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Increased Energy Efficiency in LTE Networks through Reduced Early Handover

by

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Abstract

Long Term Evolution (LTE) is enormously adopted by several mobile operators and has been introduced as a solution to fulfil ever-growing Users (UEs) data requirements in cellular networks. Enlarged data demands engage resource blocks over prolong time interval thus results into more dynamic power consumption at downlink in Basestation. Therefore, realisation of UEs requests come at the cost of increased power consumption which directly affects operator operational expenditures. Moreover, it also contributes in increased CO_2 emissions thus leading towards Global Warming. According to research, Global Information and Communication Technology (ICT) systems consume approximately 1200 to 1800 Terawatts per hour of electricity annually. Importantly mobile communication industry is accountable for more than one third of this power consumption in ICT due to increased data requirements, number of UEs and coverage area. Applying these values to global warming, telecommunication is responsible for 0.3 to 0.4 percent of worldwide CO_2 emissions. Moreover, user data volume is expected to increase by a factor of 10 every five years which results in 16 to 20 percent increase in associated energy consumption which directly effects our environment by enlarged global warming.

This research work focuses on the importance of energy saving in LTE and initially propose bandwidth expansion based energy saving scheme which combines two resource blocks together to form single super RB, thereby resulting in reduced Physical Downlink Control Channel Overhead (PDCCH). Thus, decreased PDCCH overhead helps in reduced dynamic power consumption up to 28 percent. Subsequently, novel reduced early handover (REHO) based idea is proposed and combined with bandwidth expansion to form enhanced energy saving scheme. System level simulations are performed to investigate the performance of REHO scheme; it was found that reduced early handover provided around 35% improved energy saving while compared to LTE standard in 3rd Generation Partnership Project (3GPP) based scenario. Since there is a direct relationship between energy consumption, CO_2 emissions and vendors operational expenditure (OPEX); due to reduced power consumption and increased energy efficiency, REHO subsequently proven to be a step towards greener communication with lesser CO_2 footprint and reduced operational expenditure values. The main idea of REHO lies in the fact that it initiate handovers earlier and turn off freed resource blocks as compare to LTE standard. Therefore, the time difference (Transmission Time Intervals) between REHO based early handover and LTE standard handover is a key component for energy saving achieved, which is estimated through axiom of Euclidean geometry. Moreover, overall system efficiency is investigated through the analysis of numerous performance related parameters in REHO and LTE standard. This led to a key finding being made to guide the vendors about the choice of energy saving in relation to radio link failure and other important parameters.

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List of Publications

JOURNALS

1) K. Kanwal and G. A. Safdar, "Reduced Early Handover for Energy Saving in LTE Networks," *in IEEE Communications Letters*, vol. 20, no. 1, pp. 153-156, Jan. 2016.

2) K. Kanwal; G. Safdar; M. Ur Rehman; X. yang, "Energy Management in LTE Networks," in *IEEE Access*, vol.PP, no.99, pp.1-1, 2017.

3) G. A. Safdar and K. Kanwal, "Euclidean Geometry Axioms Assisted Target Cell Boundary Approximation for Improved Energy Efficacy in LTE Systems," in *IEEE Systems Journal*, vol. PP, no. 99, pp. 1-9.

4) K. Kanwal, G. Safdar, M. Ur Rehman, "Energy Efficiency Led reduced CO2 Emission in Green LTE Networks", in *EAI Endorsed Transactions on Energy Web and Information Technologies*, vol. 4, October 2017.

5) K. Kanwal, G. Safdar, M. Ur Rehman, "Call blocking and outage probability in energy-efficient LTE networks", Transactions on Emerging Telecommunications Technologies" in Wiley, December 2017.

CONFERENCES

5) K. Kanwal, G. A. Safdar and S. Haxha, "Joint resource blocks switching off and bandwidth expansion for energy saving in LTE networks," 2015 *21st International Conference on Automation and Computing (ICAC)*, Glasgow, 2015, pp. 1-6.

6) K. Kanwal and G. A. Safdar. “Growing green with improved profit through reduced power consumption in LTE networks”. In Proceedings of the Second International Conference on Internet of things and Cloud Computing (ICC '17). ACM, New York, NY, USA, Article 16, 6 pages, 2017.

