at low and medium traffic.

1.3 AIM AND OBJECTIVES

The aim of this research work is to improve energy savings in heterogeneous networks through the use ofdata rate-based pico eNodeB sleep mode.

The objectives of this research are to:

i. Adopt the traffic model of Ambrosy *et al*., (2012), user data rate model of Khirallah*et al*., (2014) and HetNet power consumption model of Richter *et al*., (2009).

ii. Develop abase station data rate-based sleep mode algorithm for pico cells in a HetNet using Matrix Laboratory (MATLAB) R2013a software.

iii. Validate the developed algorithm in terms of energy savings and energy efficiencythrough simulations, by comparing with thestandard 3rd Generation Partnership Project(3GPP) always-on scheme.

1.4 SIGNIFICANCE OF RESEARCH

This research work proposed a sleep mode algorithm for pico eNodeB cells in HetNet. The algorithm coulddynamically switch the operating mode of a pico eNodeB to sleep/active mode using average user data rate as a metric. The algorithm could improve energy savings and energy efficiency for low and medium traffic load when compared with the 3GPP always-on scheme in LTE HetNet respectively.This improvement is reduction in network power consumption leading to a reduction in operational cost.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Several literature were reviewed to carry out this research. The review of literature is categorized into two parts, namely: Review of fundamental concepts and Review of similar works.

2.2 REVIEW OF FUNDAMENTAL CONCEPTS

In this section,fundamental concepts relevant to the proposed research workare reviewed. These include: LTE Network Architecture, Quality of Service (QoS) and Evolved Packet System (EPS) bearers, power consumption in base stations, energy saving in base stations, heterogeneous networks for LTE-Advanced, 3GPP heterogeneous network topologies,base station sleep mode algorithms.

2.2.1 LTE Network Architecture

The Long Term Evolution (Long Term Evolution) encompasses the evolution of the Universal Mobile Telecommunications radio access through Evolved UTRAN. It is accompanied by an evolution of the non-radio aspects under the term System Architecture Evolution (SAE) which includes the Evolved Packet Core (EPC) network. Together LTE and SAE comprise the Evolved Packet System (EPS).

The access network of LTE, E-UTRAN, simply consists of a network of eNodeBs as illustrated in Figure 2.1. For normal user traffic (as opposed to broadcast), there is no centralized controller in E-UTRAN; hence the E-UTRAN architecture is said to be flat.

The eNodeBs are normally connectedwith each other by means of an interface known as “X2” and to the EPC by means of “S1” interface; more specifically to the Mobility ManagementEntity (MME) by means of S1-MME interface and to the Serving Gateway (S-GW) by means of S1-U interface(“LTE Alcatel White Paper: The LTE Network Architecture, Strategic White Paper, 2009”).

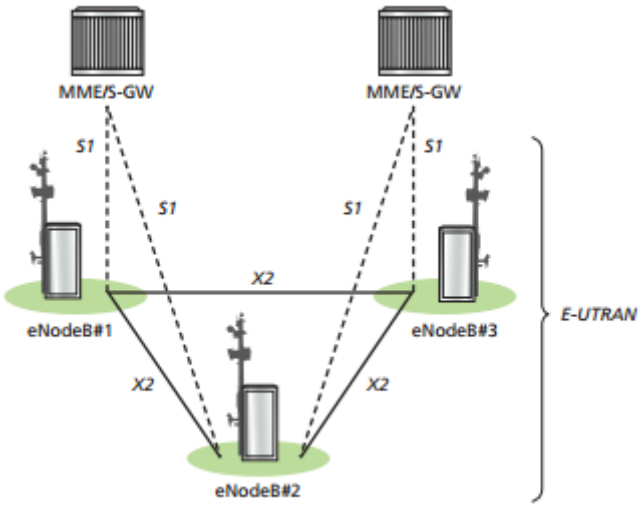


Figure 2.1: Overall E-UTRAN Architecture (LTE Alcatel White Paper, 2009)

2.2.2 QoS and EPS Bearers

Multiple applications maybe running in a UE at any time, each one having different QoS requirements. Voice over IP (VoIP) has more stringent requirements in terms of delay and delay jitter than web browsing and File Transfer Protocol (FTP), while the latter requires a much lower packet loss rate. In order to support multiple QoS requirements, different bearers are setup within the Evolved Packet System each being associated with a quality of service.

Bearers are classified into two categories based on the QoS which they provide:

i. Minimum Guaranteed Bit Rate (GBR) bearers that can be used for applications such as VoIP. These have an associated GBR value for which dedicated transmission

resources are allocated at bearer establishment or modification. Bit rates higher than the GBR may be allowed for a GBR bearer if resources are available. In such cases, a Maximum Bit Rate (MBR) parameter, which can also be associated with a GBR bearer, sets an upper limit on the bit rate that can be expected from the GBR bearer.

ii. Non-GBR bearers that do not guarantee any particular bit rate. These can be used for applications such as web browser or FTP transfer. For these bearers, no bandwidth resources are allocated permanently to the bearer ("LTE Alcatel White Paper: The LTE Network Architecture, Strategic White Paper", 2009).

2.2.3 Power Consumption in Base Stations

Amacrocell base station consists of six power-consuming components as discussed hereunder (Deruyck, *et al.,* 2012):

i. **Rectifier**: converts alternating current (AC) to direct current (DC), also known as the AC-DC converter.

ii. **Digital signal processing**: is concerned with the conversion of the signal to a sequence of bits or symbols and the processing of these signals.

iii. **Transceiver**: is responsible for transmitting and receiving the signals.

iv. **Power amplifier**: converts the DC input power into a significant radio-frequency (RF) signal.

v. **Air conditioning**: regulates the temperature in the base station cabin.

vi. **Microwave link**: is responsible for the communication with the backhaul network (sometimes replaced by a fiber link).

The total power consumption of the base station is a sum of the power consumption of all the above named components. The power consumption of these components should be multiplied by

their number of occurrences to determine the base station power consumption. Some of the components depend on the number of sectors,n_{sector} and the number of transmitting antennas, n_{Tx}.The n_{sector} determines the number of rectifiers, digital signal processing, transceivers and power amplifiers. Each sector requires one rectifier, one digital signal processing unit, one transceiver and one power amplifier. Therefore, the power consumption of these components should be multiplied by n_{sector}.The n_{Tx} determines the number of transceivers and power amplifier. For each transmitting antenna, one transceiver and one power amplifier are needed. This means that the power consumption of the transceiver and the power amplifier should not only be multiplied by n_{sector} but also by the number of transmitting antennas n_{Tx}. Taken this into account, the power consumption per macrocell base station for High Speed Packet Access (HSPA)and LTE (Advanced) is upto about1672.6W(Deruyck, *et al.,* 2012).

The same components used for a macrocell base station are used for a microcell base station except for the backhauling. The backhauling of a microcell base station is typically established through the overlaying macrocell base station. A microcell base station supports only one sector covered by one antenna.This results in a power consumption of 376.6W per microcell base station.The size of a femtocell base station is much smaller than that of a macrocell and microcell base station and is comparable to that of a WiFi access point. Therefore, the power consuming components are different from those of a macrocell and microcell base station. The femtocell base station consists of a microprocessor, a transceiver and a power amplifier. Taking into account the values shown in Table 2.1, femtocell base station power consumption is 12W per base station. Similarly, the power consumption breakdown for some of the components of a picocell base station is shown in Table 2.1 (Auer *et al*., 2012). It doesn't represent the total power consumption of a picocell.

Table 2.1: Power Consumption of the Components of the Different Base Station Types(Deruyck *et al.,* 2012)& (Auer *et al*., 2012)

Component	Macrocell Base Station (W)	Microcell Base Station (W)	Picocell Base Station	Femtocell Base Station (W)
Digital signal processing	100	100	3.0	7.9
Power Amplifier	24.7, 156.3	16.6	1.9	2.4
Transceiver	100	100	1.0	1.8
Rectifier	100	100	1.0	-
Air Conditioning	225	60	-	-
Microwave Link	80	-	-	-

2.2.4 Energy Saving in Base Stations

As a result of rapidly growing demand for mobile communication technology, the number of worldwide cellular base stations has increased from a few hundred thousand to many millions within the last 15 years. Such a number of generators that power a base station in a cellular network accounts for the sudden increase in gas emissions, in addition to higher energy costs to operate them. Power consumption for each base stationis about 1400 watts and energy cost per BS is about $3200 per annum with a carbon emission of 11 tons of CO_2. The radio network itself adds up to 80% of the total network energy consumption. Therefore BS equipment manufacturers have begun to offer a number of eco-friendly solutions to reduce power demands of base stations. A typical cellular network consists of three main elements; a core network that takes care of switching, base stations providing radio frequency interface, and mobile terminals for making voice or data connections (Hasan *et al.,* 2011).

There are different ways to reduce energy consumption in base stations, such as (Ekti *et al.,* 2013):

i. Employing power saving protocols such as base station sleeping which enables an inactive operation mode for base stations under load conditions.

ii. Improved power amplifier technology which makes the hardware design of a typical basestation more energy efficient.

iii. Cell size adjustment schemes such as cell – breathing and cell – zooming where different cells adapt their size depending on the received interference or traffic load conditions.

iv. Deployment of relays (e.g. amplify – forward) improves the power reduction with reduced complexity, albeit at an increased cost for deployment of infrastructure.

2.2.5 Heterogeneous Networks for LTE – Advanced

LTE-A networks were developed to offer considerably high data rates than the existing 3rd Generation (3G) networks. In order to meet the requirements of LTE-A (e.g. peak data rates upto 1Gbps), more spectrum bands are needed. Besides the existing carriers for 3G networks, spectrum bands located at 450– 470 MHZ, 698–790 MHZ and 2.3–2.4 GHZ, and 3.4–3.6 GHZ can be used for the deployment of LTE and LTE-A networks. LTE-A has been designed to support scalable carrier bandwidth exceeding 20 MHZ, potentially up to 100 MHZ. The LTE-A consists of eNodeBs that are interconnected with each other by means of X2 interface. The eNodeBs are connected through the S1 interface to thecore network (Zhang *et al*., 2014).

Network coverage and high data rate requirements in hotspot and indoor environments have brought new challenges to LTE systems. In order to improve the system capacity and energy efficiency for hotspot and indoor environments, HetNets and their enhancements have been proposed.The architecture of a HetNet for an LTE-A system is shown in Figure 2.2. Among the different technologies that have been proposed and studied in 3GPP HetNet, small cell (pico cell)

enhancement is one of the major techniques. The benefits of using pico cell enhancements include (Zhang *et al*., 2014):

i. Flexible pico cell deployment according to users and traffic distributions.

ii. Optimized pico cell mobility by reducing Radio Access Network (RAN) to core network signaling.

iii. Increased data rates by using macro and pico cells together.

iv. Energy saving by using dynamic pico cell sleeping.

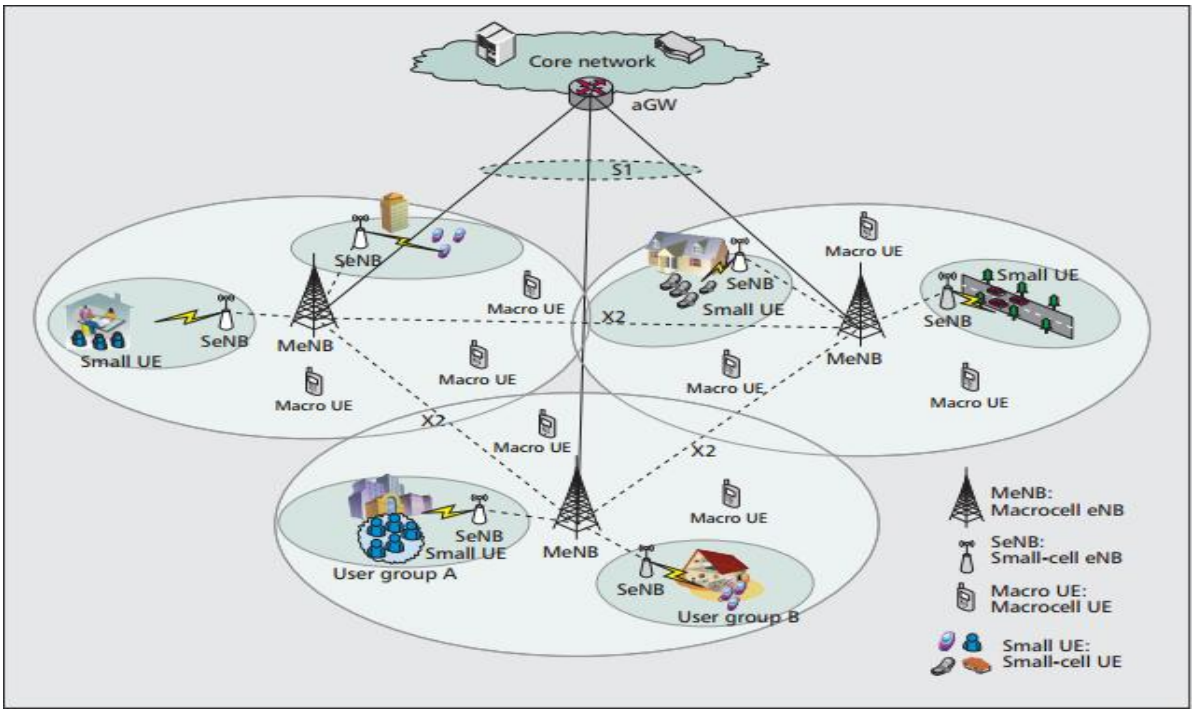


Figure 2.2: Architecture of HetNet for LTE-Advanced Systems (Zhang *et al*., 2014)

Under the coverage of one Macro eNodeB there are several hotspot areas (e.g. offices, shops and classrooms). Several small cells are deployed dynamically according to certain criteria (e.g. spectral efficiency, energy efficiency).The users (both macro UE and pico UE) and their traffic volume will be heterogeneously distributed and exhibit a convergent pattern in both the temporal and spatial domains. Under this condition, these small cells can be managed smartly. Many network

configurations can be determined based on users' characteristics (e.g. the optimal density of pico cells, sleeping mode control for pico cells, homogeneous/heterogeneous coordinated multipoint, and the coordination of macro and pico cells)(Zhang *et al*., 2014).

2.2.6 3GPP Heterogeneous Network Topologies

Two heterogeneous network topologies are supported in the LTE system level simulator toolbox developed by Wireless Systems Research Lab, Hitachi America Ltd. Thesetopologies are in line with the standard 3GPP specifications that are widely used in industrial simulations. They are used for evaluating performance metrics such as coupling loss (link gain) and geometry (received SINR) distributions (Acharya *et al* 2014). The heterogeneous network scenarios as specified by3GPP (TR 36.814 V9.0.0, 3GPP 2010) are as follows:

i. **HetNet Configuration 1**: 3GPP specified HetNet Configuration 1 as shown in Appendix E. (Acharya *et al* 2014) implemented the configuration in the system level simulator toolbox in MATLAB to illustrate the pictorial representation of the topology. In this configuration, small cells (Pico eNodeB cells)are overlaid in the macro coverage area with uniform density. The macro and small cells serve both indoor and outdoor users that are uniformly located in the macro coverage area as shown in Figure 2.3.

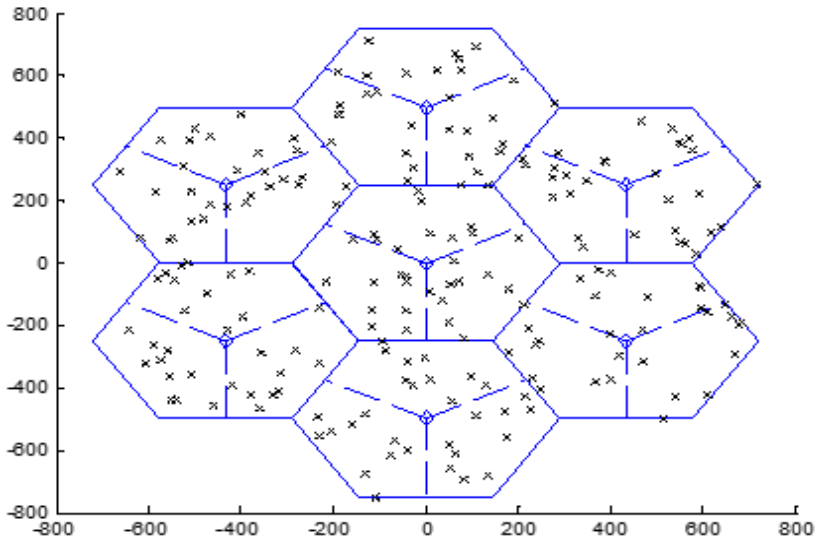


Figure 2.3: Schematic Diagram of HetNet Configuration 1 (Acharya *et al*., 2014)

ii. **HetNet Configuration 4b**: 3GPP specified this configuration and was implemented in the system level simulator toolbox in MATLAB by (Acharya *et al*., 2014). Itcomprises urban area with small cells overlaid in macro coverage area with uniform density. The macro and small cells serve both indoor and outdoor users, a fraction of whom are clustered around the Pico eNodeB cells modeling a hot-spot scenario as shown in Figure 2.4.

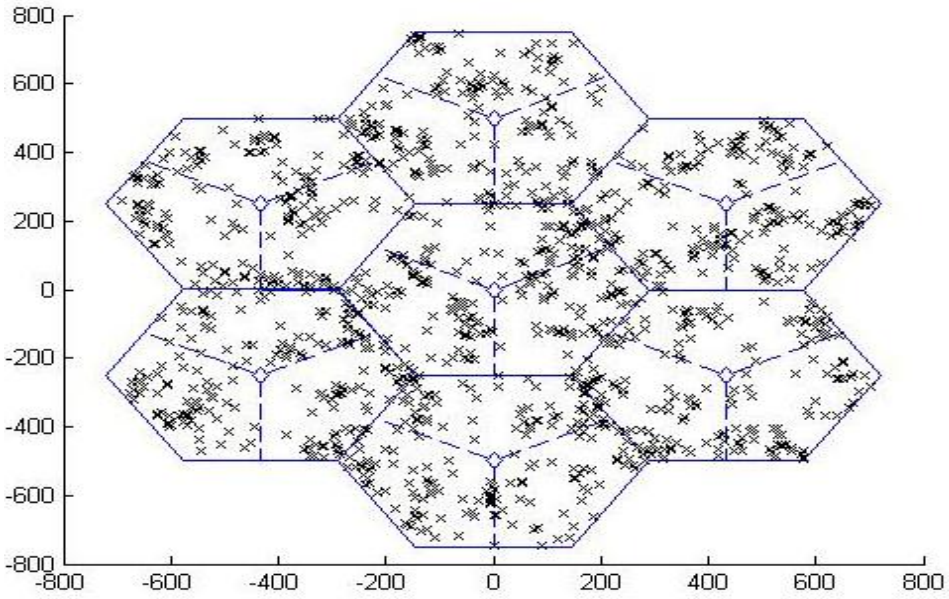


Figure 2.4: Schematic Diagram of HetNet Configuration 4b (Acharya *et al* 2014)

2.2.7 Base Station Sleep Mode Algorithms

Whenever a base station is working in sleep mode, the other energy consuming equipment such as air-conditioner have to be switched off. The energy consumption of cellular network can be largely reduced when the base station is sleeping. However, in such a case the cell with base station working in sleep mode will be zoomed in to 0 and its neighbouring cell will zoom out to guarantee coverage (Gundawar *et al.,* 2015).

The idea of sleep mode activation in pico base stations is the introduction of a low-power state in the hardware, referred to as the SLEEP state. According to Ashraf *et al.,* (2011), pico cells are in one of the following states at any given time;

i. **READY state (RE)**: In this state, all hardware components in the pico base station are fully switched on. This can also be referred to as the ACTIVE state.
ii. **SLEEP state (SL)**: In this state, some of the hardware components in the pico cells are either completely switched off or operated in low-power modes. The base station is correspondingly said to be in SLEEP mode. The exact components to be switched off are a function of the specific hardware architecture and the particular energy saving algorithm. During SLEEP mode, it is assumed that the power consumption is 0 W.

In order to enable transition of pico cells between RE and SL, three sleep mode algorithms were introduced, namely: Small cell controlled, core network controlled and user equipment (UE) controlled. These are explained below (Ashraf *et al.,* 2011):

i. **Small Cell Controlled Sleep Mode**: The pico cell hardware is equipped with a low-power capability that allows the detection of an active call from a UE.If UE is

close enough to be potentially covered by a pico cell based on the received signal strength, the pico cell switches to the RE state.The pico cell transitions to SLEEP state when no active calls are being made by the UE in its coverage area.

ii. **Core Network Controlled Sleep Mode**: The transition of pico cells from SL to RE state is controlled by the core network via the backhaul using a wake-up control message. The pico cell base stations are configured to reside in the SL state by default and move to the RE state.

iii. **UE Controlled Sleep Mode**: The SLEEP mode control is at the UE side, which can broadcast wake-up signals in order to wake up pico cell base stations within its range. The pico cell transitions to RE state whenever it receives wake-up signal transmissions from the UE. The UE broadcasts periodic wake-up signals in the absence of sufficient macrocell coverage (Ashraf *et al.*, 2011).