BOOK CHAPTER

7) "LTE Communications and Networks: Femtocells and Antenna Design Challenges", Wiley Publisher, 2^{nd} / 3^{rd} Quarter 2017

Chapter 5: Energy Management in LTE Femtocells (25 Pages) - (Kapil Kanwal and Ghazanfar A. Safdar)

Acronyms

3GPP	3rd Generation Partnership Project
4G	4th Generations
AI	Antenna Interface
BS	Base-Station
BBU	Baseband Units
BLER	Block Error Rate
BEM	Bandwidth Expansion
BAA	Bandwidth Allocation Algorithm
BB	Base Band
CAPEX	Capital Expenditure
CC	Component Carriers
CQI	Channel Quality Indicator
CDF	Cumulative Distribution Function
DTX	Discontinuous Transmission
EE	Energy Efficiency
ES	Energy Saving
EPC	Evolved Packet Core
EPC	Evolved Packet System
EE-VBEM	Energy Efficient Virtual Bandwidth Expansion
ECG	Energy Consumption Gain
GAS	Green Antenna Switching
ICT	Information and Communication Technology
IOT	Interoperability Testing
LTE	Long Term Evolution
MME	Mobility Management Entity
MBSFN	Multicast and Broadcast Single Frequency Network
MIB	Master Information Block

MCS	Modulation and Coding Scheme
MAC	Medium Access Control
MLB	Mobility Load Balancing
MIMO	Multiple Input Multiple Output
NRT	Non-Real-Time
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
QoS	Quality Of Service
PDN-GW	Packet Data Network Gateway
PAPR	Peak-to-Average Power Ratio
PA	Power Amplifier
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PMI	Precoding Matrix Indicator
PCC	Primary Component Carrier
PDCCH	Physical Downlink Control Channel
PA	Power Amplifier
PL	Path Loss
RF	Radio Frequency
RRU	Radio Resource Unit
RBs	Resource Blocks
RI	Rank Indicator
RS	Reference Signals
RT	Real Time
RBAA	Resource Block Allocation Algorithm
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RBs	Resource Blocks
RF	Radio Frequency

RLF	Radio Link Failure
RWP	Random Waypoint Mobility
RAN	Radio Access Network
SC-FDMA	Single Channel Frequency Division Multiple Access
S.GW	Serving Gateway
SON	Self Organized Networks
SF	Sub Frames
SINR	Signal-to-Noise Ratio
SCC	Secondary Component Carrier
SDN	Software Defined Networking
SWM	Straight Walking Model
TCoM	Time Compression Mode
TRX	Transceivers
TTT	Time To Transmit
UE	User Equipment
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
VLB	Virtual Load Balancing

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Chapter 1

1. Introduction

1.1 Long Term Evolution

The 4rth Generation (4G) technology offers long term evolution (LTE), wireless fidelity (WiFi) and wireless interoperability for microwave access (WiMax) [1-2] whereas LTE is specifically designed for mobile networks and has been adopted by many operators to fulfil subscribers data rate requirements. Wireless communication systems have seen a massive growth in the last few decades from having a couple of individuals to most of the world as their Users (UEs). The tremendous growth in number of mobile UEs and their data rate require more Energy Efficient (EE) network designs, which has become challenging for mobile operators. In the same context, the 3rd generation partnership project (3GPP) [3] laid down ground for future LTE networks and approved its standardization. Operators deploy LTE network over large geographical area in number cells formed by base-stations (BS) which provides seamless link between UEs and network for voice and data transmission. When UE moves from one cell to the next, its control information is passed to the target cell through the process called handover. All BSs have ability to exchange handover related information with each other through X2 interface [4-5] which provides link between BSs as shown in Figure 1.1. However detailed LTE architecture is explained in chapter 2.

In LTE networks, one of the major issues is to avoid or limit signalling overhead and overlapping in control part of the network. Large number of connections between nodes and network fragmentation causes rapid increase in signalling traffic. Any failure in signalling system will drag operators toward increased system latency and outages resulting in to loss of revenues [6-7]. Increased signalling traffic also leads toward increased energy consumption and needs to be looked in carefully. In the same context, next section presents the motivation of this research work.