The power consumption from pico cell base stations is calculated according to Ashraf *et al.,* (2011) as expressed equation (2.1):

$$P_{pico} = \eta_{pico,RE} \cdot P_{pico,RE} + \eta_{pico,SL} \cdot P_{pico,SL} \quad (2.1)$$

where: $\eta_{pico,RE}$ and $\eta_{pico,SL}$ represent the average number of picocells in RE state and SL state, respectively, $P_{pico,RE}$ and $P_{pico,SL}$ denote the picocell power consumption in RE and SL states respectively.

The total energy consumption per annum (= 8760 h)of the network $E_{network}$, can be written according to Ashraf *et al.,* (2011) as expressed in equation (2.2):

$$E_{network} = \left(\eta_{macro} \cdot P_{macro} + \eta_{pico} \cdot P_{pico}\right) \cdot 8760 \quad (2.2)$$

where: η_{macro} and η_{pico} denote the number of macrocell and picocells respectively. P_{macro} and P_{pico} are the macro and pico power consumptions respectively.

2.3 REVIEW OF SIMILAR WORKS

Base station sleep mode and HetNethas been an active research topic over the years and different techniques have been presented for solving this problem.Many researchers worked on these areas including those critically reviewed below:

Arshad *et al.,* (2012)presented a power consumption model of a macro-pico HetNet incorporating sleep mode.They considered two different base stations, namely:concentrated and distributed. The power consumption model of the concentrated and distributed base stations consisted of a static part, a dynamic load dependent part, and the backhaul power consumption.Path loss and slow fading were considered as factors deteriorating the signal quality. Simulation results showed that at limited pico base station resource utilization, the pico base station showed around 9% power saving for concentrated base station during busy hour, but the average power saving over a day was marginal, around 1%. Sleep mode in pico base station during low traffic hours reduced the power lost by almost 50%. Similarly, the number of hotspots and the user distribution in hotspots hadimpacted on energy savings.Their results showed that if all pico base stations' resources were utilized, upto 80% reduction in energy per bit could be achieved.The effect of average user data rate was not considered which could have significant effect on service provisioning.

Dini *et al.,* (2013)presented a model to analyze the energy consumption of LTE HetNets considering two different types of base stations comprising a radio access network (macro and micro) and their different radio resource utilizations. They considered that energy consumed by macro cell is not constant but rather variable with the traffic load while power consumption of

micro base stations is constant.Two sleep mode algorithms were developed namely; single sleep and multiple sleep to determine the time instant that will enable micro or pico base stations' sleep mode. Single sleep-mode algorithm scheduleda single event to put to sleep the entire small base stations whereas the multiple sleep algorithmdefines the time instant at which each single micro base station was put to sleep.Their results showed energy savings ofup to about 10% when sleep modewas enabled depending on system capacity.However, by assuming constant macro base station power consumption, higher energy savings were achieved (up to 35% and 27% for macro and pico respectively). Their scheme only considered traffic load as a criteria for triggering the sleep mode,overlooking the effect of average user data rate which has greater impact on service provisioning.

Fu *et al.,* (2013)proposed two step allocation algorithms for a HetNet system to deploy multiple picostations and allocate transmission power thereby maximizing both the number of active picostations that can achieve the required capacity and the sum cell capacity under individual capacity constraints.Their scheme considered picostation interference. Simulation results demonstratedthat their algorithm performs better than the traditional cell capacity maximum scheme in terms of user fairness and energy saving. However, average user data rate was not consideredwhich has significant effect on service provisioning.

Abdulkafi *et al.,* (2013) proposed a theoretical model for evaluating the energy efficiency in HetNets. They considered different transmit powers, achievable data rate, coverage and energy efficiency for the base stations.Their model consists of a macro, micro and pico base stations. The cell radius for each type of base station was calculated by assuming coverage degree to be 95% by setting the transmit powers of macro, micro and pico to 46, 35 and 30dBm respectively. Their

simulation results show that picocell impacts energy efficiency in HetNet compared to microcell and certain ratios of microcells and picocells per macro BS will result in sub-optimal of Area energy efficiency where the picocell provides higher data rate than the macro and micro BSs. Again, the Area energy efficiency of HetNet increases as the density of microcell/picocells increases. However, they did not consider implementing a sleep mode algorithm resulting in energy wastage during low traffic times.

Ekti *et al.,* (2013)proposed a probabilistic traffic model in order to calculate the number of active microbase stations and thereby control the downlink power consumption of HetNets. Their model ensures that the downlink power consumption in HetNets is reduced by switching – off the microbase stations intelligently under low and medium traffic load conditions. They derived a mathematical model to calculate the required proportion of smallcells based on the probabilistic traffic models where the number of total mobile users and number of active mobile users have different traffic distributions such as different combinations of binomial and Poisson distributions.However, the probabilistic model only considered traffic load conditions ignoring theeffect of average user data rate and this may bring about poor service provisioning.

Xu *et al.,* (2013)presented an energy power management scheme designed for LTE femto cells using user and service classification, the proposed algorithm balances the network coverage, average data rate and energy consumption. Their scheme considers QoS of different types; VOIP, data and web services. The VOIPusers with the highest priorityhave a fixed data rate of 64kbps, the data rate requirement for data users is between (512-2000)kbps while the WEB users'requirement is maximized subject to power limit.However, the proposed work did not implement sleep mode which could provide better energy savings.

Oh *et al.,* (2013) proposed a distributed dynamic base station switch on/off algorithm. The algorithm turns off the base stations one by one taking into account the additional load

increments brought to its neighbouring base stations. The algorithm considered a fixed power consumption model.The energy savings were estimated through a first-order analysis. Their simulation results demonstrated that the algorithm can achieve significant energy savings up to 50-80% for a metropolitan area.However, average user data rate was not considered which may result in poor service provisioning.

He *et al.,* (2014)presented a combined coordinated multi-point (CoMP)transmission and base station sleeping scheme under the HetNets scenario. The proposed scheme adopted a stochastic geometric analysis (random spatial patterns) for evaluating the performance of the scheme rather than conventional hexagonal grid-based approach.CoMP was applied to avoid coverage holes when the required signal to interference and noise ratio could not be obtained. Their results showed that the combined CoMP and base station sleeping can improve the energy efficiency and increase coverage probability compared with implementing base station sleep mode only. However, their work did not consider average user data rate which is a metric for service provisioning.

Pourmoghadas & Poonacha, (2014) proposed a base station association algorithm which helps the HetNets base stations to direct the network in finding congested traffic areas, and also decide to stay awake or stay in stanby mode considering the downlink traffic in LTE. Their scheme simulates two tiers of HetNets; deployment of macro-micro base stations. The proposed work is based on controlling the micro base station by macro base station, based on the channel state information (CSI) of the channels and handover commands been exchangedin the network. Network traffic distribution was considered in three scenarios; low load, medium load and high load traffic. The number of online base stations was minimized therefore reducing energy requirements. Simulation results showed significant power saving improvement over the available algorithm for

HetNet deployments of Long Term Evolution Release–10.However, average user data rate was not considered which may bring about poor service provisioning.

Wu *et al.,* (2015)proposed two centralized algorithms namely; Heuristic Dynamic Switching Off(HDSO) and Progressive Dynamic Switching Off (PDSO), to dynamically switch off redundant pico base stations. Theyconsideredthe total rate of served pico user equipment, the pico base station's traffic load, the number of served pico user equipment, the number of blocked pico user equipment and the received interference signal strength from the nearby cells as factors to switch off the redundant pico base stations. The HDSO algorithm developed switches off the pico base stations one by one at each step. The PDSO was developed to overcome the inefficiency of the HDSO. A user equipment transferring algorithm was also developed to transfer the user equipment of the pico base stations which was switched off to the nearby pico base station. Simulation results showed that the execution time for the progressive algorithm was at most one third of that of the heuristic algorithm which enabled the network to respond to traffic variations more promptly. Similarly, the progressive algorithm can switch off more pico base stations than the heuristic algorithm while slightly affecting the network blocking probability, which indicates that the progressive algorithm has a better potential to save energy.However, the work considered a constant bit rate to represent user data rate which does not efficiently represent load condition.

Li *et al.,* (2015)proposed an iterative heuristic algorithm to jointly optimize the precoding, load balancing and base station operation modes (active or sleep) in HetNets.They assumed that all base stations are able to transmit to all users at the same time-frequency resource. The work also assumed imperfect channel state information at base stations and users. The work minimized the weighted power consumption of the system while satisfying a set of spectral efficiency constraints

for each user and a set of transmit power constraints for each base station. An iterative convex approximation of power consumption functions was used to tackle the problem. A convex objective function was updated each iteration, such that the most of the base stations with the small transmit powers in the solution are driven to sleep mode. Simulation results showed that the algorithm significantly reduced the total power consumption by putting a base station into sleep mode using proper load balancing, compared to the scheme where all base stations are continuously active. However the work did not consider the effect of average user data rate which has a significant effect on service provisioning.

Cai *et al.,* (2016)proposed a micro-cell dynamic operation scheme that changes the operating states (on and off) of micro base stations while keeping the macro base station on to avoid any service failure in heterogeneous networks. The work first considered that the wireless users are uniformly distributed in the network and developed an optimal location-based operation algorithm to decide the operation modes of the micro base stations according to their distances to the macro base stations to minimize the total HetNet power consumption. Secondly, the work then considered a more general case where users are non-uniformly distributed in the network and developed a location-and-density-based operation algorithm that provided a near-optimal solution to decide the micro base stations on/off states. Simulation results showed that the optimal location-based algorithm efficiently saved energy compared to two benchmark schemes; no micro base station on/off adaptation and probability-based micro base station adaptation. Simulation results also showed that the location-and-density-based algorithm achieved less than 1% performance loss as compared to the optimal one.However, the work did not consider the effect of average user data rate which has a greater impact on service delivery.

It is evident from the literature reviewed, that the use ofsleep mode inHetNets for energy saving has been given significant research attention.However, most of the reviewed work considered

base station transmit power, number of users, traffic load, and SINR. They did not consider the effect of average user data rate which may bring about poor service delivery.Therefore, there is a need to develop an average user data rate-based sleep mode algorithm for a pico eNodeB cell to ensure that service delivery is not disrupted.

CHAPTER THREE

MATERIALS AND METHODS

3.1 INTRODUCTION

This chapter describes the detailed procedure employed for the successful modeling and implementation of the; (i) traffic model, (ii) data rate model based on instantaneous channel conditions, (iii) power consumption model of the eNodeB and (iv) proposed sleep mode algorithm.

3.2 METHODOLOGY

The methodology adopted in carrying out this research work is as follows:

i. Adoption of the traffic model of Ambrosy *et al*., (2012) based on round robin resource allocation in LTE HetNet for fair sharing of resource blocks among users.

ii. Adoption of the data rate model of Khirallah *et al*., (2014)) based on Signal-to-Interference and Noise Ratio (SINR) mapping for link adaptation to accurately estimate individual user data rate

iii. Adoption of the power model of Richter *et al*., (2009) based on power consumption parameters to evaluate energy consumption in the eNodeB cell.

iv. Development of a sleep mode algorithm for pico eNodeB cells based on the average user data rate, traffic situations and energy consumption to save energy and achieve good service delivery (user data rate).

v. Implementation of all the models and the algorithm in (iv) in a Long Term Evolution system level simulator using MATLAB R2013a.

vi. Comparison and evaluation of the system level performance of the developed algorithm in terms of energy savings and energy efficiency improvement with the 3GPP Always-on scheme.

3.2.1 Traffic Model

Round robin resource allocation was used. The simulations were based on fair share scheduling of resources. Thus, all the available resources are scheduled among all the users and the users are utilizing all the allocated resources.In order to efficiently allocate equal number of resource blocks to users, theNumber of Resource Blocks (NRB) was divided by the number of UEin the eNodeB cell. Thus, the number of resource blocks allocated to a user at distance d from an eNodeBcell per transmission time interval according to Ambrosy *et al*., (2012) is expressed in equation (3.1).

$$\mathrm{NRB}(d) = \frac{\mathrm{NRB}\ /\mathrm{TTI}}{\mathrm{NumUEperCell}} \tag{3.1}$$

where:$\mathrm{NRB}(d)$is the number of resource blocks per eNodeB cell,$\mathrm{NumUEperCell}$ is the number of UE per eNodeB cell, TTI is the transmission time interval (1ms).

Therefore,substituting TTI(1ms) and the numberof UE per cell into equation (3.1),the number of resource blocks for aUEin a pico cell and a UE in a macro cell respectively is shown in equation (3.2) and (3.3) respectively.

$$\mathrm{NRB}_{\mathrm{Pico}}\ (x, y) = \frac{\mathrm{NRB}}{\mathrm{m}} \tag{3.2}$$

$$\mathrm{NRB}_{\mathrm{macro}}\ (x) = \frac{\mathrm{NRB}}{\mathrm{n}} \tag{3.3}$$

where: $x$hasvalues from 1 to the number of Macro eNodeB and y hasvalues from 1 to the number of pico eNodeB per macro cell, $\mathrm{NRB}_{\mathrm{Pico}}\ (x, y)$ is the resource block available to a user connected to a pico cell y in a macro cell x, $\mathrm{NRB}_{\mathrm{macro}}\ (x)$ is the resource block available to a user connected to a macro cell x, while m and n, are the number of users connected to pico cell y and macro cell x respectively.

In this research work, MATLAB was used as the simulation environment and therefore all the developed models are based on MATLAB codes. Thus, equations (3.1), (3.2) and (3.3) were used to

develop the traffic model to show how resource blocks are shared equally among the users in MATLAB as shown in the Appendix D.

3.2.2 Data Rate Model

The Data rate model was based on Signal-to-Interference and Noise Ratio (SINR) mapping for link adaptation to accurately estimate individual user data rate. Equation (3.4) gives the expression for the SINR which was adopted in this research work. For a UE placed at distance *d* from the eNodeB (eNB), the average Signal-to-Interference and Noise Ratio (SINR) at the UE is given according to Khirallah *et al.,*(2014) as equation (3.4).

$$SINR(d) = P_{TX} + G_{TX} + G_{RX} - N - I - SF(d) - PL(d) - PLN \qquad (3.4)$$

where:$P_{TX}$is the eNB transmission power (per cell sector); $G_{TX}$and$G_{RX}$are the eNB and UE antenna gains respectively.$N$and$I$are the noise and the inter-cell-interference (ICI) power from all the interfering eNBs at the UE location respectively.$PLN$is the wall penetration loss for signals received by indoor UE. Finally $PL(d)$and $SF(d)$are the path loss and shadow loss in dB respectively measured at different UE position (Khirallah *et al.,* 2014).

Link adaptation requires the selection of a proper Modulation and Coding Scheme (MCS) according to the channel quality which is usually indicated by the SINR reported by each UE(Wang, 2010). A physical Transmission Block Size (TBS) which depends on the modulation and coding schemeis selected by the Media Access Control (MAC) layer scheduler, based on the Channel Quality Indicator (CQI) reported by the UE after every Transmission Time interval (TTI) of 1ms. The physical transmission resource block represents a unit of time-frequency resources: 0.5ms time duration (half of TTI) and 12 subcarriers. The physical resource blocks are allocated in pairs, thus the physical TBS depends on the number of resource block (RB) pairs(Khirallah *et al.,* 2014).

In order to obtain the data rate$R(i)$ of a UE, the NRB and the TBS are required. The NRB was obtained using equations (3.2) or (3.3) depending on whether a UE is connected to a pico eNB or a

macro eNB cell. Obtaining the TBS of a UE depends on the SINR that a particular user equipment reports. The SINR was mapped to the corresponding TBS as discussed subsequently to determine the exact TBS for a UE.

Therefore, depending on the SINR (d) at the user equipment (UE) calculated using equation (3.4), and the intervals of CQI state, the data rate at the UE is expressed according toKhirallah *et al.,*(2014) by equation (3.5).

$$R(i) = \frac{TBS(i)\text{x}NRB(i)}{TTI}(1 - BLER(i)) \quad (3.5)$$

where $TBS(i)$ is the physical transmission block information capacity (in bits), and$BLER(i)$ is the average Block Error Rate (BLER) for the CQI state *i*, TTI is the transmission time interval and $NRB(i)$ is the number of resource blocks allocated to UE *i*.

Three modulation levels of QPSK, 16-QAM and 64-QAM are supported according to the LTE specification in 3GPP TR 36.213. Together with turbo coding there are 26 MCSs, this implies that there are 26 CQI. The SINR toTBS mapping for these MCSs, assuming a Block Error Rate (BLER) target of 10% was established using the following procedure. Firstly, the effective SINR of a UE was obtained and used in the system level simulator in MATLAB by substituting for $SINR(d)$obtained from equation (3.4) into equation (3.6) as;

$$SINR_{eff}(d) = \max\{SINR(d), SINR_{threshold}\} \quad (3.6)$$

where:$SINR_{eff}(d)$is the effective SINR of a UE for mapping to correspondingCQI andTBS.$SINR(d)$ is the SINR as a result of the UE's instantaneous channel conditions as in equation (3.4). And $SINR_{threshold}$ is the SINR value corresponding to the 26 MCSs level.

In order to efficiently map the SINR to the TBS(bits), when a UE reports a $SINR(d)$ equal to a SINR on Table (3.1), the UE is allocated the corresponding TBS(bit). When a UE reports a $SINR(d)$ value not corresponding to any exact SINR value in Table (3.1) but in between any two MCS levels, the user is allocated the higher MCS level getting the higher SINR. The SINR value which is finally allocated to the UE is the $SINR_{eff}\ (d)$ as shown in equation (3.6).

Using the SINR value allocated to the UE, the mapping of the SINR to TBS was obtained in the system level simulator in MATLAB substituting for $SINR_{eff}\ (d)$obtained from equation (3.6) into equation (3.7) as follows;

$$TBS(d) = TBS(SINR_{eff}\ (d)) \quad (3.7)$$

where: $TBS(d)$is the TBS in bits allocated to UE based on $SINR_{eff}\ (d)$ as in Table (3.1).

This implies that a UE is allocated the TBS(bits) corresponding to $SINR_{eff}\ (d)$ which was obtained from equation (3.6).The TBS (bits) in Table 3.1 was obtained as discussed below and mapped with the $SINR_{eff}\ (d)$ to calculate the data rate.

Table 3.1: Link Adaptation Table (Technical Report 36.814.v9.0.0, 3GPP 2010)

Modulation	Coding Rate	TBS (bits)	SINR threshold (dB) for 10% BLER
QPSK	1/5	67.20	-2.7
	¼	84.00	-1.3
	1/3	112.00	-0.8
	2/5	134.40	-0.2
	½	168.00	1.3
	3/5	201.60	2.7
	2/3	224.00	3.4
	¾	252.00	4.6
16-QAM	2/5	268.80	5.3
	9/20	302.40	6.2
	½	336.00	6.8
	11/20	369.60	7.8
	3/5	403.20	8.7
	2/3	448.00	9.3

	¾	504.00	10.7
	4/5	537.60	11.2
	5/6	560.00	12.2
64-QAM	3/5	604.80	13.6
	5/8	630.00	14.0
	2/3	672.00	14.5
	17/24	714.00	15.4
	¾	756.00	16.3
	4/5	806.40	16.8
	5/6	840.00	17.8
	7/8	882.00	18.8
	9/10	907.20	19.2

There are 7 symbols in a resource block (RB) and TTI of 0.5ms. For two resource block pairs the TTI is 1ms andthe number of subcarriers is 12. Hence the number of symbols in a resource block is equal to 12 multiplied by 7 which is 84 in TTI of 0.5ms, and 168 in TTI of 1ms for a resource block pair (Rathi *et al*., 2014). The Transmission Block Size (TBS) depends on the number of symbols in a resource block pair, modulation index (number of bits per symbol) and the coding rate.Therefore, the TBS (bits) was obtained as the modulation index multiplied by the coding rate multiplied by 168. The obtained TBS(bits), $\mathrm{NRB}_{\mathrm{Pico}}$ (x,y) and $\mathrm{NRB}_{\mathrm{macro}}$ (x) were substituted into equation (3.5) to compute the data rate of the connected UE. Therefore, the data rate for a UE connected to the macro cell and a pico cell wasobtained as shown in equation (3.8) and equation (3.9) respectively using equation (3.5).

$$R_{MUE} = \frac{TBS(i)\mathrm{x}NRB_{macro}}{TTI}(1 - BLER) \quad (3.8)$$

$$R_{PUE} = \frac{TBS(i)\mathrm{x}NRB_{Pico}}{TTI}(1 - BLER) \quad (3.9)$$

where:R_{MUE} and R_{PUE} are the data rate for a user equipment (UE) connected to the macro cell and pico cell respectively.$\mathrm{NRB}_{\mathrm{Pico}}\ (x, y)$ and $\mathrm{NRB}_{\mathrm{macr\ o}}(x)$ are the number of resource blocks for a pico UE and macro UE respectively.

In order to obtain the data rate of the overall HetNet, the data rate for all the UE connected to the pico cells and all the UE connected to the macro cell were summed. Therefore, the summations of the data rate for all the pico UE and the macro UE obtained using equations (3.8) and (3.9) were added to calculate the overall data rate of the HetNet as shown in equation (3.10).

$$R_{TotalUE} = \sum R_{MUE} + \sum R_{PUE} \quad (3.10)$$

where: $R_{TotalUE}$ is the total data rate in a macro area coverage, R_{MUE} is the data rate for a UE connected to the macro eNB and R_{PUE} is the data rate for a UE connected to the pico eNB cell.

Therefore, to obtain the average user data rate (realistic data rate of a user) of a single UE, the overall data rate of the HetNet was divided by the total number of user equipment. Thus, using equation (3.10) and the total number of users, the average user data rate was obtained as shown in equation (3.11) and (3.12) respectively.

$$Average\ UE\ Data\ Rate = \frac{R_{TotalUE}}{NumUE} \quad (3.11)$$

$$Average\ Macro\ Data\ Rate = \frac{R_{TotalUE}}{NumCell} \quad (3.12)$$

where: $NumUE$ the total number of UE and $NumCell$ is the total number of macro eNodeB.

The data rate model was implemented in the system level simulator in MATLAB using equations (3.4) to (3.12) to create the codes shown in the Appendix D. The average user data rate was used as the metric for changing the operating state (active or sleep) of the pico eNodeB cells.

3.2.3 Power Consumption Model

To obtain the base station power consumption, the power consumption equation for a base station according to Richter *et al*. (2009) was adopted and expressed by equation (3.13).

$$Pc_i = N_{sec}\, N_{ant}\, (A_i P_{TX} + B_i) \quad (3.13)$$

where: N_{sec} and N_{ant} denote the number of sectors of the eNBs and the number of antennas persector, respectively.$Pc_i$is the average total power per base station in Watts and $P_{TX}$is the power fed to the antenna. The coefficient $A_i$accounts for the part of the power consumption that is proportional to the transmitted power, which includes radio frequency amplifier power and feeder losses. While $B_i$denotes the power that is consumedindependent of the average transmit power which include signal processing and site cooling (Abdulkafi *et a*l., 2013). The values for A_i and B_i are given in Table 3.2.

Table 3.2: Power Consumption Parameters (Abdulkafi *et al.* 2013)

Base Station Type	**Ai (W)**	**Bi (W)**
Macro	21.45	354.44
Pico	5.5	38

In order to efficiently obtain the power consumption of the macro eNodeB, equation(3.13) was modified by Richter *et al*. (2009) as expressed in equation (3.14).

$$Pc_{macro} = N_{sec}\, N_{ant} \left(A_{i\{macro\ \}} P_{TXmacro} + B_{i\{ma\ cro\}}\right) \qquad (3.14)$$

where: Pc_{macro} is the power consumption of the macro eNodeB in Watts,$P_{TXmacro}$is the transmit power of the macro eNodeB in Watts, $A_{i\{macro\ \}}$ and $B_{i\{macro\ \}}$ are the coefficients A_i and $B_i$for the macro eNodeBrespectively.

Substituting for values of N_{sec}, N_{ant}, $A_{i\{macro\ \}}$, $P_{TXmacro}$ and $B_{i\{macro\ \}}$into equation (3.14), the power consumption of a macro eNodeB was obtained as;

$$Pc_{macro} = 1\ x\ 1\ (21.45\ x\ 40 + 354.44) = 1212.44W$$

Similarly, the power consumption of the pico eNodeB was obtained using equation (3.13) and modified by Richter *et al*.,(2009) as expressed by equation (3.15):

$$Pc_{pico} = N_{sec} N_{ant} \left(A_{i\{pico\}} P_{TXpico} + B_{i\{pico\}}\right) \quad (3.15)$$

where: Pc_{pico} is the power consumption of the pico eNodeB in Watts, P_{TXpico} is the transmit power of the pico eNodeB in Watts, $A_{i\{pico\}}$ and $B_{i\{pico\}}$ are the coefficients A_i and B_i for the pico eNodeB respectively.

Substituting for values of N_{sec}, N_{ant}, $A_{i\{pico\}}$, P_{TXpico} and $B_{i\{pico\}}$ into equation (3.14), the power consumption of a pico eNodeB was obtained as;

$$Pc_{pico} = 1\ x\ 1\ (5.5\ x\ 1 + 38) = 43.5W$$

In order to obtain the overall power consumption of the HetNet, the Pc_{macro} obtained using equation (3.14) was multiplied by the total number of macro eNB cells, and the Pc_{pico} obtained using equation (3.15) was multiplied by the total number of pico eNB cells as discussed in Section 3.2.1and added based on equation (3.16).

$$Pc_T = x \cdot Pc_{macro} + x \cdot y \cdot Pc_{pico} \quad (3.16)$$

where: Pc_T is the total power consumed in Watts in the overall HetNet, Pc_{macro} and Pc_{pico} are the power consumed in Watts by the macro eNodeB and pico eNodeB respectively. x is the number of macro eNodeB (21 cells) while y is the number of pico eNodeB (4 cells).

Substituting the values for x, y, Pc_{macro} and Pc_{pico} into equation (3.16), the total power in the network was obtained as;

$$Pc_T = 21\ (1212.44) + 21\ (4)\ 43.5 = 29.1kW$$

In order to assess the energy consumption of various components and the overall network, Energy Efficiency (EE) metric of (Abdulkafi *et al.,* 2013) was used. The Energy efficiency (EE) is defined as

the ratio of the overall data rate delivered, R_T and total power consumed PC_T, which is expressed by Abdulkafi *et al.,* (2013) and shown in equation (3.17).

$$EE = \frac{Overall\ \ data\ \ rate}{Total\ \ power\ \ consumed} = \frac{R_T}{PC_T} \qquad (3.17)$$

where: EE is the energy efficiency is bits per sec per Watts (bits/Joule), R_T is the overall data rate in bits/s and PC_T is the total power consumption in Watts (Abdulkafi *et al.,* 2013).

Therefore, substituting equations (3.10) and (3.16) into equation (3.17) the total energy efficiency according to Abdulkafi *et al.,* (2013) is a shown in equation (3.18).

$$EE_{Total} = \frac{R_{TotalUE}}{Pc_{macro} + Pc_{pico}} \qquad (3.18)$$

where: EE_{Total} is the energy efficiency of the overall network in bits/Joules, $R_{TotalUE}$ is the total data rate in a macro coverage area in bits/s, Pc_{macro} and Pc_{pico} are the power consumption of macro eNodeB and pico eNodeB in Watts respectively.

The energy efficiency of a macrocell was obtained by substituting equations (3.8) and (3.14) into equation (3.17) according to Abdulkafi *et al.,* (2013) is shown in equation (3.19)

$$EE_{macro} = \frac{R_{MUE}}{Pc_{macro}} \qquad (3.19)$$

where: EE_{macro} is the energy efficiency of the macro eNodeB in bits/Joules, R_{MUE} is the data rate of the macro user equipment in bits/s and Pc_{macro} is the power consumption of the macro eNodeB in Watts.

Similarly, the energy efficiency of a pico eNB cell was obtained by substituting equations (3.9) and (3.15) into equation (3.17) as follows (Abdulkafi *et al.,* 2013);

$$EE_{pico} = \frac{R_{PUE}}{Pc_{pico}} \quad (3.20)$$

where: EE_{pico} is the energy efficiency of the pico eNodeB in bits/Joules, R_{PUE} is the data rate of the pico user equipment in bits/s and Pc_{pico} is the power consumption of the pico eNodeB cell in Watts.

In order to effectively determine the energy efficiency of the overall HetNet, the average energy efficiency was obtained using equation (3.18) and dividing the total number of cells as follows:

$$Average\ EE = \frac{\sum EE_{Total}}{NumCell} \quad (3.21)$$

where: Average EE is the average energy efficiency in bits/Joules and $NumCell$ is the total number cells. Equations (3.13) to (3.21) were used to develop codes used to modify the system level simulator toolbox in MATLAB to develop the power consumption model as shown in the Appendices.

3.2.4 Developed Sleep Mode Algorithm

In the 3GPP always-on scheme, the standard is having all the pico eNodeB cells always on irrespective of traffic load conditions, i.e. there is no on/off adaptation of pico eNodeBs. Pico eNodeB cells that form an overlay layer on the existing macrocell network offer tremendous potential in terms of satisfying high data rate traffic requirements. However, pico eNodeB deployments can pose negative energy-efficiency implications if not equipped with advanced power saving mechanisms (Ashraf *et al.*, 2010). In order to efficiently reduce power consumption, it is cost effective to implement sleep mode in the pico eNodeBs during low and medium traffic. Therefore, a sleep mode algorithm was proposed to dynamically put pico eNodeB cells into sleep

mode based on traffic situations and obtained average user data rate. It is assumed that the power consumption of a pico eNodeB cell is 0W during sleep mode(Ashraf *et al.,* 2011).

Average user data rate is the view of a single user equipment data rate which can vary greatly depending on the number of user equipment on a cell using the services, but it gives a realistic expectation of what users are likely to experience on a real life network. It is often expressed as a range of minimum – maximum values ranging from 2Mbps – 7.5Mbps for LTE 10MHz and 2Mbps – 12.5Mbps for LTE 20MHz (Motorola White Paper, 2009).

As traffic decreases (less than or equal to 10 user equipment per macro area coverage), the algorithm efficiently estimates the varying traffic load, based on which a number of pico eNodeB cells are put to sleep mode. Then the average user data rate is estimated to determine whether a pico eNodeB cell will remain in sleep or not, ensuring that the overall data rate of the HetNet does not go below the minimum value of 2Mbps (Motorola White Paper, 2009). This will ensure reduction in power consumption in the LTE HetNet.

The proposed algorithm requires that the average user data rate be estimated once the sleep mode has been activated, then determine whether or not the pico eNodeB cells will remain in sleep mode depending on a threshold limit. The threshold value is to ensure service delivery to users is not obstructed. The condition for the threshold limit is given as (Motorola White Paper, 2009); Overall Average UEData Rate ≥ 2 Mbps.

If the estimated average user data rate of the overall network is greater than the set threshold value, the pico eNodeB cell will remain in sleep mode otherwise it will become active. As traffic increases (greater than 10 user equipment per macro area coverage) and the average user data rate goes below the threshold value, the algorithm will dynamically change the operating state of the pico eNodeB cells to active.

The flow chart of the developed sleep mode algorithm is given in Figure 3.1. It was implemented in MATLAB with additional codes used to modify the system level simulator toolbox in MATLAB as shown in Appendix D. Appendix A comprises the main m-file that runs all the codes and plots the required charts.

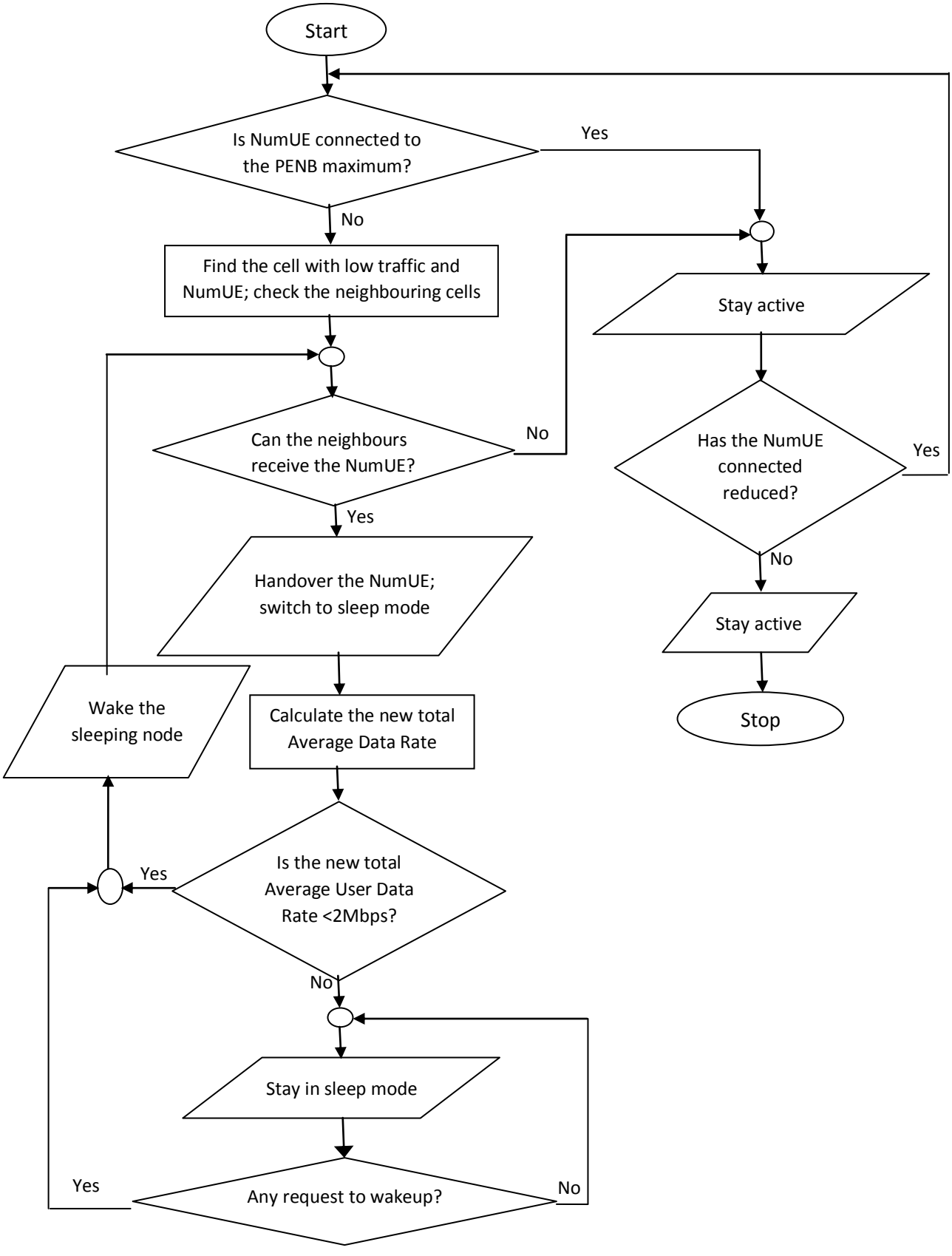


Figure 3.1: Flow Chart of the Developed Sleep Mode Algorithm

The novelty in this research workis the development of a data rate-based sleep mode algorithm using average user data rate as the sleep mode metric.The algorithm provides better energy savings at lowand medium traffic load which was demonstrated in Chapter Four.

Furthermore, the proposed algorithm differs from those reviewed in chapter two. Firstly, the sleep mode metric used in the literature which includes; number of UE, SINR, number of base stations, total number of users andconstant data rate,cannot efficiently represent cell load conditions. The proposed method uses average user data rate in addition to the above factors as sleep mode metric which was estimated based on instantaneous channel conditions using link adaptation. This work considers a more accurate and realistic LTE system. Secondly, this work employs the standard HetNet topologies (configuration 1 and 4b) as specified by 3GPPand implemented in LTE system level simulator toolbox in MATLAB.

3.3 SIMULATION SETUP

The 3GPP specified standards for HetNet Configuration 1 and Configuration 4b as shown in Appendix E. These were implemented in the system level simulator toolbox in MATLAB by (Acharya *et al.*, 2014). In order to implement the developed sleep mode algorithm for this research work, additional codes were written and added to the codes developed by Acharya *et al.,* (2014) in the system level simulator toolbox in MATLAB.

The simulation area involves 21 hexagon cells with wrap around which simulates an infinite hexagonal grid of macro base stations as shown in Figure 3.2. The inter site distance between macro base stations is 500m. Each macro site covers 3 cells (3 sectors, each sector is an eNodeB cell), and there are 7 macro sites. So the total number of macro eNodeB cells is 21 (i.e. 3 eNodeB cells in 1 macro site multiplied by 7 macro sites). The macro sites use 3 directional antennas to provide coverage in 3 cells. The pico nodes are placed along with the macro base station within the cell area to offload the traffic from the macro base station andthe number of pico nodes in

each cell is constant. The pico base station used omni directional antennas for transmission(Acharya *et al*., 2014).

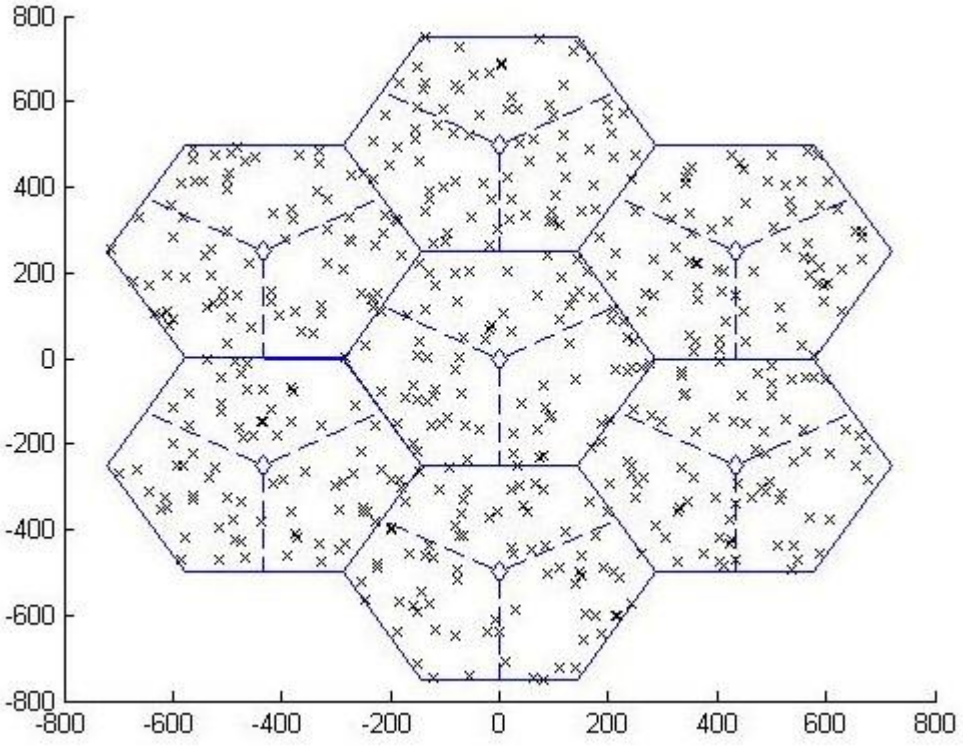


Figure 3.2: HetNet Configuration1 Topology with 25 UE per macro cell area (Acharya *et al*., 2014)

There are 4 pico eNodeB cells in each macro eNodeB cell, and there is a total of 21 macro eNodeB cells. Therefore, there are 84 pico eNodeB cells in the whole HetNet configuration.The UEs are denoted by a star as shown in Figure 3.2. User mobility comprising different locations is represented by each drop (Acharya *et al*., 2014). Table 3.2 shows some of the simulation parameters used in this research, others are shown in Appendix E.

Table 3.3: System Level Simulation Parameters (TR 36.814 V9.0.0, 3GPP 2010)

Parameters	**Description/Values**
Cell layout	7 Hexagonal MeNBs with 3 Sectors
Total Number of MeNB	21
Total Number of PeNB	84
Number of Antennas/Sectors for PeNB	1
Number of Antennas/Sectors for MeNB	1

MeNBs radius		500m
System bandwidth		10MHz
Number of resource blocks		50
Number of PeNBs per sector		4
Hotspot radius		40m
Minimum distance	MeNBs and PeNBs	75m
	Among PeNBs	40m
	Between MeNBs and UE	35m
	Between PeNBs and Ues	10m
Transmission power	MeNBs	46 dBm (40W)
	PeNBs	30 dBm (1W)
Pathloss	MeNBs	128.1 +37.6$\log_{10}$(r[km])
	PeNBs	140.7 +36.7$\log_{10}$(r[Km])
Number of UEs per sector		60 in config4b, 25 in config1
UE distribution		Clustered and uniformly distributed
Link Adaptation	QPSK (1/5 to 3/4), 16-QAM (2/5 to 5/6) & 64-QAM(3/5 to 9/10) CQI reporting every 1ms	

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents simulation results and discussions. A number of plots describing the condition of the HetNet scenarios during simulations are generated, presented and discussed.

Furthermore, the effectiveness of the developed algorithm is also demonstrated through the simulation of the 3GPP always-on scheme having all the pico eNodeB cellsactive in the HetNet scenarios (configuration 1 and configuration 4b) irrespective of traffic conditions.

4.2 VALIDATION

In order to evaluate the system level performance of the Developed sleep mode algorithm, three performance metrics were considered. These are (i) power consumption (ii) average UE data rate and (iii)average energy efficiency. Simulations were carried out for different number of user equipment per cell for theAlways-on scheme and the Developed sleep mode algorithm.