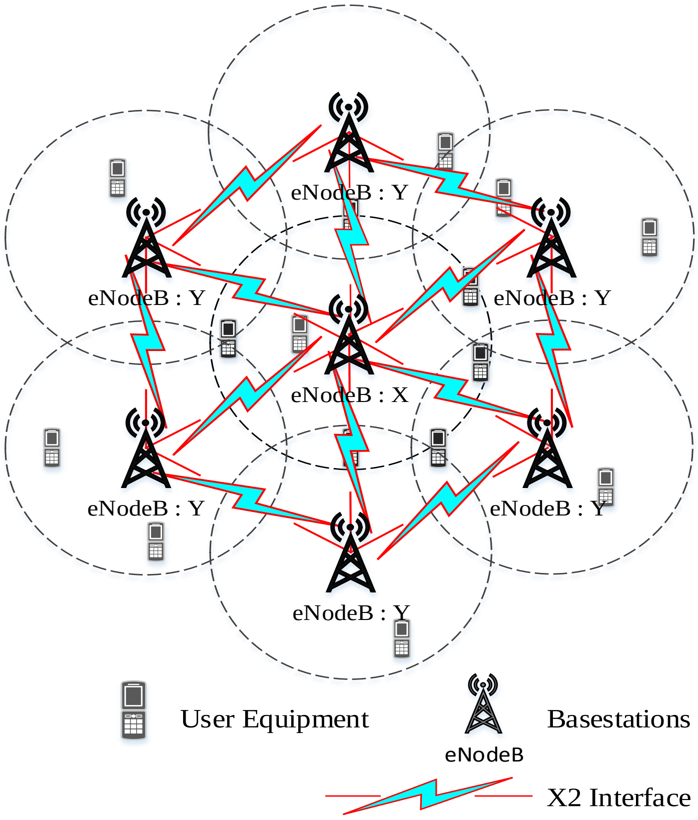


Figure 1.1. X2 interface between BSs

1.2 Motivation

The growing global warming and increased operational expenditures (OPEX) have become major challenges in telecommunication. Therefore, this research focus on reduced power consumption and aim to develop energy saving (ES) scheme for BS in LTE networks. This will help to reduce dynamic power consumption and promote green communication.

1.3 Research Question

LTE is well known technology which has been deployed by numerous mobile operators. In recent years; technological advancements in smart phones and their applications have rapidly raised the number of UEs and their data demands. In order to fulfil enlarged UEs data requirements, BS engages their resources over prolong time intervals thus resulting into increased power consumption. In parallel operators are expanding their network infrastructure by employing additional BSs, thus provision of required Quality of Service (QoS) further adds in increased power consumption. Importantly, BS power consumption is one of the major contributors in OPEX therefore it directly affects OPEX thus impacting operators profit. Both profitability and global warming in cellular networks have become major challenge for operators to survive in competitive markets. Consequently, there is a serious need to undertake research, firstly to achieve increased energy efficiency and secondly to successfully achieve reduced CO_2 emission thereby leading toward greener communication.

This research fully align itself with the above research questions/objectives. It proposes system level EE technique which implement itself in the existing LTE system by intelligently modifying A3 event, i.e. handover process. Our proposal exploits the phenomenon of handover and present as novel idea of reduced early handover with bandwidth expansion to achieve increased energy saving (ES).

1.4 Main Contribution

The objective of this research is to investigate increased power consumption in LTE networks and its impact on OPEX and global warming. To proposed ES scheme; detailed critical analyse of numerous existing solutions have been discussed. On the bases of critical analysis, novel ES scheme is proposed which help reduced BS dynamic power consumption thus resulting into reduced OPEX and carbon emission. Proposed ES scheme is implemented and compared with LTE standard and other state of the art using network simulation tools. Moreover, this research can be used to guide the vendors about the choice of ES percentage in relation to radio link and profitability. Following presents chapter wise contribution of this research in detail.