4.2.1 Power Consumption

The power consumption for the various nodes (pico eNodeBs (PeNB), macro eNodeBs (MeNB) and all the eNodeBs in the HetNet (AlleNB))was obtained using equations (3.14), (3.15), (3.16) and (3.17)which were used to develop the power consumption model. The performance evaluation for the power consumption of the Developed sleep mode algorithm was carried out by comparing it with the 3GPP Always-on scheme.

At high traffic, the power consumption remains unchanged for the pico, macro and the overall HetNet both for the Always-on scheme and the Developed sleep mode algorithm for both Configurations, since sleep mode was not activatedbecause the network is at its peak (25 and 60 UE per cell for Configuration 1 and Configuration 4b respectively).All the 84 pico eNodeB cells are active.

It is observed from Figure 4.1 that the Developed sleep mode algorithm performed better than the Always-on scheme, because 63 pico cells are in sleep mode, with only 21 active PeNB cells while 84 PeNB are active for always-on.This implies, there is only 1 active pico cell per macro cell coverage, and 3 sleeping pico cells per macro cell coverage. The Developed sleep mode algorithm was able to determine the required number of active pico cells by considering the average user

data rate. With this low traffic, the power consumption of the MeNB remained the same for both algorithms because the sleep mode was only implemented for the PeNB cells. The same applies to Configuration 4b.

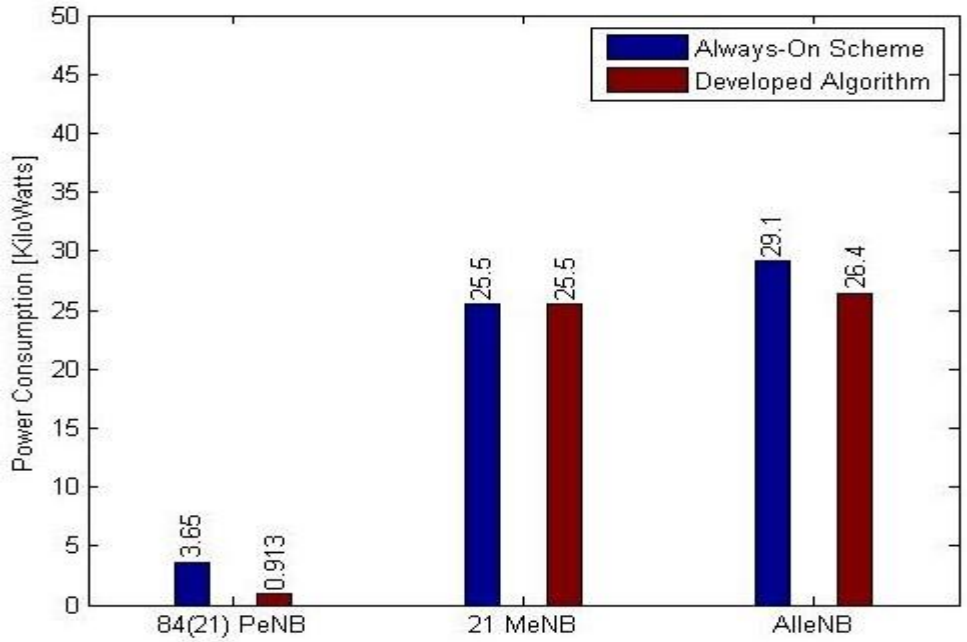


Figure 4.1:Power Consumption for 5 UE per Cell in Configuration 1

There was a decrease in power consumption for the overall HetNet (AlleNB) as a result of the PeNB power consumption improvement during low traffic.In order to calculate the percentage improvement in the reduction of power consumption, the expression in equation (4.1) was used.

$$P_{Saving} = \frac{P_{Always\ _on} - P_{Sleepmode}}{P_{Always\ _on}} X\ 100\% \qquad (4.1)$$

Where: P_{Saving} is the amount of power saved, $P_{Always\ _on}$ is the power consumed with Always-on scheme and $P_{Sleepmode}$ is the power consumed in sleep mode.

Therefore, substituting for the values from Fig. 4.1 into equation (4.1), the amount of power saved within the PeNB was obtained as expressed below.

$$P_{Savings} = \frac{3.65 - 0.913}{3.65} X\ 100\%$$

$$P_{Savings} = 75\%$$

While the amount of power saved in the overall HetNet was obtained as expressed below.

$$P_{Savings} = \frac{29.1 - 26.4}{29.1} X\ 100\%$$

$$P_{Savings} = 9.28\%$$

Power savings of 75.0% and 9.28% was achieved for the PeNB and AlleNB respectively with the developed sleep mode algorithm as compared to the always-on (without sleep) in Configuration 1. Same results were obtained for Configuration 4b.

From Figure 4.2, as the number of user equipment increased, it is observed that the powerconsumption for the developed sleep mode algorithm is lower than the always-on schemebecause 42 PeNB (two pico cells per macro cell coverage) are active while the other 42 PeNB cells are in sleep mode to save energy. The MeNB power consumption is still constant with an improvement in the overall HetNet (AlleNB) power consumption.

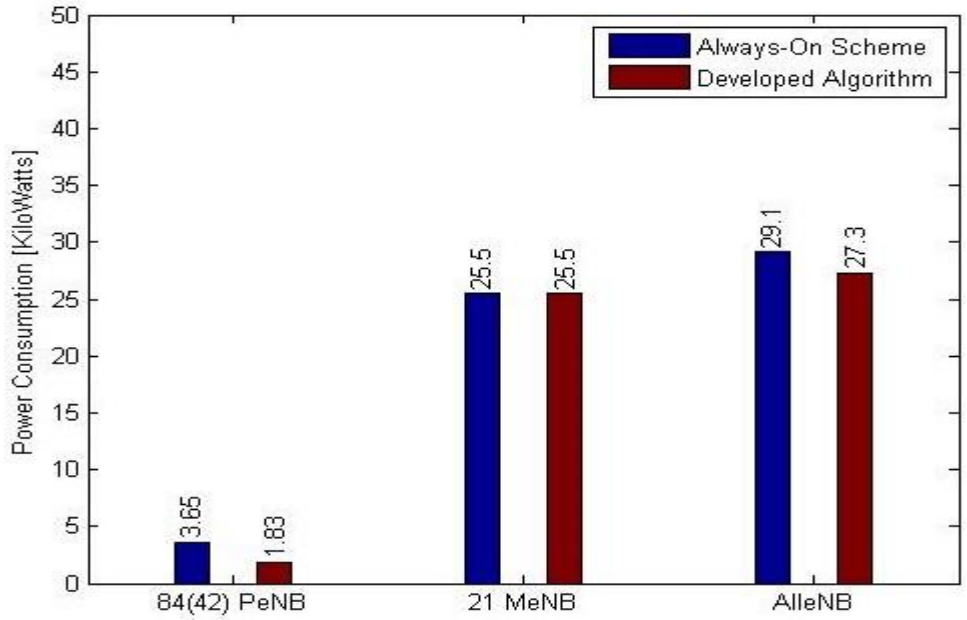


Figure 4.2:Power Consumption for 12 UE per Cell in Configuration 1

The percentage power reduction was obtained using equation 4.1 by substituting the power consumption values obtained from Fig. 4.2. The reduction in power consumption was about 50% and 6.19% for the pico eNodeB cells and the overall HetNet(AlleNB)respectively.

$$P_{Pico\ _Savings} = \frac{3.65 - 1.83}{3.65} X\ 100\%$$

$$P_{Pico\ _Savings} = 50\%$$

$$P_{Total\ _Savings} = \frac{29.1 - 27.3}{29.1} X\ 100\%$$

$$P_{Total\ _Savings} = 6.19\%$$

4.2.2 Average UE Data Rate

The average UE data rate for the various nodes (PeNB, MeNB and AlleNB) was obtained using equations (3.4) to (3.12)which were used to develop the data rate model.The performance evaluation for the average UE data rate of the developed sleep mode algorithm was carried out by

comparing it with the 3GPP always-on scheme. The data rate is the same for theDeveloped algorithm and the Always-on Scheme at high traffic (25 UE per cell for Configuration 1 and 60 UE per cell for Configuration 4b). This is because none of the pico cells is in sleep mode.

From Figure 4.3 and Figure 4.4, it can be observed that average UE data rate for the Always-on scheme is the same for all the four pico cells when the traffic is minimal (5 UE per cell in both Configuration 1 and Configuration 4b). With the developed algorithm, only one of the pico cells is activeproviding a data rate of 3.96Mbps and 5.40Mbps in Figure 4.3 and Figure 4.4 respectively, for the connected UE while the other three cells are in sleep mode.These average UE data rate values still exceed the minimum data threshold. Some of the UEs are connected to the MeNB, and only one pico cell is sufficient to provide the required data rate to the pico cell users even though the Always-on Scheme is higher. The cells with an average UE data rate of zero for the Developed sleep mode algorithmare in sleep mode in other to reduce power consumption. There are no users connected to the sleeping cells. A UE is either connected to the active pico cell or the MeNB. In Figure 4.3 and Figure 4.4, Cells 1, 2 and 3 are in sleep mode.

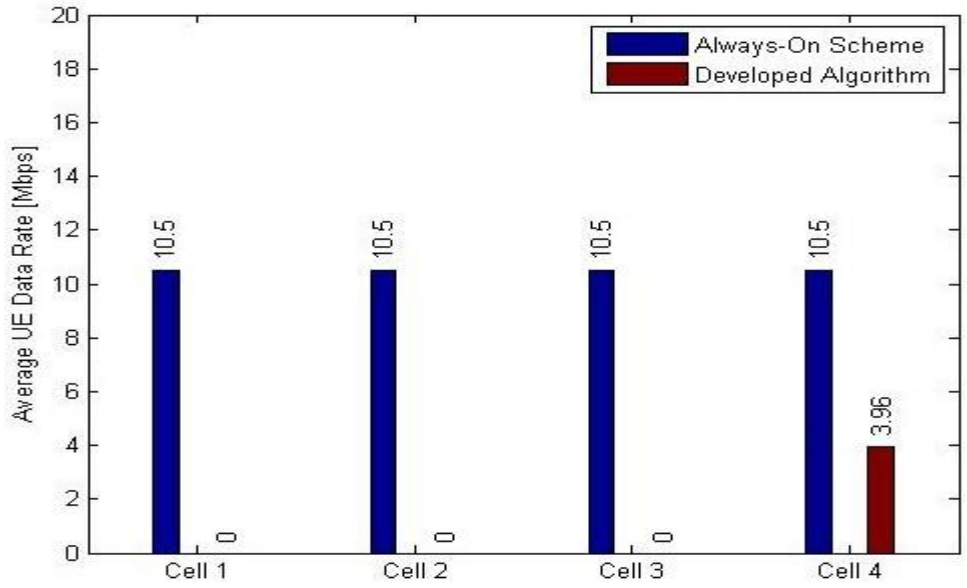


Figure 4.3: Configuration 1 Pico Cells Average UE Data Rate for 5 UE per Cell

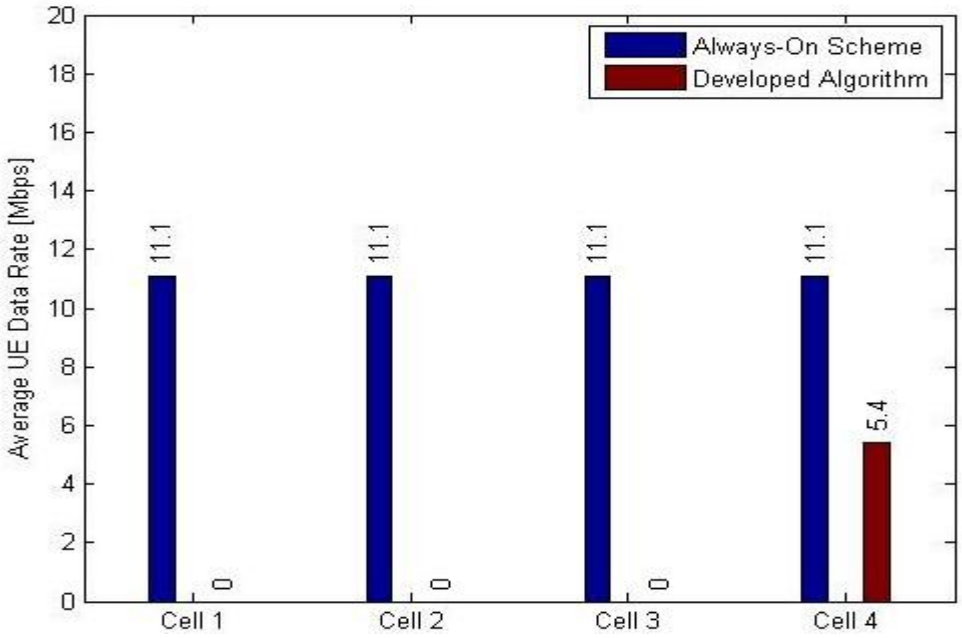


Figure 4.4: Configuration 4b Pico Cells Average UE Data Rate for 5 UE per Cell

From Figure 4.5 and Figure 4.6,as the number of user equipmentper cell increases (at medium traffic) and AllUE data reduces below the set threshold, some of the pico cellsbecome active dynamicallyin the case of the Developed algorithm so that service provisioning is not obstructed.

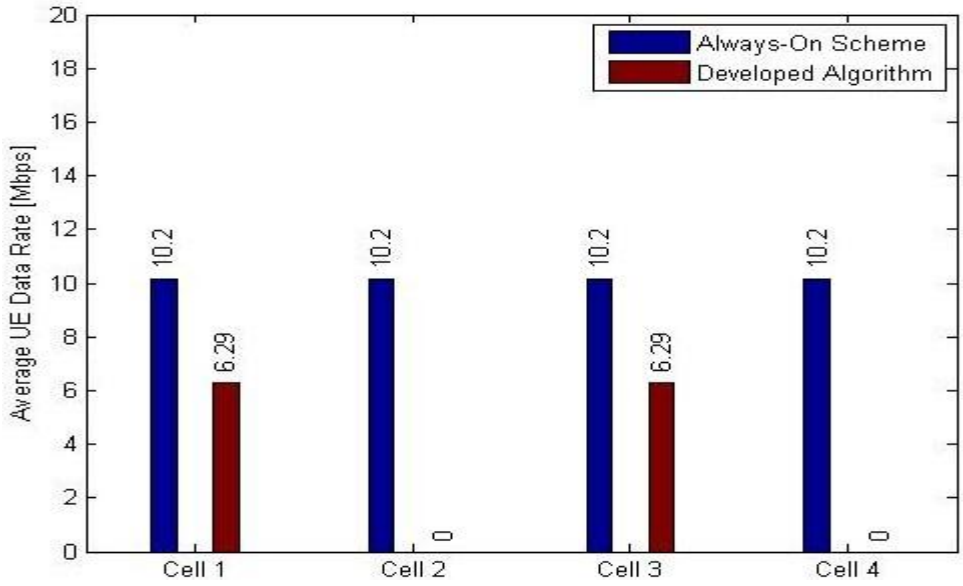


Figure 4.5: Pico Cells Average UEData Rate for 12 UE per Cell in Configuration 1

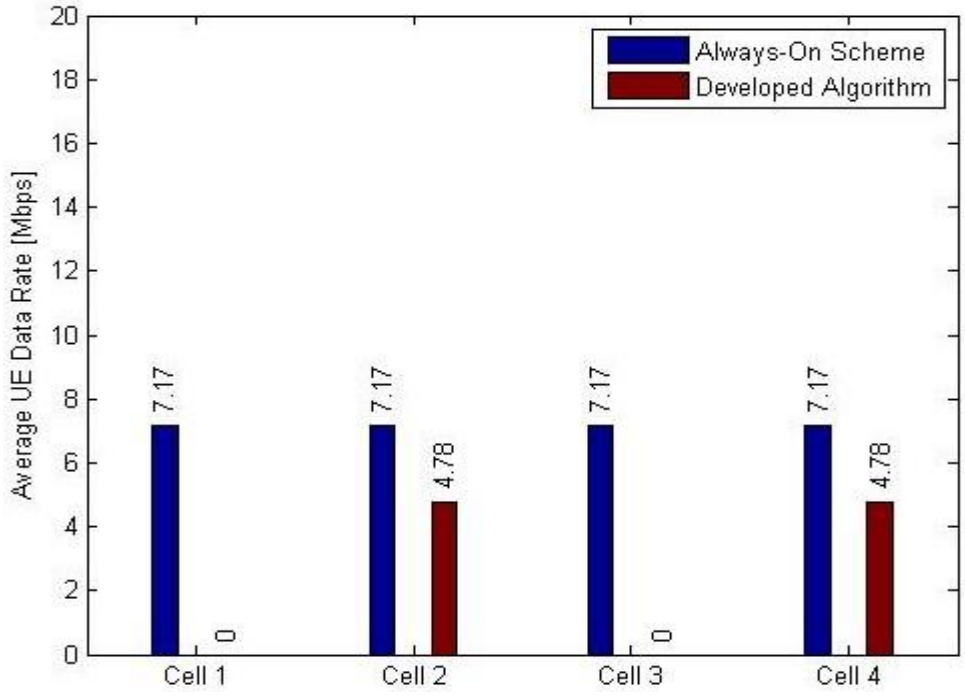


Figure 4.6: Pico Cells Average UE Data Rate for 20 UE per Cell in Configuration 4b

The algorithm was able to determine the required number of pico cells that should become active to provide a good data rate for the UE. From Figure 4.5 and Figure 4.6, two pico cells are now active. i.e. an additional one pico cell was added to the initial one pico cell serving the UE.

When the number of user equipment per cell became minimal (5 UE per cell) as shown in Figure 4.7, the sleep mode was activated thereby having only one active pico cell serving the connected user equipment. It is observed from Figure 4.7 that the AllUE Data is not less than the set threshold of 2Mbps so the pico cells in sleep mode remained in that state, while those connected to the active cell get 3.96Mbps.

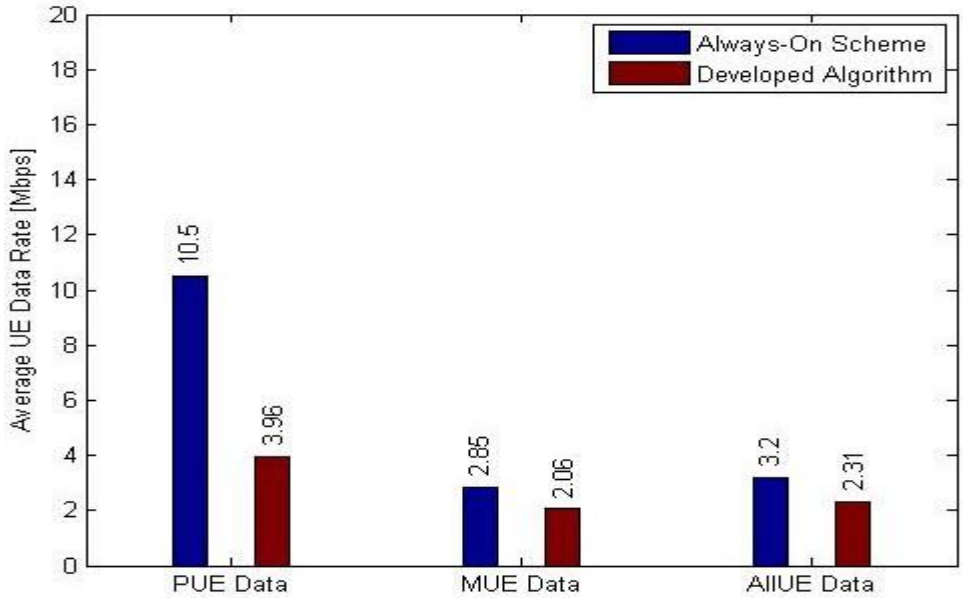


Figure 4.7: Average UE Data Rate for Low Traffic in Configuration 1

As shown in Fig. 4.8, although the PUE data rate for the Always-on Scheme is higher than that of the Developed algorithm, the average user data rate of 5.40Mbps is a good value when compared to minimum requirement for average user data rate. Therefore, with pico cells in sleep mode, the UE still achieved a reasonable data rate at low traffic.

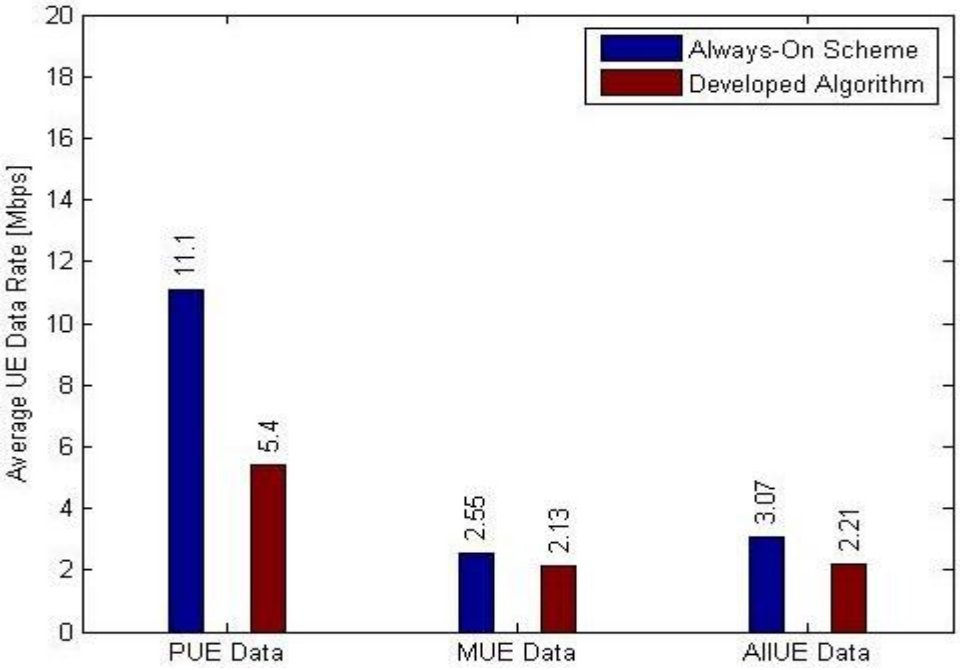


Figure 4.8: Average UE Data Rate for Low Traffic in Configuration 4b

From Figure 4.9, the PUE data rate for the Always-on scheme was higher than that of the Developed algorithm, but the 6.29Mbps still exceeds the minimum requirement. The MUE data for the Developed algorithm has reduced because some UEs have been offloaded to the MeNB. The MUE data rate is lower than the PUE data rate because, it is expected that pico cells should provide higher data rates. From the AllUE Data, it is observed that the threshold value was achieved. Although, the data rate been experienced by the users connected to the pico cells is 6.29Mbps.

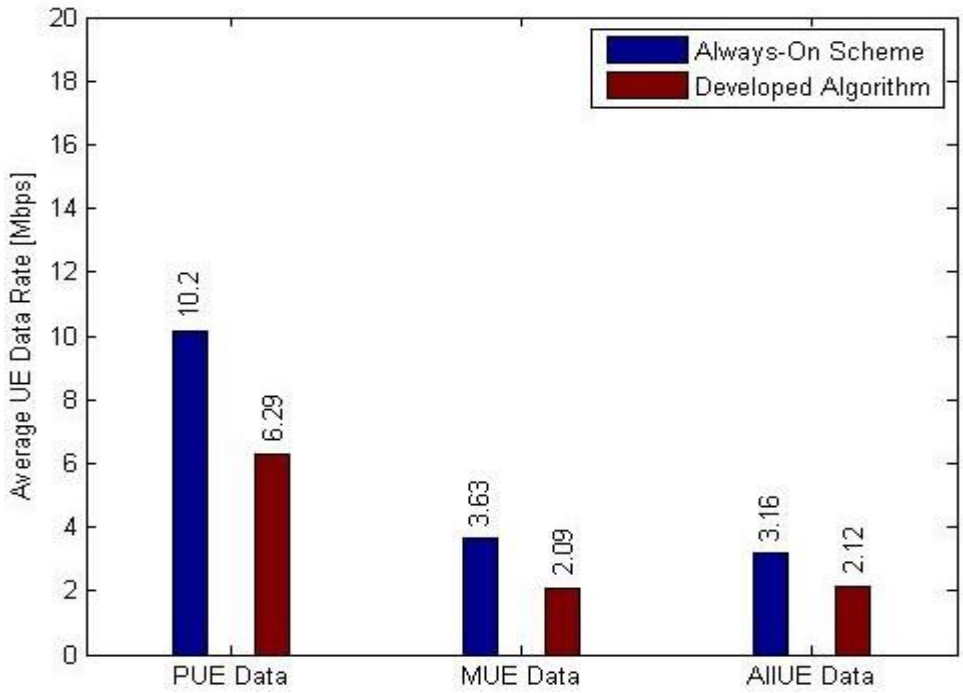


Figure 4.9: Configuration 1 Average UE Data Rate for Medium Traffic

Similarly, from Figure 4.10 (medium traffic for conf4b), the PUE data of the Developed algorithm appearsto be lower with a value of 4.78Mbps. This value is greater than the minimum requirement of 2Mbps. This justifies that the average user data rate was not compromised at medium traffic

with the developed algorithm and some amount of power hasbeen saved. For the overall network, the average user data rate value of 2.16Mbps is also greater than the minimum requirement.

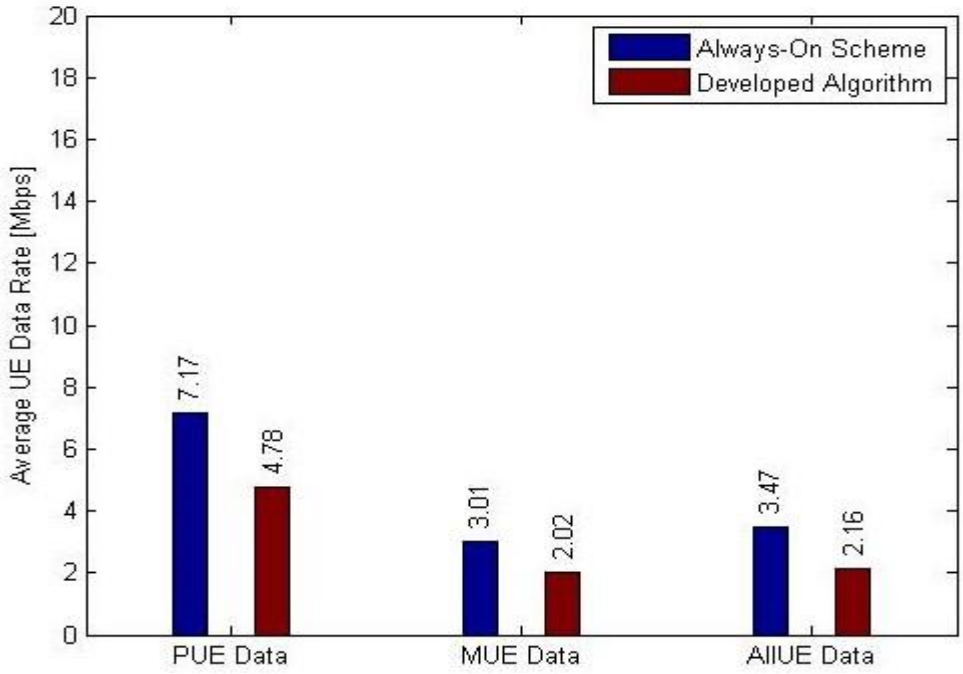


Figure 4.10: Configuration 4b Average UE Data Rate for Medium Traffic

4.2.3 Average Energy Efficiency

Performance evaluation was carried out for the average energy efficiency for Configuration 1 and Configuration 4b for different number of user equipment.The average energy efficiency of the pico, macro and the overall HetNet for the Always-on scheme and the Developed algorithm was the same at high traffic, attributed to the fact that sleep mode was not activated. As such, the energy efficiency tends to be equal. The pico cells are more energy efficient than the macro cells because of low power consumption and high data rates resulting in an improvement of the overall energy efficiency.

At low traffic as shown in Figure 4.11, the Developed algorithm achieved the highest energy efficiency compared to the Always-on Scheme in the pico cells, attributed to higher data rates and sleep mode in some pico cells which reduced the power consumption.

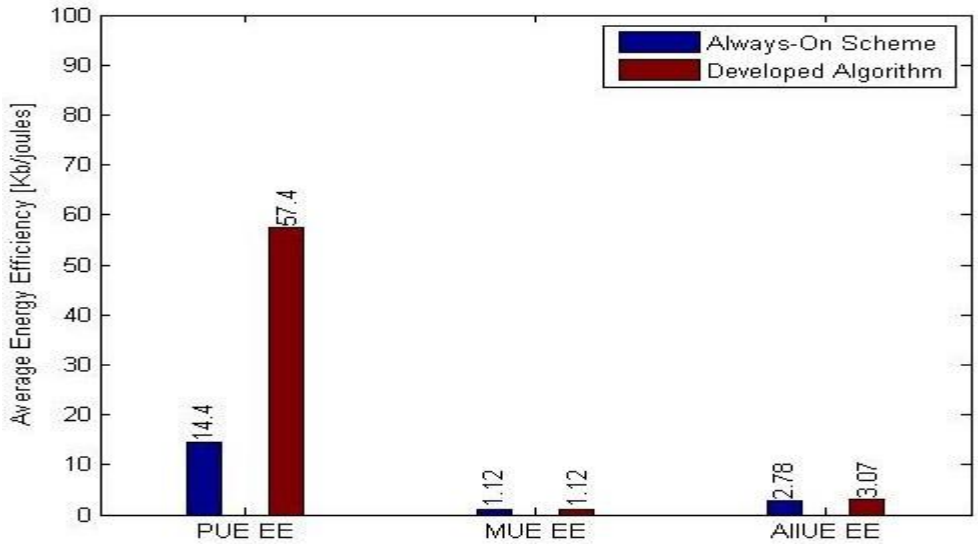


Figure 4.11: Average Energy Efficiency for Low Traffic in Configuration 1

It is observed that with the Developed sleep mode algorithm in Figure 4.11, the overall average energy efficiency improved. To evaluate the energy efficiency improvement, the expression below was used.

$$EE_{Pico\ _Efficiency} = \frac{EE_{Sleepmode} - EE_{Always\ _on}}{EE_{Sleepmode}} X\ 100\%$$

Where: $EE_{Pico\ _Efficiency}$ is the pico cells energy efficiency, $EE_{Sleepmode}$ is the energy efficiency in sleep mode, $EE_{Always\ _on}$ is the energy efficiency for the Always-on Scheme.

$$EE_{Pico\ _Efficiency} = \frac{57.4 - 14.4}{57.4} X\ 100\%$$

$$EE_{Pico\ _Efficiency} = 75\%$$

The Developed sleep mode algorithm achieved an energy efficiency of 75% as compared to the Always-on Scheme. The energy efficiency achieved for the overall network with the Developed sleep mode algorithm was obtained as 9.45% using the above expression.

$$EE_{Total\ _Efficiency} = \frac{EE_{Sleepmode} - EE_{Alway\ s_on}}{EE_{Sleepmode}} X\ 100\%$$

$$EE_{Total_Efficiency} = \frac{3.07 - 2.78}{3.07} X\ 100\%$$

$$EE_{Total_Efficiency} = 9.45\%$$

Where: $EE_{Total_Efficiency}$ is the energy efficiency of the overall Heterogeneous network.

Similarly, from Figure 4.12, it is observed that the Developed algorithm performed better than the Always-on Scheme in terms of the average energy efficiency at low traffic. The pico cells achieved the best energy efficiency, thus this justifies the need to sleep some pico cells at low traffic.

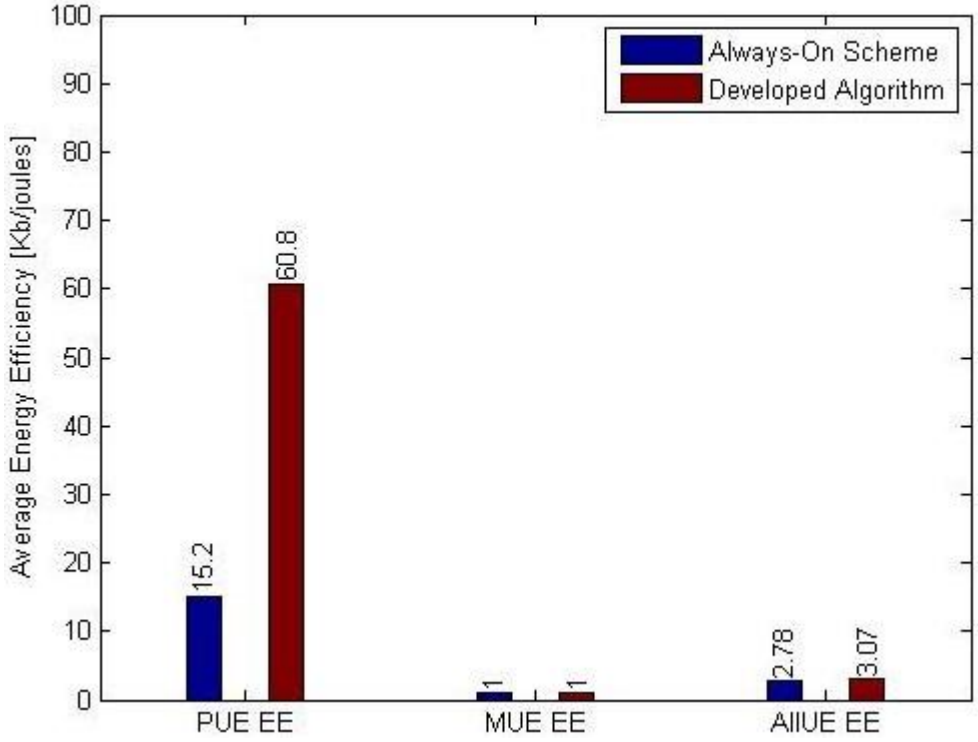


Figure 4.12: Average Energy Efficiency for Low Traffic in Configuration 4b

An improvement of about 75% was achieved for the PeNB cells. This is because 75% of the pico cells in the network are in sleep mode and also as a result of higher data rates.

$$EE_{Pico_Efficiency} = \frac{EE_{Sleepmode} - EE_{Always_on}}{EE_{Sleepmode}} X\ 100\%$$

$$EE_{Pico_Efficiency} = \frac{60.8 - 15.2}{60.8} X\ 100\%$$

$$EE_{Pico_Efficie\ ncy} = 75\%$$

In the case of the overall network, the sleeping pico cells contributed to the improvement of energy efficiency in the network. An energy efficiency improvement of about 9.60% was achieved as shown below.

$$EE_{Total_Efficiency} = \frac{EE_{Sleepmode} - EE_{Always_on}}{EE_{Sleepmode}} X\ 100\%$$

$$EE_{Total_Efficiency} = \frac{3.07 - 2.78}{3.07} X\ 100\%$$

$$EE_{Total_Efficiency} = 9.45\%$$

When the number of UE increased from 5 to 12 UE per cell (medium traffic) as shown in Figure 4.13, it is observed that the average energy efficiency forthe pico UE with the Developed algorithm increased compared to the Always-onbecause some of the pico cellsare in sleep mode. An improvement of 50% energy efficiency was achieved also due to pico cells in sleep mode.

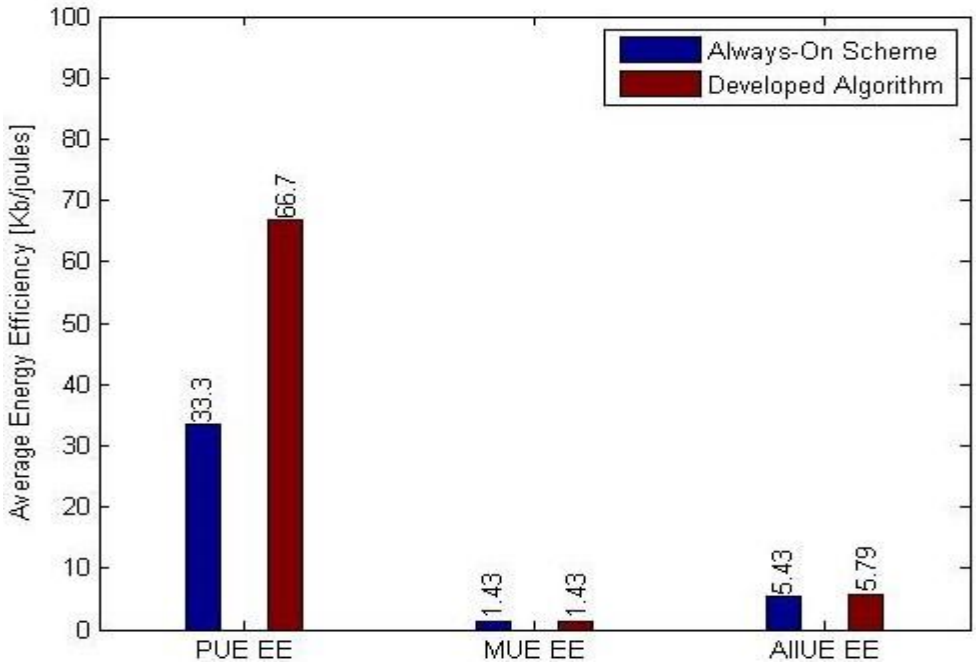


Figure 4.13: Configuration 1 Average Energy Efficiency for Medium Traffic

$$EE_{Pico_Efficiency} = \frac{EE_{Sleepmode} - EE_{Always_on}}{EE_{Sleepmode}} X\ 100\%$$

$$EE_{Pico_Efficiency} = \frac{66.7 - 33.3}{66.7} X\ 100\%$$

$$EE_{Pico_Efficiency} = 50\%$$

On the other hand, the Developed algorithm performed better than the Always-on (without sleep) for the overall HetNet. As a result, an improvement of about 6.22% was achieved at medium traffic in the average energy efficiency of the overall HetNet when compared to the Always-on scheme.

$$EE_{Pico_Efficiency} = \frac{5.79 - 5.43}{5.79} X\ 100\%$$

$$EE_{Pico_Efficiency} = 6.22\%$$

Similarly, from Figure 4.14 at medium traffic in Configuration 4b, the Developed algorithm performed better than the Always-on Scheme for the PeNB cells by achieving higher average energy efficiency attributed also to sleep mode in some pico eNodeB cells. Improvement in energy efficiency was about 50%.

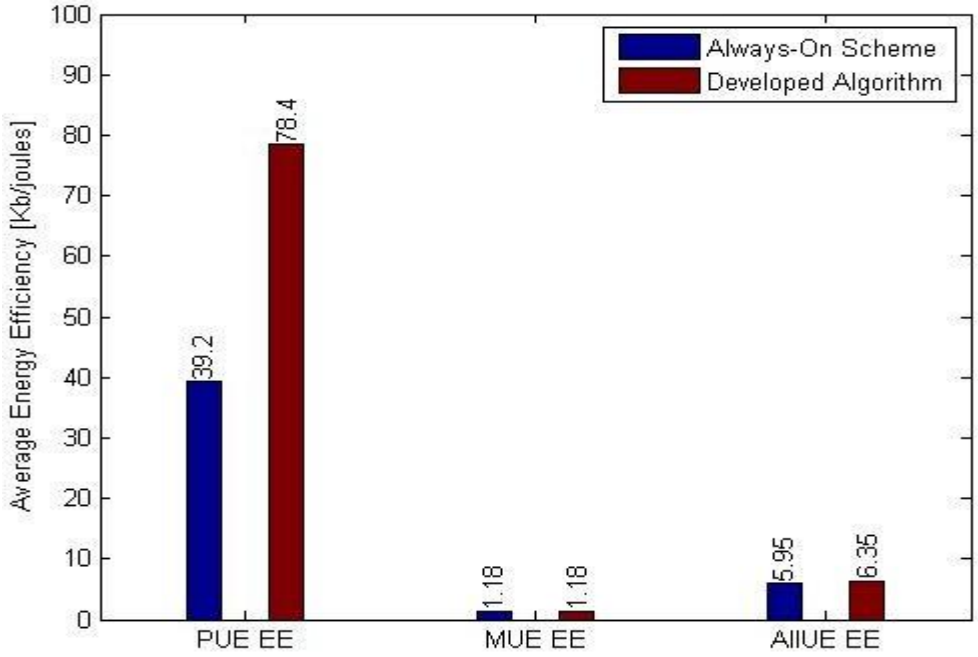


Figure 4.14: Configuration 4b Average Energy Efficiency for Medium Traffic

$$EE_{Pico_Efficiency} = \frac{78.4 - 39.2}{78.4} X\ 100\%$$

$$EE_{Pico_Efficiency} = 50\%$$

The energy efficiency for the overall network also improved as a result of sleeping pico cells. The improvement in energy efficiency was 6.30%.

$$EE_{Pico_Efficiency} = \frac{6.35 - 5.95}{6.35} X\ 100\%$$

$$EE_{Pico_Efficiency} = 6.30\%$$

4.3 SUMMARY OF RESULTS

Simulations were carried out for power consumption, average user data rate and average energy efficiency for HetNet Configuration1 and HetNet Configuration4b for the overall heterogeneous network. It was observed that the Developed sleep mode algorithm performed better than the Always-on Schemeat low and medium traffic in terms of power consumption and average energy efficiency providing a reasonable user data rate to the user equipment.

In HetNet Configuration 1, the Developed algorithm achieved a reduction in power consumption for low (5UE per cell) and medium traffic (12 UE per cell) in the pico eNodeB cells of about 75% and 50% respectively. On the other hand, 9.28% and 6.19% reductionwas achieved for the overall HetNet for low and medium traffic respectively.

In terms of power consumption reduction, the Developed sleep mode algorithm performed better up to about 20UE per cell than the Always-on as shown in Figure 4.15. The power consumption increases with increase in the number of users and becomes maximum at high traffic.