1.4.1 Contribution of the Research (Chapter wise)

The main contribution of this thesis in terms of chapters is summarized below:

Chapter 2

This chapter presents the importance of ES in of LTE networks, whereas comprehensive study of the existing ES techniques is offered. In addition, various ES schemes are critically analyzed through detailed investigation into their strengths and weaknesses. The open research issues and challenges are also described in this chapter which further used to propose bandwidth expansion based ES technique in next chapter.

Contribution of this chapter is **literature review,** and has been published as Chapter 5 in *"LTE Communications and Networks: Femtocells and Antenna Design Challenges"*, Wiley Publisher, 2nd / 3rd Quarter 2017

This work is also published in **IEEE ACCESS.**

Chapter 3

On the bases of critical analysis of existing ES schemes discussed in previous chapter; In this chapter, novel ES scheme is proposed to reduce dynamic power consumption at downlink in BS. Proposed scheme employs the bandwidth expansion through time compression with resource blocks (RBs) switching off thus resulting into reduced physical downlink control channel (PDCCH) signaling. The novel feature of proposed scheme lies in the fact that it offers hybrid ES by merging bandwidth expansion with RBs turning OFF. Proposed scheme reduces PDCCH overhead through extended bandwidth which results into decreased dynamic power consumption. Additionally, turning OFF idle resources provides enhanced ES opportunities. The proposed work is proven to be step towards reduced OPEX and lesser CO_2 footprint. Continuing on, propose ES scheme is combined with novel handover idea in next chapter.

Contribution of this chapter is a **novel Joint Resource Blocks Switching Off and Bandwidth Expansion for ES in LTE Networks and its impact on Greener Communication and OPEX.** This research work has been published in *ICAC Conference 2016* and *ICC Conference 2017*. Part of this work has also published in *Endorsed Transactions on Energy Web and Information Technologies.*

Chapter 4

This chapter exploits the phenomenon of handover and presents a novel *hybrid* idea of *reduced early handover (REHO)* with bandwidth expansion (proposed in chapter 3) to achieve improved ES in LTE networks. Work presented takes the idea of early handover further, and incorporates it with bandwidth expansion, and offers a complete work by investigating the impact of improved energy on CO_2 emission, OPEX and profitability by the employment of commercial tariffs. System level simulations have been performed to analyze the performance of proposed scheme. The time difference between REHO based early handover and LTE standard handover provide opportunities for turning off resources for ES purpose. In the same line the estimation of time difference is discussed in detail in next chapter.

Contribution of this chapter is **novel Reduced Early Handover for ES in LTE Networks.** The proposed ES scheme has published in *IEEE Communication letter*.

Chapter 5

This chapter further investigates previously proposed REHO scheme (chapter 4), through comprehensive performance analysis of various parameters over varying hysteresis and velocity. *REHO*, compared to standard LTE A3 event, initiates early handover thereby resulting into reduced energy consumption. In the same context, this chapter presents axioms of Euclidean geometry to estimate the target cell boundary towards calculation of the time difference ΔT between standard LTE and REHO. Early handover (ΔT) in REHO is calculated in terms of transmission time intervals (TTIs) and results into improved energy efficiency at the cost of slightly increased radio link failure (RLF). The key finding of the chapter is the non-sensitivity of UEs towards velocity in standard LTE, whereas REHO leads to considerably improved energy efficiency at low velocity thereby making it an advantageous scheme for urbanised densely deployed LTE networks. Outcomes of chapter 5 provided also deliver a guideline for vendors to choose suitable value of hysteresis, while achieving appropriate results of ES and RLF.

Contribution of this chapter has been published in *IEEE System Journals*.

Chapter 6

This chapter concludes research work carried out in the thesis. Future work and open research issues are also discussed in this chapter, which could be very useful for future research work.