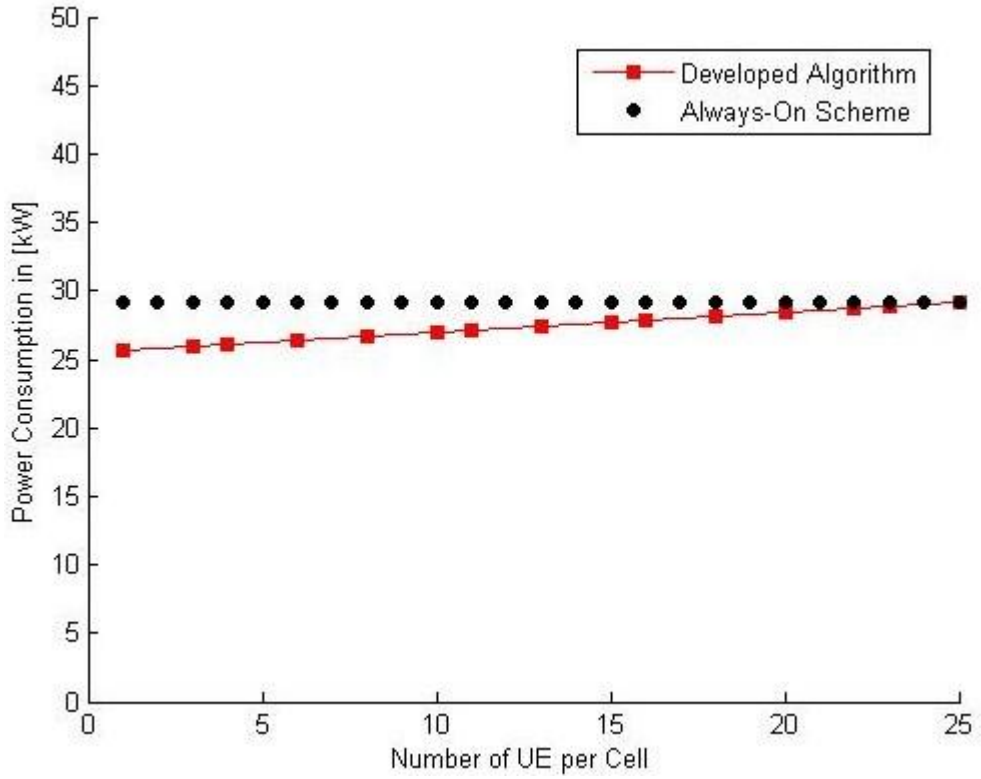


Figure 4.15: Power Consumption in HetNet Configuration1

Similarly, in HetNet Configuration 4b, the Developed algorithm achieved a power consumption improvement for low (5 UE per cell) and medium traffic (20 UE per cell) of about 75% and 50% respectively in the pico eNodeB cells. About 9.28% and 6.19% was achieved with the developed algorithm for the overall HetNet al low and medium traffic respectively. The Developed sleep mode algorithm performed better than the Always-on scheme upto about 50UE per cell.

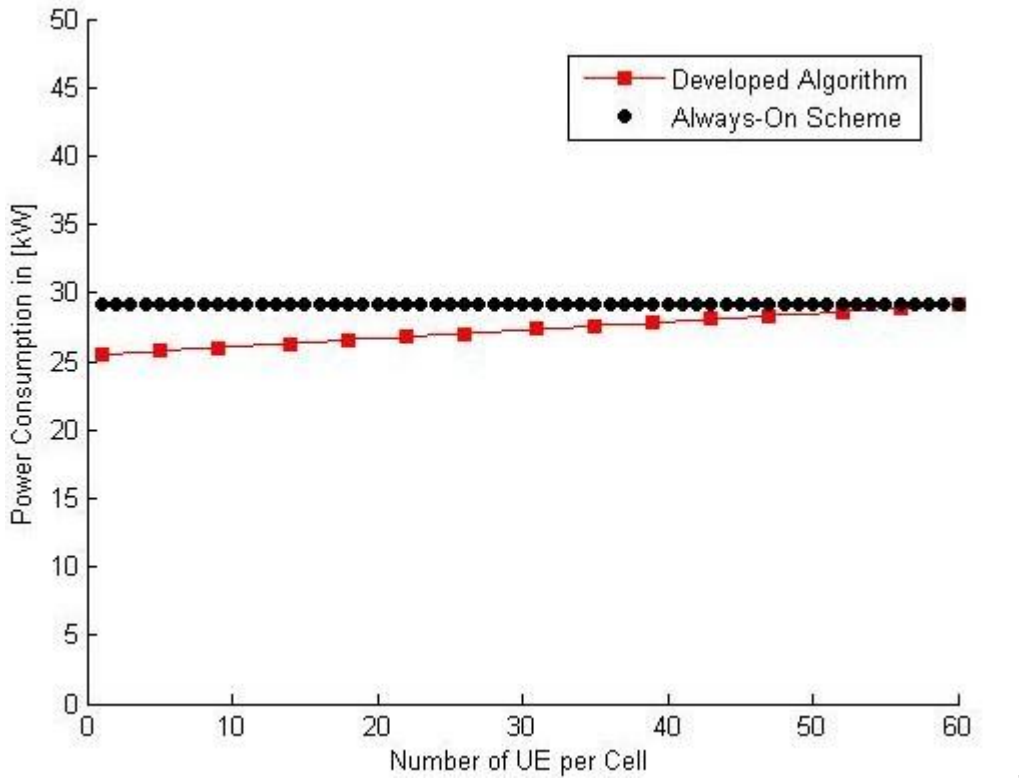


Figure 4.16: Power Consumption in HetNet Configuration4b

The total power saved, $P_{S,}$ with the Developed algorithm at low traffic is about 2.7kW at low traffic. This is obtainable from the total power of the Always-on scheme ($P_{Always\ _On}$) and the Developed algorithm ($P_{Sleepmode}$).

$$P_S = P_{Always\ _On} - P_{Sleepmode} \quad (4.1)$$

$$P_S = (29.1 - 26.4)\ kW = 2.7kW$$

From Figure 1.2, there is about 6 hours of low traffic on working days over a 24 hour period and about 8 hours on weekends and holidays. Therefore, the energy saved at low traffic on a working day is;

$$Energy\ Saved = 2.7\ x\ 6 = 16.2kWh$$

While the energy saved at low traffic on weekends and holidays per day is;

$$Energy\ Saved\ =\ 2.7\ x\ 8\ =\ 21.6kWh$$

Thus, the total amount of energy saved with the Developed algorithm over a period of 24 hours is 16.2kWh and 21.6kWh for a working day and weekend/holidays respectively.This is a significant amount when it is spanned over five working days.

The energy efficiency improvement achieved for the overall HetNet with the Developed algorithm in Configuration 1 at low and medium traffic is about 9.45% and 6.22% respectively. In Configuration 4b, the Developed algorithm achieved an energy efficiency improvement of about 9.45% and 6.30% for low and medium traffic situations respectively.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 INTRODUCTION

This chapter presents the summary of the work done. The limitations encountered in the course of this research work and recommendations for future work are itemized.

5.2 CONCLUSIONS

In this report,a data rate-based sleep mode algorithm for energy savings for a pico eNodeB in LTE-AdvancedHetNet has been proposed and implemented. The algorithm is a function of traffic situations, data rate and power consumption in the system. Simulations were carried out to evaluate the system level performance of the developed data rate-based sleep mode algorithm. The algorithm performed better in terms of energy savings when compared with the 3GPP Always-on scheme. However, the Developed algorithm did not consider the effect of interference. Interference management could further improve the service delivery and energy savings.

5.3 SIGNIFICANT CONTRIBUTIONS

This research work offers the following contributions:

i. Development of a data rate-based sleep mode algorithm for energy savings for a pico eNodeB cell in a heterogeneous network that can improve the power savings of a heterogeneous networkin LTE-Advanced network by 75% and 50%.

ii. An improvement in power savings for the overall LTE-Advanced heterogeneous network by 9.28% and 6.19% for low and medium traffic respectively.

iii. The algorithm improved the energy efficiency in LTE–Advanced heterogeneous network at low traffic by 9.45% for both Configurations 1 and 4b. While for medium traffic, the energy efficiency improvement was about 6.22% and 6.30% for configuration 1 and configuration 4b respectively when compared with the 3GPP Always-on scheme.

5.4 LIMITATIONS

The limitations of this research work are as follows:

i. The Developed sleep mode algorithm did not consider the effect of interference.

ii. Due to the absence of HetNet in Nigeria, the Developed algorithm was implemented using simulations and could not be implemented in reality with measurements.

iii. The Developed algorithm did not consider sleeping macro eNodeB which would save more power at low traffic.

5.5 RECOMMENDATIONS FOR FUTURE WORK

The following are recommendations for advancement of this research work:

i. Implementation of the Developed algorithm in a deployed LTE-Advanced HetNet in reality to aid a more practical scenario.

ii. Development of other sleep mode algorithms based on interference management in order to improve the average user data rate and energy efficiency.

iii. Development of a sleep mode for the macro eNodeB cells at low traffic taking into consideration load balancing.

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APPENDIX A

MATLAB m-File: ConfigureSimulatorInputs.m

```
%% Initial Paramaters
NumBS = 21; % Assuming 3 sectors/eNB and 7 eNBs(one center eNB with
single tier of interferers) or 19 (two tiers of interferers)
BandWidth = 10; % units of MHz
NumDrops = 5 ;
HandOverMargin = 1;
```

```
EVM=0.08; %  8 percent Error Vector Magnitude (EVM)
BW_eff=0.56; % Bandwidth efficiency 0.56
SINR_eff=2.0;% SINR implementation efficiency 2.0
SE_max = 5.02;
EFF_MIMO=4; %(when we use 4x4 Mimo antennas, i.e 4 TRx and 4 RCx)
BLER= 0.1; % 10 percent Block Error Rate
SINR_threshold = [-2.7 -1.3 -0.8 -0.2 1.3 2.7 3.4 4.6 5.3 6.2 6.8 7.8 8.7
9.3 10.7 11.2 12.2 13.6 14.0 14.5 15.4 16.3 16.8 17.8 18.6 19.2];% from
the Table
No_bits= [67.20 84.00 112.56 134.40 168.00 201.60 223.44 252.00 268.80
302.40 336.00 369.60 403.20 448.56 504.00 554.40 559.44 604.80 630.00
672.00 714.00 756.00 806.40 840.00 882.00 907.20]/(1 * 10^-3);% from the
table
NoRBs=50;
Always_on=1;
Sleep_mode=2;
AvrgDataRate=0;
CellState=length(AvrgDataRate);
%%_

Scenario =  'HetNetConf4b'; % Options:
'UrbanMacro','UrbanMicro','HetNetConf1','HetNetConf4b'

%% Scenarion Specific Parameters
SetSysPara;

if strcmpi(Scenario, 'HetNetConf1') || strcmpi(Scenario, 'HetNetConf4b')
    AppendSysParaHetNet
end

CouplingLoss1AllUEs = zeros(1, NumUEperCell*NumBS*NumDrops);
CouplingLoss2AllUEs = zeros(1, NumUEperCell*NumBS*NumDrops);
SinrAllUEs = zeros(1, NumUEperCell*NumBS*NumDrops);
RxSinrAllUEs = zeros(1, NumUEperCell*NumBS*NumDrops);
RxSinr1AllUEs = zeros(1, NumUEperCell*NumBS*NumDrops);
%SE_HomoNetAllUEs= zeros(CellState, NumUEperCell*NumBS*NumDrops);
%%_
```

APPENDIX B

MATLAB main m-File for the Developed Average User Data Rate-based Sleep mode Algorithm:

main.m

```
clc
clear all
close all
```

```
dbstop iferror
tic
%  Main Function that simulates the network topology
%% Global file that stores all the network topology and UE related
parameters. Created in next step
global SysPara
%% Specify network topology and UE related paramaters to be simulated and
accordingly create SysPara
ConfigureSimulatorInputs

%% Generate the hexagonal eNodeB layout
eNB = GenMacroTopology;

%% Generate UE and/or RRH locations and UE -> Macro/RRH channels for
different drops and different network scenarios

for k = 1:NumDrops,

    disp(['Drop Number = ',num2str(k)]);

switch Scenario
case'UrbanMacro'

% Generate UE topologies
            UELocation = GenUEPosForMacro(eNB);

% Generate the Channels
            Loss = GenChannelUMa(eNB, UELocation);

case'UrbanMicro'

% Generate UE topologies
            UELocation = GenUEPosForMacro(eNB);

% Generate the Channels
            Loss = GenChannelUMi(eNB, UELocation);

case'HetNetConf1'

% Generate the RRHs
            [rrh] = GenRRH(eNB);

% Generate UE topologies
            UELocation = GenUEPosForHetNet1(eNB, rrh);

% Generate the Channels
            Loss = GenChannelHetNet(eNB, rrh, UELocation);

case'HetNetConf4b'

% Generate the RRHs
            [rrh] = GenRRH(eNB);

% Generate UE topologies
            UELocation = GenUEPosForHetNet4b(eNB, rrh);
```

```
% Generate the Channels
            Loss = GenChannelHetNet(eNB, rrh, UELocation);

end
% UE to Base Station Association

[CouplingLoss1,CouplingLoss2,Sinr,RxSinr,RxSinr1,PUE,cPUE,MUE,All_UE,avrg
_cPUE,avrg_PUE,avrg_MUE,SE_HetNet,PicoData,PCAS,A,B,C,A1,B1,C1,...

avrg_AllUE,fa,fc,fd,recordm,recordu,recordm3,recordu3,energy_efficiency_A
llUE,energy_efficiency_MUE,energy_efficiency_PUE,PComAwalysON,PComSleepMo
de,p1] = UE2BSAssoc(Loss);

    CouplingLoss1AllUEs( (k-1)*NumUE + 1: k*NumUE ) = CouplingLoss1;
    CouplingLoss2AllUEs( (k-1)*NumUE + 1: k*NumUE ) = CouplingLoss2;
    RxSinrAllUEs( (k-1)*NumUE + 1: k*NumUE ) = RxSinr;
    RxSinr1AllUEs(1, (k-1)*NumUE + 1: k*NumUE ) = RxSinr1;
end
toc
%% Plot 1: Example Network Topology
PlotNetworkTopology(UELocation, eNB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%figure(2)
%%bar(energy_efficiency_PUE);
%%xlabel('Pico Base Sataion index')
%%ylabel ('Energy Efficiency for PicoCells (in bits/joule)')
%%title('Energy Efficiency of picocell with 25 UEperCell for
HetNetConf1')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%figure(3)
%%bar(energy_efficiency_MUE);
%%xlabel('Macro Base Station index')
%%ylabel ('Energy Efficiency for MacroCells(in bits/joule)')
%%title('Energy Efficiency of macrocell with 25 UEperCell for
HetNetConf1' )
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%figure(4)
%%bar(energy_efficiency_AllUE);
%%xlabel('All Base Station index')
%%ylabel ('Energy Efficiency of cells (in bits/joule)')
%%title('Energy Efficiency with 25 UEperCell for HetNetConf1')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(5)
Y=[A;B;C];
 h= bar(Y,0.4,'group');%,colormap(summer);
ybuff=0.4;
for i=1:length(h)
    XDATA=get(get(h(i),'Children'),'XData');
    YDATA=get(get(h(i),'Children'),'YData');
for j=1:size(XDATA,2)
        x=XDATA(1,j)+(XDATA(3,j)-XDATA(1,j))/2;
        y=YDATA(2,j)+ybuff;
        t=num2str(YDATA(2,j),3);
```

```
text(x,y,t,'Color','k','HorizontalAlignment','left','Rotation',90)
end
end
ylim([0 20])
ylabel('Average UE Data Rate [Mbps]')
xlabel('Different UE Data for Configuration4b')
h1=legend('Always On','Developed Algorithm');
p = get(h1,'Position');
p(1) = 0.15;
p(2)=0.64;
set(h1,'Position',p);
title( 'Average UE Data Rate for 60 UEperCell Config4b')
 set(gca,'Xtick',1:5,'XTickLabel',{'PUE Data', 'MUE Data','AllUE Data'})
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
figure(6)
Y=[A1;B1;C1];
 h= bar(Y,0.4,'group');%,colormap(summer);
ybuff=0.4;
for i=1:length(h)
    XDATA=get(get(h(i),'Children'),'XData');
    YDATA=get(get(h(i),'Children'),'YData');
for j=1:size(XDATA,2)
        x=XDATA(1,j)+(XDATA(3,j)-XDATA(1,j))/2;
        y=YDATA(2,j)+ybuff;
        t=num2str(YDATA(2,j),3);

text(x,y,t,'Color','k','HorizontalAlignment','left','Rotation',90)
end
end
ylim([0 100])
ylabel('Average Energy Efficiency [Kb/joules]')
xlabel('Different UE Efficiency for Configuration4b')
h1=legend('Always On','Developed Algorithm');
p = get(h1,'Position');
p(1) = 0.55;
p(2)=0.64;
set(h1,'Position',p);
title( 'Average Energy Efficiency for 60 UEperCell Config4b')
 set(gca,'Xtick',1:5,'XTickLabel',{'PUE EE', 'MUE EE','AllUE EE'})
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(7)
 h= bar(PicoData,0.4,'group');
ybuff=0.4;
for i=1:length(h)
    XDATA=get(get(h(i),'Children'),'XData');
    YDATA=get(get(h(i),'Children'),'YData');
for j=1:size(XDATA,2)
        x=XDATA(1,j)+(XDATA(3,j)-XDATA(1,j))/2;
        y=YDATA(2,j)+ybuff;
        t=num2str(YDATA(2,j),3);

text(x,y,t,'Color','k','HorizontalAlignment','left','Rotation',90)
```

```
end
end
ylim([0 20])
ylabel('Average UE Data Rate [Mbps]')
xlabel('Pico Cells in 1 Macro eNodeB for Configuration4b')
h1=legend('Always on','Developed Algorithm');
p = get(h1,'Position');
p(1) = 0.55;
p(2)=0.64;
set(h1,'Position',p);
title( 'Average UE Data Rate for 60 UEperCell Config4b')
set(gca,'Xtick',1:5,'XTickLabel',{'Cell 1','Cell 2','Cell 3','Cell 4'})
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(8)
h= bar(PCAS,0.4,'group');
ybuff=0.4;
for i=1:length(h)
    XDATA=get(get(h(i),'Children'),'XData');
    YDATA=get(get(h(i),'Children'),'YData');
for j=1:size(XDATA,2)
        x=XDATA(1,j)+(XDATA(3,j)-XDATA(1,j))/2;
        y=YDATA(2,j)+ybuff;
        t=num2str(YDATA(2,j),3);

text(x,y,t,'Color','k','HorizontalAlignment','left','Rotation',90)
end
end
ylim([0 50])
ylabel('Power Consumption [KiloWatts]')
xlabel('Different Power Consumption for Configuration1')
h1=legend('Always on','Developed Algorithm');
p = get(h1,'Position');
p(1) = 0.55;
p(2)=0.72;
set(h1,'Position',p);
title( 'Power Consumption for 60 UEperCell Config4b')
set(gca,'Xtick',1:5,'XTickLabel',{'84 PeNB', '21 MeNB','AlleNB'})
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(9)
line_fewer_markers(p1,PComSleepMode',15,'rs', 'Spacing',
'curve','linewidth',1.4,'MarkerSize', 4.5, 'MarkerFaceColor', 'r');hold
on
plot(p1,PComAwalysON,'ko','LineWidth',1.4,'MarkerEdgeColor','k','MarkerFa
ceColor','k','MarkerSize',4.5);
ylim([0 50])
ylabel('Power Consumption in [KW]')
xlabel('Number of UE per Cell')
h1=legend('Developed Algorithm','Always on');
z = get(h1,'Position');
z(1) = 0.15;
z(2)=0.65;
set(h1,'Position',z);
title( 'Power Consumption in HetNet Config4b')
```

APPENDIX C

MATLAB m-File: SetSysParameter.m

```
f = 1000/3600;
switch Scenario
case'UrbanMacro'
        UEHeight = 1.5 ;
        BSHeight = 25 ;
        InterSiteDist = 500;
        theta_tilt = 12 + 90;
        theta_3db = 15;
        phi_3db = 70;
        SLL_h = 20;
        SLL_v = 20;
        SLL = 20;
        MinDistMacroUE = 35;
        UEVel = 30*f;
        CenterFrequency = 2e9;
        BSAntennaGain = 17;
        TxPower = 46 + 10*log10(BandWidth/10);
        NumUEperCell = 10;
        IndoorUEProb = 0;
        FeederLoss = 2;

        Ai_macro = 21.45;
        Bi_macro = 354.44;
        PCi_macro = Ai_macro*40 + Bi_macro;

        Ai_pico = 5.5;
        Bi_pico = 38;
        PCi_pico = Ai_pico + Bi_pico;

case'UrbanMicro'
        UEHeight = 1.5 ;
        BSHeight = 10 ;
        InterSiteDist = 200;
        theta_tilt = 12 + 90;
```

```
        theta_3db = 15;
        phi_3db = 70;
        SLL_h = 20;
        SLL_v = 20;
        SLL = 20;
        MinDistMacroUE = 10;
        UEVel = 3*f;
        CenterFrequency = 2.5e9;
        BSAntennaGain = 17;
        TxPower = 41 + 10*log10(BandWidth/10);
        NumUEperCell = 10;
        IndoorUEProb = 0.5;
        FeederLoss = 2;

        Ai_macro = 21.45;
        Bi_macro = 354.44;
        PCi_macro = Ai_macro*40 + Bi_macro;
        Ai_pico = 5.5;
        Bi_pico = 38;
        PCi_pico = Ai_pico + Bi_pico;

case'HetNetConf1'
        UEHeight = 1.5 ;
        BSHeight = 25 ;
        InterSiteDist = 500;
        theta_tilt = 12 + 90;
        theta_3db = 10;
        phi_3db = 70;
        SLL_h = 25;
        SLL_v = 20;
        SLL = 25;
        MinDistMacroUE = 35;
        UEVel = 3*f;
        CenterFrequency = 2e9;
        BSAntennaGain = 17;
        TxPower = 46 + 10*log10(BandWidth/10);
        NumUEperCell = 25;
        IndoorUEProb = 0.8;
        FeederLoss = 0;

        Ai_macro = 21.45;
        Bi_macro = 354.44;
        PCi_macro = Ai_macro*40 + Bi_macro;

        Ai_pico = 5.5;
        Bi_pico = 38;
        PCi_pico = Ai_pico + Bi_pico;

case'HetNetConf4b'
        UEHeight = 1.5 ;
        BSHeight = 25 ;
        InterSiteDist = 500;
        theta_tilt = 12 + 90;
        theta_3db = 10;
        phi_3db = 70;
        SLL_h = 25;
```

```
        SLL_v = 20;
        SLL = 25;
        MinDistMacroUE = 35;
        UEVel = 3*f;
        CenterFrequency = 2e9;
        BSAntennaGain = 17;
        TxPower = 46 + 10*log10(BandWidth/10);
        NumUEperCell = 60;
        IndoorUEProb = 0.8;
        FeederLoss = 0;

        Ai_macro = 21.45;
        Bi_macro = 354.44;
        PCi_macro = Ai_macro*40 + Bi_macro;

        Ai_pico = 5.5;
        Bi_pico = 38;
        PCi_pico = Ai_pico + Bi_pico;
end% end switch

NumUE = NumUEperCell * NumBS;
Total_PCi_macro = PCi_macro * NumBS;
Total_PCi_pico = PCi_pico * NumBS * 4;

SysPara=struct('InterSiteDistance',InterSiteDist,...
'Total_PCi_macro',Total_PCi_macro,...
'Ai_macro',Ai_macro,...
'Bi_macro',Bi_macro,...
'PCi_macro',PCi_macro,...
'Total_PCi_pico',Total_PCi_pico,...
'Ai_pico',Ai_pico,...
'Bi_pico',Bi_pico,...
'PCi_pico',PCi_pico,...
'BSHeight',BSHeight,...
'MinDistMacroUE',MinDistMacroUE,...
'UEHeight',UEHeight,...
'UEVel',UEVel,...
'phi_3db',phi_3db,...
'theta_3db',theta_3db,...
'theta_tilt',theta_tilt,...
'rot',[0 2*pi/3 -2*pi/3],...
'SLL_h',SLL_h,...
'SLL_v',SLL_v,...
'SLL',SLL,...
'BandWidth',BandWidth,...
'CenterFrequency',CenterFrequency,...
'BSAntennaGain',BSAntennaGain,...
'TxPower',TxPower,...
'UENoiseFigure',7,...
'NumUEperCell',NumUEperCell,...
'NumBS',NumBS,...
'NumUE',NumUE,...
'EVM',EVM,...
'SINR_eff',SINR_eff,...
'BW_eff',BW_eff,...
'SE_max',SE_max,...
```

```
'SINR_threshold',SINR_threshold,...
'EFF_MIMO',EFF_MIMO,...
'FeederLoss',FeederLoss,...
'No_bits',No_bits,...
'Always_on',Always_on,...
'Sleep_mode',Sleep_mode,...
'AvrgDataRate',AvrgDataRate,...
'CellState',CellState,...
'NoRBs',NoRBs,...
'BLER',BLER,...
'HandOverMargin',HandOverMargin,...
'Scenario',Scenario,...
'IndoorUEProb',IndoorUEProb);
```

APPENDIX D

MATLAB m-File: UE2BSAssoc.m

```
function
[CouplingLoss1,CouplingLoss2,Sinr,RxSinr,RxSinr1,PUE,cPUE,MUE,All_UE,avrg
_cPUE,avrg_PUE,avrg_MUE,SE_HetNet,PicoData,PCAS,A,B,C,A1,B1,C1,...

avrg_AllUE,fa,fc,fd,recordm,recordu,recordm3,recordu3,energy_efficiency_A
llUE,energy_efficiency_MUE,energy_efficiency_PUE,PComAwalysON,PComSleepMo
de,p1] = UE2BSAssoc(Loss)

global SysPara

[NumUE, ~] = size(Loss);
if NumUE ~= SysPara.NumUE  % all the UEs in the system
    disp('Mismatch in number of UES');
    keyboard;
end

%% initializations

    NumBS=SysPara.NumBS;
    NumRRH=SysPara.NumRRHperMacro;
    CellState=SysPara.CellState;
    CouplingLoss1 = zeros(NumUE,1); % HetNet
    CouplingLoss2 = zeros(NumUE,1);%
    recordm=zeros(NumBS,CellState);
    recordu=zeros(NumUE,CellState);
    recordm3=zeros(NumBS,CellState);
    recordu3=zeros(NumUE,CellState);
    SE_HetNet=zeros(NumUE,CellState);
    Sinr=zeros(NumUE, CellState);
    RxSinr1 =Sinr(NumUE,1); % for HetNet Plot
    RxSinr = zeros(NumUE,1);
    Nobits_HetNet=zeros(NumUE,CellState);
    indibandwidth=zeros(NumBS,CellState);
```

```
    picobandwidth=zeros(NumBS,NumRRH,CellState);

   %% Noise Figure
   N0dB = -174 + SysPara.UENoiseFigure + 10*log10(SysPara.BandWidth*1e6)
;
   N0 = 10^(N0dB/10);
   %%  Scenario Selection

switch SysPara.Scenario
case {'UrbanMacro', 'UrbanMicro'}
        TxPowerVect = ones(1,SysPara.NumBS)*SysPara.TxPower;

case {'HetNetConf1','HetNetConf4b'}
        TxPowerVect = [ones(1,SysPara.NumBS)*SysPara.TxPower,
ones(1,SysPara.NumBS* SysPara.NumRRHperMacro)*SysPara.TxPowerRRH];
end


    %% Counters
    fa=0;
    fc=0;
    fd=0;
%%%%%%%%%%
    PUE=zeros(NumBS,2);
    cPUE=zeros(NumBS,2);
    MUE=zeros(NumBS,2);
    All_UE=zeros(NumBS,2);
    avrg_cPUE=zeros(NumBS,2);
    avrg_PUE=zeros(NumBS,2);
    avrg_MUE=zeros(NumBS,2);
    avrg_AllUE=zeros(NumBS,2);

for uid = 1: NumUE
    NumBS=SysPara.NumBS;
    NoRBs=SysPara.NoRBs;
    BLER=SysPara.BLER;
    NumUEperCell=SysPara.NumUEperCell;
    SINR_threshold=SysPara.SINR_threshold;
    No_bits=SysPara.No_bits;

    [~, index0] = max(Loss(uid,:) + TxPowerVect); % BS or PeNB index
where UEs recieves max transmitted power in hetnet scenario

if index0>NumBS
       fa=fa+1; % count number of UE associated to Pico cell
       recordm(fa)=fa; %index0; % record the index of Pico cell
       recordu(fa)=uid; % record the index of UE that connect to pico
cell
else

           fc=fc+1; % count the number of UE associated to macro cell
           recordm3(fc)=fc; %index0;% record the index of macro cell
           recordu3(fc)=uid; % record the index of UE that connect to
macro cell
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% HetNet Cases

    CouplingLoss1(uid) = Loss(uid,index0);
    Signal = 10^( (CouplingLoss1(uid) + TxPowerVect(index0))/10 );
    TotalRxPower = sum(10.^( (Loss(uid,:) + TxPowerVect)/10 ));
    Interference = TotalRxPower - Signal ;
    Sinr(uid,1) = 10*log10(Signal/(N0+Interference));
    RxSinr_idx=max(size((find(Sinr(uid)>= SINR_threshold))));% SINR_idx
for link adaptation lookup table
    Nobits_HetNet(uid)=No_bits(RxSinr_idx); % symbol efficiency of hetnet
UEs with 10% BLER
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for x=1:NumBS
fory=1:NumRRH
m=0;
for uid=1:NumUE
for za=1:fa
if (recordm(za)==(NumBS+NumRRH*(x-1)+ y)&&
recordu(za)==uid)%recordm(za)>=(NumBS+3*(x-
1)+1)&&recordm(za)<=(NumBS+3*h)&&recordu(za)==uid
m=m+1;
break
end
end
end
if m~=0
         picobandwidth(x,y,1)=(NoRBs/m);
end
end
end

for x1=1:NumBS
n=0;
for uid1=1:NumUE
for w=1:fc
if (x1==recordm3(w)&& recordu3(w)==uid1)
n=n+1;
break
end
end

end
    indibandwidth(x1)=NoRBs/n;% macro UEs bandwidth
end
%%%%%%%%%

for x4=1:NumBS
    qa=0;
    qc=0;

for uid4=1:NumUE
for zc=1:fc
if (h4==recordm3(zc) && recordu3(zc)==uid4)
              qc=qc+1;
             PR=indibandwidth(h4)*2*Nobits_HetNet(uid4)*(1-BLER);
```

```
            MUE(h4,1)=PR + MUE(h4,1);

break
end
end
for y=1:NumRRH
for cc=1:fa
if (recordm(cc)==(NumBS+NumRRH*(x4-1)+ y)&&recordu(cc)==uid4)
%recordm(cc)>=(NumBS+3*(h-
1)+1)&&recordm(cc)<=(NumBS+3*h)&&recordu(cc)==uid
             qa=qa+1;
          PP=picobandwidth(x4,y,1)*2*Nobits_HetNet(uid4)*(1-BLER);    %
2x2 MIMO Capacity= BW x BW_eff x 7 symbols (1PRB)/0.5 x 10^3 BW_eff=No of
mod bits x coding
             cPUE(h4,1)=PP+cPUE(h4,1);                                  %
Capacity=1RB x 7symbols x No_mod bits x coding rate/ 0.5 x 10^-3
             PUE(h4,1)=PP+PUE(h4,1);

break;
end
end
end
end

   All_UE(h4,1)= MUE(h4,1)+ PUE(h4,1);
   q1=qa;
   q=q1+qc;

        avrg_MUE(h4,1)=MUE(h4,1)/qc;
 avrg_AllUE(h4,1)=All_UE(h4,1)/m;
end
%%%%%%%%%%%%%%%%%%%%%%%%

avrg_PUE(:,1)=PUE(:,1)/(NumBS*NumUEperCell);
%%
            avrg_PUE(:,2)=avrg_PUE(:,1);
            avrg_MUE(:,2)=avrg_MUE(:,1);
            avrg_AllUE(:,2)=avrg_AllUE(:,1);
%
A=[sum(avrg_PUE(:,1)) sum(avrg_PUE(:,2))]/(1e6);  %
B=[sum(avrg_MUE(:,1)) sum(avrg_MUE(:,2))]/(NumBS*10e6);    %
C=[sum(avrg_AllUE(:,1)) sum(avrg_AllUE(:,2))]/(NumBS*10e6); %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%switch SysPara.Scenario
case'HetNetConf1'

       NumUE_PicoCell=7;
        gj=0;
    sleep=0;
    Qos=2;
for gh=1:NumBS
if PUE(gh,1)~=0;
            gj=gj+1;
end
end
%avrg_PUEactive=zeros(gj,1);
```

```
    avrg_PUEactive=avrg_PUE(1:gj,1);
    lu=fix((gj)/NumRRH);
%%%%%%%%%%%%%%%%%%%%%%%%%%
if
((NumUEperCell>(NumUE_PicoCell*2))&&(NumUEperCell<=(NumUE_PicoCell*3)));
for na=1:lu
            ra=randi(length(avrg_PUEactive));
            avrg_PUEactive(ra)=sleep;
end

            avrg_PUE(1:gj,2)=avrg_PUEactive;
        avrg_MUE(:,2)=avrg_MUE(:,1)./(lu);
            avrg_AllUE(:,2)=avrg_AllUE(:,1)./(lu);
end

if ((NumUEperCell>(NumUE_PicoCell))&&(NumUEperCell<=(NumUE_PicoCell*2)));

for na=1:lu*2
             ra=randi(length(avrg_PUEactive));
             avrg_PUEactive(ra)=sleep;
end

         avrg_PUE(1:gj,2)=avrg_PUEactive;
         avrg_MUE(:,2)=avrg_MUE(:,1)./(lu*2);
         avrg_AllUE(:,2)=avrg_AllUE(:,1)./(lu*2);
end
if
((NumUEperCell<=(NumUE_PicoCell))&&(NumUEperCell<(NumUE_PicoCell*2))&&(Nu
mUEperCell<(NumUE_PicoCell*3)));

for na=1:lu*3
             ra=randi(length(avrg_PUEactive));
             avrg_PUEactive(ra)=sleep;
end

         avrg_PUE(1:gj,2)=avrg_PUEactive;
         avrg_MUE(:,2)=avrg_MUE(:,1)./(lu*3);
         avrg_AllUE(:,2)=avrg_AllUE(:,1)./(lu*3);
end
       %%
    A=[sum(avrg_PUE(:,1)) sum(avrg_PUE(:,2))]/(1e6);  %
    B=[sum(avrg_MUE(:,1)) sum(avrg_MUE(:,2))]/(NumBS*10e6);    %
    C=[sum(avrg_AllUE(:,1)) sum(avrg_AllUE(:,2))]/(NumBS*10e6); %

    Qa=fix(A(2));
    Qb=fix(B(2));
    Qc=fix(C(2));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while Qa<Qos;
for u=1:gj;
if avrg_PUE(u,2)==0;
                avrg_PUE(u,2)=A(2)*gj;
                A=[sum(avrg_PUE(:,1)) sum(avrg_PUE(:,2))]/(1e6);
                Qa=fix(A(2));
break
end
```

```
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while Qb<Qos;
        avrg_MUE(:,2)=avrg_MUE(:,2) + avrg_MUE(:,1)./(gj);
%avrg_MUE(:,2)=avrg_MUE(:,2).*(B(1)/Qos);
            B=[sum(avrg_MUE(:,1)) sum(avrg_MUE(:,2))]/(NumBS*10e6);
            Qb=fix(B(2));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while Qc<Qos;
        avrg_AllUE(:,2)=avrg_AllUE(:,2) + avrg_AllUE(:,1)./gj;
            C=[sum(avrg_AllUE(:,1)) sum(avrg_AllUE(:,2))]/(NumBS*10e6);
            Qc=fix(C(2));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%
case'HetNetConf4b'
        %%
if NumUEperCell>60;
            MaxNumUE_Pico=60;
else
            MaxNumUE_Pico=round(2*NumUEperCell/3);
end;

        NumUE_PicoCell=10;
        gj=0;
    sleep=0;
    Qos=2;
for gh=1:NumBS
if PUE(gh,1)~=0;
            gj=gj+1;
end
end
%avrg_PUEactive=zeros(gj,1);
    avrg_PUEactive=avrg_PUE(1:gj,1);
    lu=fix((gj)/NumRRH);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
if
((MaxNumUE_Pico>(NumUE_PicoCell*2))&&(MaxNumUE_Pico<=(NumUE_PicoCell*3)))
;
for na=1:lu
            ra=randi(length(avrg_PUEactive));
            avrg_PUEactive(ra)=sleep;
end

            avrg_PUE(1:gj,2)=avrg_PUEactive;
        avrg_MUE(:,2)=avrg_MUE(:,1)./(lu);
            avrg_AllUE(:,2)=avrg_AllUE(:,1)./(lu);
end

if
((MaxNumUE_Pico>(NumUE_PicoCell))&&(MaxNumUE_Pico<=(NumUE_PicoCell*2)));
for na=1:lu*2
             ra=randi(length(avrg_PUEactive));
             avrg_PUEactive(ra)=sleep;
```

```
end

         avrg_PUE(1:gj,2)=avrg_PUEactive;
         avrg_MUE(:,2)=avrg_MUE(:,1)./(lu*2);
        avrg_AllUE(:,2)=avrg_AllUE(:,1)./(lu*2);
end

if
((MaxNumUE_Pico<=(NumUE_PicoCell))&&(MaxNumUE_Pico<(NumUE_PicoCell*2))&&(
MaxNumUE_Pico<(NumUE_PicoCell*3)));

for na=1:lu*3
             ra=randi(length(avrg_PUEactive));
             avrg_PUEactive(ra)=sleep;
end

         avrg_PUE(1:gj,2)=avrg_PUEactive;
         avrg_MUE(:,2)=avrg_MUE(:,1)./(lu*3);
         avrg_AllUE(:,2)=avrg_AllUE(:,1)./(lu*3);
end
       %%
    A=[sum(avrg_PUE(:,1)) sum(avrg_PUE(:,2))]/(1e6);  %
    B=[sum(avrg_MUE(:,1)) sum(avrg_MUE(:,2))]/(NumBS*10e6);    %
    C=[sum(avrg_AllUE(:,1)) sum(avrg_AllUE(:,2))]/(NumBS*10e6); %

    Qa=fix(A(2));
    Qb=fix(B(2));
    Qc=fix(C(2));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while Qa<Qos;
for u=1:gj;
if avrg_PUE(u,2)==0;
                avrg_PUE(u,2)=A(2)*gj;
                A=[sum(avrg_PUE(:,1)) sum(avrg_PUE(:,2))]/(1e6);
                Qa=fix(A(2));
break
end
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while Qb<Qos;
        avrg_MUE(:,2)=avrg_MUE(:,2) + avrg_MUE(:,1)./gj;
            B=[sum(avrg_MUE(:,1)) sum(avrg_MUE(:,2))]/(NumBS*10e6);
            Qb=fix(B(2));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%{
    if ((Qc>=Qa)&&(C(1)==C(2)));
        C=(A+B)/A(1);
    end

%}
while Qc<Qos;
        avrg_AllUE(:,2)=avrg_AllUE(:,2) + avrg_AllUE(:,1)./gj;
            C=[sum(avrg_AllUE(:,1)) sum(avrg_AllUE(:,2))]/(NumBS*10e6);
            Qc=fix(C(2));
```

```
end

if ((Qc>=Qa)&&(C(1)==C(2)));
        C=(A+B)/min(A(1),B(1));
while C(1)<Qos;
            C(1)=C(1) + C(1)/min(A(1),B(1));
            C(2)=C(1);
end
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Av_data=zeros(4,2);
Av_data(:,1)=A(1);
Av_data(:,2)=A(2);
switch SysPara.Scenario
case'HetNetConf1'
        PC_PeNodeB=SysPara.Total_PCi_pico;
        PC_MeNodeB=SysPara.Total_PCi_macro;
        PC_ALL=PC_PeNodeB+PC_MeNodeB;

        PC_PSleep=PC_PeNodeB;
        PC_MSleep=PC_MeNodeB;
       %%
if NumUEperCell>25;
        MaxNumUE_Pico=25;
else
        MaxNumUE_Pico=NumUEperCell;
end;
        NumUE_PicoCell=7;
        PicoSleep=zeros(4,1);
       %%
        y=zeros(1,4);

if
((MaxNumUE_Pico>(NumUE_PicoCell*2))&&(MaxNumUE_Pico<=(NumUE_PicoCell*3)))
;

            ra=randi(length(y));
            Av_data(ra,2)=PicoSleep(ra);
            PC_PSleep=PC_PeNodeB*(NumRRH-1)/NumRRH;
end

if
((MaxNumUE_Pico>(NumUE_PicoCell))&&(MaxNumUE_Pico<=(NumUE_PicoCell*2)));

            ra1=randi(length(y));
            ra2=randi(length(y));

if ((ra1==ra2)&&(ra1==1))
                ra1=ra1+1;
end
if ((ra1==ra2)&&(ra1>1))
                ra1=ra1-1;
end

            Av_data(ra1,2)=PicoSleep(ra1);
```

```
            Av_data(ra2,2)=PicoSleep(ra2);
            PC_PSleep=PC_PeNodeB*(NumRRH-2)/NumRRH;
end

if
((MaxNumUE_Pico<=(NumUE_PicoCell))&&(MaxNumUE_Pico<(NumUE_PicoCell*2))&&(
MaxNumUE_Pico<(NumUE_PicoCell*3)));
            ra3=randi(length(y));
            newr=Av_data(ra3,2);
            Av_data(:,2)=PicoSleep;
            Av_data(ra3,2)=newr;
            PC_PSleep=PC_PeNodeB*(NumRRH-3)/NumRRH;
end
        PicoData=Av_data;

        %%
        PC_ALLSleep=PC_PSleep+PC_MSleep;
        PCAS=zeros(3,2);
        PCAS(1,1)=PC_PeNodeB/1e3;
        PCAS(2,1)=PC_MeNodeB/1e3;
        PCAS(3,1)=PC_ALL/1e3;
        PCAS(1,2)=PC_PSleep/1e3;
        PCAS(2,2)=PC_MSleep/1e3;
        PCAS(3,2)=PC_ALLSleep/1e3;

case'HetNetConf4b'
        PC_PeNodeB=SysPara.Total_PCi_pico;
        PC_MeNodeB=SysPara.Total_PCi_macro;
        PC_ALL=PC_PeNodeB+PC_MeNodeB;

        PC_PSleep=PC_PeNodeB;
        PC_MSleep=PC_MeNodeB;
        %%
if NumUEperCell>60;
        MaxNumUE_Pico=60;
else
        MaxNumUE_Pico=round(2*NumUEperCell/3);
end;
        NumUE_PicoCell=10;
        PicoSleep=zeros(4,1);
       %%
        y=zeros(1,4);

if
((MaxNumUE_Pico>(NumUE_PicoCell*2))&&(MaxNumUE_Pico<=(NumUE_PicoCell*3)))
;

            ra=randi(length(y));
            Av_data(ra,2)=PicoSleep(ra);
            PC_PSleep=PC_PeNodeB*(NumRRH-1)/NumRRH;
end

if
((MaxNumUE_Pico>(NumUE_PicoCell))&&(MaxNumUE_Pico<=(NumUE_PicoCell*2)));

            ra1=randi(length(y));
```

```
            ra2=randi(length(y));

if ((ra1==ra2)&&(ra1==1))
                ra1=ra1+1;
end
if ((ra1==ra2)&&(ra1>1))
                ra1=ra1-1;
end

            Av_data(ra1,2)=PicoSleep(ra1);
            Av_data(ra2,2)=PicoSleep(ra2);
            PC_PSleep=PC_PeNodeB*(NumRRH-2)/NumRRH;
end

if
((MaxNumUE_Pico<=(NumUE_PicoCell))&&(MaxNumUE_Pico<(NumUE_PicoCell*2))&&(
MaxNumUE_Pico<(NumUE_PicoCell*3)));
            ra3=randi(length(y));
            newr=Av_data(ra3,2);
            Av_data(:,2)=PicoSleep;
            Av_data(ra3,2)=newr;
            PC_PSleep=PC_PeNodeB*(NumRRH-3)/NumRRH;
end

        PicoData=Av_data;

  PC_ALLSleep=PC_PSleep+PC_MSleep;

        PCAS=zeros(3,2);
        PCAS(1,1)=PC_PeNodeB/1e3;
        PCAS(2,1)=PC_MeNodeB/1e3;
        PCAS(3,1)=PC_ALL/1e3;
        PCAS(1,2)=PC_PSleep/1e3;
        PCAS(2,2)=PC_MSleep/1e3;
        PCAS(3,2)=PC_ALLSleep/1e3;

end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
PComAlwaysON=PCAS(3,1);
PComPSleep=PCAS(1,2);
PComMSleep=PCAS(2,2);
PComInc=PComPSleep/NumUEperCell;
PComSleepMode=zeros(1,NumUEperCell);
PComSleepMode(1)=PComMSleep+PComInc;
    p1=1:NumUEperCell;
for j=1:(NumUEperCell-1);
        PComSleepMode(j+1)=PComSleepMode(j)+PComInc;
end; % PComAwalysON,PComSleepMode,p1,
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
switch SysPara.Scenario
case'HetNetConf1'
if NumUEperCell==25;

            energy_efficiency_AllUE(:,1)= All_UE(:,1)/(PC_ALL);
            energy_efficiency_MUE(:,1)=MUE(:,1)/(PC_MeNodeB);
            energy_efficiency_PUE(:,1)=PUE(:,1)/(PC_PeNodeB);
```

```
            energy_efficiency_AllUE(:,2) = energy_efficiency_AllUE(:,1);
            energy_efficiency_MUE(:,2) = energy_efficiency_MUE(:,1);
            energy_efficiency_PUE(:,2) = energy_efficiency_PUE(:,1);
else
            avrg_PUE(:,2)=PUE(:,1)/(NumBS*NumUEperCell*((60-
fa/NumBS)/40));
            avrg_MUE(:,2)=avrg_MUE(:,1);
            avrg_AllUE(:,2)=avrg_AllUE(:,1)*(1-NumUEperCell/60);

            energy_efficiency_AllUE(:,1)= All_UE(:,1)/(PC_ALL);
            energy_efficiency_MUE(:,1)=MUE(:,1)/(PC_MeNodeB);
            energy_efficiency_PUE(:,1)=PUE(:,1)/(PC_PeNodeB);

            energy_efficiency_AllUE(:,2)= All_UE(:,1)/(PC_ALLSleep);
            energy_efficiency_MUE(:,2)=MUE(:,1)/(PC_MSleep);
            energy_efficiency_PUE(:,2)=PUE(:,1)/(PC_PSleep);

end

case'HetNetConf4b'
if NumUEperCell==60;

            energy_efficiency_AllUE(:,1)= All_UE(:,1)/(PC_ALL);
            energy_efficiency_MUE(:,1)=MUE(:,1)/(PC_MeNodeB);
            energy_efficiency_PUE(:,1)=PUE(:,1)/(PC_PeNodeB);

            energy_efficiency_AllUE(:,2)=energy_efficiency_AllUE(:,1);
            energy_efficiency_MUE(:,2)=energy_efficiency_MUE(:,1);
            energy_efficiency_PUE(:,2)=energy_efficiency_PUE(:,1);
else
            avrg_PUE(:,2)=PUE(:,1)/(NumBS*NumUEperCell*((60-
fa/NumBS)/40));
            avrg_MUE(:,2)=avrg_MUE(:,1);
            avrg_AllUE(:,2)=avrg_AllUE(:,1)*(1-NumUEperCell/60);

            energy_efficiency_AllUE(:,1)= All_UE(:,1)/ (PC_ALL);
            energy_efficiency_MUE(:,1)=MUE(:,1)/(PC_MeNodeB);
            energy_efficiency_PUE(:,1)=PUE(:,1)/(PC_PeNodeB);

            energy_efficiency_AllUE(:,2)= All_UE(:,1)/(PC_ALLSleep);
            energy_efficiency_MUE(:,2)=MUE(:,1)/(PC_MSleep);
            energy_efficiency_PUE(:,2)=PUE(:,1)/(PC_PSleep);

end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A1=[sum(energy_efficiency_PUE(:,1))
sum(energy_efficiency_PUE(:,2))]/(21e3)   ;  %
B1=[sum(energy_efficiency_MUE(:,1))
sum(energy_efficiency_MUE(:,2))]/(21e3);    %
C1=[sum(energy_efficiency_AllUE(:,1))
sum(energy_efficiency_AllUE(:,2))]/(21e3); %
```