The contribution of this chapter is the **open research areas with guideline for future research work.**

1.5 Thesis organization

Following the introduction and objectives of this research in chapter 1, Chapter 2 presents comprehensive critical analysis of existing ES techniques in LTE networks. It discusses advantages/disadvantages and working of existing state of the art. On the bases of critical analysis presented in chapter 2; bandwidth expansion based ES scheme is proposed in chapter 3. Further system level LTE simulator with its important parameters is also described in this chapter. Subsequently the power consumption, profitability and CO_2 emission models are defined. Then novel early handover based ES technique is proposed and combined with bandwidth expansion scheme (explained in chapter 3) in chapter 4. In the same line, chapter 4 presents complete proposed ES scheme based on the bandwidth expansion and reduced early handover concept. Furthermore, various mobility models are employed to validate the working of proposed ES scheme in realistic scenarios, also the benefits of ES and its impact on OPEX and global warming are thoroughly examined in this chapter. Work in chapter 5 is based on ES scheme presented in Chapter 4. This work investigates the phenomenon of early handover by calculating the time difference delta T (ΔT) between standard and early handover based on proposed ES scheme, which is further used to estimate ES for comparative analysis. In parallel overall system efficiency is also investigated through incorporating numerous performance related parameters. This research work is finally concluded in chapter 6.

Chapter 2

2. Energy Management in LTE Networks

2.1 Introduction

This chapter presents a comprehensive study of the existing ES techniques for LTE networks. Usability of various methods are critically analyzed through detailed investigation into their strengths and weaknesses. Particularly BS power consumption in LTE has become a major challenge for vendors to stay green and profitable in competitive cellular industry. Thus, importance of the topic has attracted enormous researchers worldwide. ES approaches proposed in the literature can be broadly classified in four categories; 1) EE resource allocation, 2) load balancing, 3) carrier aggregation and 4) bandwidth expansion. Each of these methods has its pros and cons leading to a trade-off between ES and other performance metrics resulting into open research questions.

Wireless communication has become one of the basic provisions of the modern world. Since the inception of first radio communication system by Marconi [8], wireless communication systems have seen a massive growth in mobile UEs over last few decades [9-10]. The concept of frequency reuse was first introduced in cellular radio communication systems by american telephone & telegraph (AT&T) [11]. Further developments in radio communication introduced digital cellular systems, which pass through a long chain of evolution known as the Generations (G). It has seen usage of 1G, 2G, 3G and now 4G as the communication standard with each resulting into enhanced performance of cellular systems [12-13]. Aiming towards the key achievements such as short transmission time, high throughput, low latency and security [14-15], these systems generally consist of BSs connected to core network. Each BS has designated coverage area, called cell and communicates directly with UEs within its coverage [16-18]. Whenever UE moves from serving cell to neighbour cell, its transfer of control is initiated through handover process [19-20]. LTE transmits digital broadband packets over Internet Protocol (IP) while offering peak data rate of 100 – 300Mbps [21-23]. The increased data rate is achieved through the employment of Orthogonal Frequency Division Multiple Access (OFDMA) which promises low latency, high data rate and packet optimized radio access [24]. This improves the performance of services compared to the previous generations of the cellular networks thus helped LTE systems to gain rapid popularity both commercially and academically.

2.2 Background

The terminology of Generations in cellular networks generally refer to the enhancements of the services i.e. higher data rates, backward compatibility, new or wider frequency bands, high capacity. New generation have seemed about every ten years since the first version called 1G introduced in 1981 which offered voice communication through analog data transmission. Since radio resources were allocated regardless of their utilization therefore 1G was not spectrum efficient. Moreover, encryption was not possible due to the analogy data transmission, which became ground for further development in this area [25] thus resulting in to global system for mobile communication (GSM) system based on 2G. The GSM was different from first generation in that it uses Time Division Multiple Access (TDMA) and digital technology, which was suitable for voice and circuit switched data communication.