APPENDIX E

3GPP TR 36.814 V9.0.0 (2010-03)

Heterogeneous deployments consist of deployments where low power nodes are placed throughout a macro-cell layout. A subset of the macro-cell layoutscould be used for heterogeneous network deployments evaluation. For calibration purpose, the following cases should be used.

- Case 1

- Case 3- Rural/high speed

To assess the benefit of adding low-power nodes to become a heterogeneous network, performance comparison should be made to homogeneous macro-cell only deployment.

The categorization of the low power nodes is as described in Table E1.

Table E1: Categorization of New Nodes

	Backhaul	**Access**	**Notes**
Remote Radio Head (RRH)	Several μs latency to macro	Open to all UEs	Placed indoors or outdoors
Pico eNB (i.e. Node for hotzone cells)	X2	Open to all UEs	Placed indoors or outdoors. Typically planned deployment
Home eNB (i.e. node for Femto cells)	No X2 as baseline (*)	Closed Subscriber Group (CSG)	Placed indoors. Consumer deployed.
Relay Nodes	Through air-interface with a macro-cell (for in-band RN case)	Open to all UEs	Placed indoors or outdoors

Note: The reference to new nodes in this TR and its corresponding characteristics are applicable to evaluations in this TR only.

(*): Baseline is in accordance to Rel-8/9 assumption. Evaluations with interference management for HeNBs(via X2 or other means) allowed to assess interference management benefits.

Table E2 presents the baseline deployment scenario for Heterogeneous network.

Table E2: Heterogeneous Network Deployment Scenario

Case	Environment	Deployment Scenario	Non-traditional node
5.1	Macro + Indoor	Macro + femtocell	femtocell
5.2		Macro + indoor relay	Indoor relay
5.3		Macro + indoor RRH/Hotzone	e.g. indoor pico
6.1	Macro + Outdoor	Macro + outdoor relay	Outdoor relay
6.2		Macro + outdoor RRH/Hotzone	e.g., outdoor pico

Note 1: Priorities are as follows:

1. Indoor HeNB clusters
2. Outdoor Hotzone cells with configuration #1 and #4 (in Table E3)
3. Indoor Hotzone scenario (RAN4 femto or pico models could be used)
4. Other scenarios can be studied with lower priority Note 2: Relay deployment scenario (5.2, 6.1) are studied separately.

Table E3. Placing of New Nodes and UEs in HetNet

Configuration	UE density across macro cells*	UE distribution within a macro cell	New node distribution within a macro cell	Comments
1	Uniform 25/macro cell	Uniform	Uncorrelated	Capacity enhancement
2	Non-uniform [10 – 100]/macro cell	Uniform	Uncorrelated	Sensitivity to non-uniform UE density across macro cell
3	Non-uniform [10 – 100]/macro cell	Uniform	Correlated**	Cell edge enhancement
4a, 4b	Non-uniform***	Clusters	Correlated**	Hotspot capacity enhancement

* New node density is proportional to the UE density in each macro cell. UE density is defined as the number of UEs in the geographic area of a macro cell.

**Relay and hotzone nodes, often deployed by planning.

*** Clustered UE Placement for Hotzone cells:

- Fix the total number of users, N_{users}, dropped within each macro geographical area, where N_{users} is 30 or 60 in fading scenarios and 60 in non-fading scenarios.

- Randomly and uniformly drop the configured number of low power nodes, N, within each macro geographical area (the same number N for every macro geographical area, where N may take values from {1, 2, 4, 10}).

- Randomly and uniformly drop N_{users_lpn} users within a 40 m radius of each low power node, where N_{users_lpn}= [$P^{hotspot}$. N_{users}/N] with $P^{hotspot}$ defined in Table E4, where $P^{hotspot}$ is the fraction of all hotspot users over the total number of users in the network.

- Randomly and uniformly drop the remaining users, N_{users} - N_{users_lpn}*N, to the entire macro geographical area of the given macro cell (including the low power node user dropping area).

Table E4. HetNet Configuration #4a and #4b Parameters for Clustered User Dropping

Configuration	N_{users}	N	$P^{hotspot}$
Configuration #4a*	30 or 60	1 2 4 10	1/15 2/15 4/15 2/3
Configuration #4b	30 or 60	1 2* 4*	2/3 2/3* 2/3*

* Baseline for Configurations #4a and #4b.

Table E5 presents the baseline parameters for initial evaluations in heterogeneous networks. More detailed modelling of new nodes propagation and channel model based on IMT.EVAL should be considered for performance evaluation at a later stage.

Table E5: Heterogeneous System Simulation Baseline Parameters

Parameter	Assumption (Pico/RRH/Hotzone)
Nodes per macro-cell	RRH/Hotzone, and outdoor relay: 1, 2, 4 or 10 (nodes) Femto and indoor relay: 1 (cluster)
Distance-dependent path loss from new nodes to UE*1	For outdoor RRH/Hotzone Model 1: Macro to UE: L= 128.1+37.6log10(R) Pico to UE: R L 10 log7.367.140 for 2GHz, R in km Model 2: Macro to UE: PLLOS(R)= 103.4+24.2log10(R) PLNLOS(R)= 131.1+42.8log10(R) For 2GHz, R in km. Penetration loss 20dB Case 1: Prob(R)=min(0.018/R,1)*(1-exp(-R/0.063))+exp(-R/0.063) Case 3 (Suburban): Prob(R)=exp(-(R-0.01)/0.2) Case 3 (Rural/

	Suburban): Prob(R)=exp(-(R-0.01)/1.0) Pico to UE: PLLOS(R)=103.8+20.9log10(R) PLNLOS(R)=145.4+37.5log10(R) For 2GHz, R in km Case 1: Prob(R)=0.5- min(0.5,5exp(-0.156/R))+min(0.5, 5exp(-R/0.03)) Case 3: Prob(R)=0.5- min(0.5,3exp(-0.3/R))+min(0.5, 3exp(-R/0.095))
Lognormal Shadowing	Similar to UMTS 30.03, B 1.41.4 [ETSI TR 101 112]
Shadowing standard deviation*2	For outdoor RRH/Hotzone for pathloss model 1: 10 dB for pathloss model 2 : ITU-R M.2135 (i.e., according to LOS, NLOS)
Shadowing correlation between cells*3	For outdoor RRH/Hotzone 0.5 For indoor RRH/Hotzone 0
Penetration Loss	For outdoor RRH/Hotzone 20 dB for Case 1,3; See ITU.Eval for ITU Rural above for both "Macro to UE" and "RRH/Pico to UE"
Antenna pattern (horizontal)	A(Θ)= 0 dB (omnidirectional
Carrier Frequency	CF= 2GHz for case 1 and case 3 CF = 0.8GHz for high speed rural
Channel model	If fast fading modelling is disabled in system level simulations for relative evaluations, theimpairment of frequency-selective fading channels shall be captured in the physical layer abstraction. For SIMO, the physical layer abstraction is based on TU link curves. For MIMO, the physical layer abstraction is FFS.
UE speeds of interest	Case 1 and Case 3: 3 km/h Rural high speed: 120 km/h for UEs served by macro, RRH, hotzone or relay nodes. 3 km/h for UEs served by femto cells.
Total BS TX power (Ptotal)	Case1: 24, 30 dBm – 10MHz carrier Case3: 24, 30, 37 dBm – 10MHz carrier (37dBm is outdoor only)
UE power class	23dBm (200mW) This corresponds to the sum of PA powers in multiple Tx antenna case
Inter-cell Interference Modelling	UL: Explicit modelling (all cells occupied by UEs), DL: Explicit modelling else cell power = Ptotal
Antenna configuration	2 tx , 2 rx antenna ports, or 4 tx , 4 rx antenna ports
Antenna gain + connector loss [Motorola: reference for these values?]	5dBi
Placing of new nodes and UEs	See Table E3
Minimum distance between new node and regular nodes	>=75m

Minimum distance between UE and regular node	>= 35m
Minimum distance between UE and new node (RRH/Hotzone, Femto, Relay)	For outdoor RRH/Hotzone > 10m For indoor RRH/Hotzone >= 3m
Minimum distance among new nodes	40 m

*1 Outdoor RRH/Hotzone model 1 is based on TR 25.814 and IMT.EVAL UMi NLOS model, outdoor relay and outdoor RRH/Hotzone model 2 LOS and NLOS path loss models are based on field measurements and LOS/NLOS probability functions for macro to UE and macro to relay are based on ITU models and probability functions for relay or pico to UE are based on field measurements; femto and indoor relay path loss is based on ITU-R M1225 single floor indoor office model. Outdoor relay antenna height for both access and backhaul link is 5m. Path loss models for case 3 with 10m antenna height are FFS.

*2 Shadowing fading value for relays is applicable to NLOS component of the path loss. Value for LOS component is FFS.

*3 Cells including macro cells of the overlay network and new nodes.

Fast fading may be modelled using any of the following:

- No fast fading as in current TR

- Fast fading with TU and fixed correlation matrix

- Fast fading with ITU/SCM models or possible simplifications [ref. R4-091103] could also be used. (Detailed proposals to be discussed, e.g., relevant propagation model to use with these.)

For preliminary simulation, all fast fading channel models can be applied. The baseline fast fading model to be used for final evaluation results should be discussed in future (or in WI).

APPENDIX F

Major Functions and System Parameters in MATLAB Toolbox

The main function of the simulator is *main.m*. This has a script *ConfigureSimulatorInputs* which in turn has a script called *SetSysPara* where the various parameters of the scenario to be simulated is specified. These parameters are described in Table I. Note that that the terms *cell* and *sector* are used interchangeably for macro and microcells. *NumBS* is three times the number of eNodeBs. The term *base station* is sometimes used to denote the three base stations in the sectors of an eNodeB. It can also denote macro and micro base stations that are differentiated from small cells. In Table II, a brief description of the major functions used in the toolbox provided.

Table F1: Description of Major Functions

Function Name	Description
GenMacroTopology	Generates the hexagonal eNodeB topology
GenRRH	Generates the small cells or remote radio heads (RRHs) in each cell/sector as per a uniform distribution with a minimum distance constraint from the base station in the cell/sector and other small cells.
GenUEPosForMacro	Generates the UEs based on a uniform distribution over each cell/sector and a minimum distance constraint from the base station in the cell. Used for homogeneous deployments such as Urban Macro and Micro Cells
GenUEPosForHetNet1	Generates the UEs based on a uniform distribution over each cell/sector and a minimum distance constraint from the base station and the small cells in that cell/sector. Used for HetNet configuration 1.
GenUEPosForHetNet4b	Generates the UEs based on a clustered distribution over each cell/sector and a minimum distance constraint from the base station and the cells in that cell/sector. A fraction of the UEs are clustered around the small cells. Used for HetNet configuration 4 b.
GenChannelUMa	Generates the large scale channel between UEs and base stations for a urban macro cell scenario. All UEs are assumed to be outdoors. Generates the path loss, shadow fading, sectorized antenna gains and incorporates other misc losses.
GenChannelUMi	Generates the large scale channel between UEs and base stations for a urban micro cell scenario. A fraction of the UEs are generated indoors. Generates the path loss, shadow fading, sectorized antenna gains and incorporates other misc losses.
GenChannelHetNet	Generates the large scale channel between UEs and base stations for the heterogeneous deployments 1 and 4 b. A fraction of UEs are generated indoors. Generates the path loss, shadow fading, sectorized antenna gains and other misc losses.
CalcAntennaGain	Generates the combined gains of the horizontal (azimuth) sectorized and the vertical (elevation) antennas for a given UE to all base cells/sectors.

UE2BSAssoc	Associates each generated UE to one base station or small cell (in case of heterogeneous deployments) based on received signal power. The node (base station or small cell) with maximum received power within the handover margin is selected.
PlotNetworkTopology	Plots the hexagonal grid layout with the eNodeBs at the center and also plots the location of the UEs. Note that the function can be easily extended to plot the location of the small cells similar to how the UEs have been plotted.

Table F2: Description of Fields in System Parameters

Field Name	Default Value	Description
Basic System Parameters		
Center Frequency (Hz)	Deployment dependant	Center frequency
TxPower (dBm)	Deployment dependant	Transmit power of the macro/micro cell
BandWidth (MHz)	10	System bandwidth
HandOverMargin (dB)	1	Handover margin
UENoiseFigure (dB)	7	UE noise figure
Basic Deployment Parameters		
NumBS	21	Number of sectors or cells.
UEHeight (m)	1.5	Height of the UE
BSHeight (m)	Deployment dependant	Height of the base station
InterSiteDist (m)	Deployment dependant	Distance between centers of two adjacent eNodeB hexagons
MinDistMacroUE (m)	Deployment dependant	Minimum distance between a macro/micro base station and a UE
UEVel (m/s)	Deployment dependant	Velocity of the UE
NumUEperCell	Deployment dependant	Number of UEs per cell
IndoorUEProb	Deployment dependant	Probability that a given UE in located indoors
FeederLoss	Deployment dependant	Loss in RF feeder cables
Antenna Related Parameters		
theta tilt (degrees)	102	Tilt of the Elevation antenna response
theta 3db (dB)	Deployment dependant	Half Power Beamwidth of the elevation antenna
phi 3db (dB)	70	Half Power Beamwidth of the azimuth antenna
SLL h (dB)	Deployment dependant	Side lobe level suppression of azimuth antenna
SLL v (dB)	20	Side lobe level suppression of elevation antenna
SLL (dB)	Deployment dependant	Side lobe level suppression of combined antenna
BSAntennaGain (dB)	Deployment dependant	Maximum gain of the macro/micro combined antenna
Small Cell Related Parameters		
RRHHeight (m)	10	Height of the small cell
MinDistMacroRRH (m)	75	Minimum distance between a small cell and the macro
MinDistRRH (m)	40	Minimum distance between two small cells

MinDistRRHUE (m)	10	Minimum distance between a small cell and a UE
RRHAntennaGain (dB)	5	Maximum gain of the combined antenna of the small cell
TxPowerRRH (dBm)	30	Transmit power of the small cell
NumRRHperMacro	4	Number of small cells per sector
rho	2/3	Fraction of UEs clustered around small cells (for configuration 4 b)
RRHRadius (m)	40	Radius of clustered UE locations (for configuration 4 b)