The employment of TDMA allow mobile UEs to share similar frequency channel by separating the signals into various time slots. UEs transmit signals (one after the other) during specific allocated time slots. which allow numerous UEs to share common wireless transmission medium using dedicated timeslot. Significantly TDMA is a type of Time Division Multiplexing (TDM). However, the major difference is that with TDMA, multiplexed signals come from different sources thus having multiple transmitters unlikely TDM where there is one transmitter and one receiver. The 2G is the first digital cellular system which offered data transmission in binary zeros and ones over narrowband digital circuits instead of analog signal waves thereby resulting into increased bandwidth for voice. Further advancements introduced 2.5G which offered data transmission in digital packets instead of circuits with peak data rate of 171 Kbps. The Global Packet Radio Access System(GPRS) is well known application of 2.5G. Since these systems were based on TDMA and operated on narrowband frequencies; therefore, they failed to fulfil enlarged number of mobile UEs data requirements [26-28] thus forced researchers to introduce more advance systems which can accommodate increased UEs and their data/voice requirements. Importantly the narrowband frequency refers to those communication operations which uses frequency contents within the coherence band of a frequency channel. More improvements in mobile technology lead towards 3G innovation which offer peak data rate of 3Mbps. Compared to earlier generations; 3G introduced completely different network architecture based on UTRA (Universal Terrestrial Radio Access) and Frequency Division Duplex (FDD) [29]. Both Universal Mobile Telecommunication System (UMTS) [30] and Enhanced Data Rates for GSM (EDGE) [31] are 3G based well known standards. In last few decades, there was fast increase in number of mobile UEs which resulted into enlarged data traffic over network. Telecommunication facilities expanded from voice communication to the higher data rate services which cover many fields including entertainment, medical, engineering and aviation. In parallel, High Speed Packet Access (HSPA) [32] protocol based 3.5G is additional enhancement in existing systems and offer peak data rate of 14Mbps. Notably 3.5G technology became outstanding invention, however it also had downsides. Since these systems were based on circuit switching technology therefore 3.5G did not used resources efficiently. In parallel Radio Network Controller (RNC) was being held outside BS, thus resulted into additional data traffic flow in network [33]. Next to this 4G which based on digital broadband packets transmission over IP instead of circuits thus offers peak data rate of 100 - 300Mbps theoretically. The RNC moved inside the BS in 4G networks thereby resulting into reduced traffic flow. Short transmission time, high throughput, low latency and security are the key achievements on 4G networks. In the same context, fundamentals of LTE networks are discussed in next section.

2.3 Fundamental of LTE Networks

Though LTE network promises high data rate, however there are many challenges in its implementation [34].

Interworking/ Interoperability: The previous technologies (i.e. 1G till 3.5G) were only required to interoperate with its predecessor technology, while LTE works with all other primary cellular mobile standards. The varying combination of devices, network interfaces and equipments which occur in LTE placements increases the complexity of both end to end functionality and Interoperability (IOT) testing. To successfully address this challenge, variety of equipments (i.e. radio network controllers, Serving Gateways (S-GW), antennas, etc) manufactured by different vendors must be tested across diverse network nodes.

All IP Networking Architecture: LTE includes new network related elements i.e. Mobility Management Entity (MME), S-GW, Packet Data Network Gateway (PDN-GW) thus resulting into complex deployment. Moreover, the Evolved Packet core (EPC) must be dimensioned to support higher data rate with lower latency. EPC must have ability to accommodate multi heterogeneous Radio Access Networks (RANS), 3GPP based and non 3GPP based systems (e-g Wimax).

Impact on Transmission and RAN: In compliance with 3GPP standard; IP Multimedia Subsystem (IMS) must be used for voice services, while the large size of network is the major hurdle in deployment of IMS. Therefore, fall back to circuit switch is an alternative, where UEs switched back to 2G/3G networks to support voice calls.

Spectrum Impact On BS: LTE employs OFDMA thus appropriate handling of multipath propagation without the necessity of complex receivers is one of the core objective. However, the Peak to Average Power Ratio (PAPR) property of transmitted signals reduces BS efficiency thus enforcing operators to more emphasis on accuracy. Next to this, the Radio Frequency (RF) planning of OFDMA is similar to GSM systems while orthogonality of radio eliminates intra cell interference. The most commonly used spectrum allocation is at carrier frequency of 2.14 GHz which is available worldwide, however it requires high capital cost for deployment.

2.4 Radio Protocol Architecture

The LTE radio protocol architecture can be separated in to UE plane and control plane architecture. Importantly radio protocol for uplink transmission is similar to downlink with little difference in transport format selection. LTE RAN provides one or more bearers to which IP is mapped according to QoS requirements. Following presents important components of radio protocol architecture [35-36]:

Packet Data Convergence Protocol (PDCP): performs IP header compression using robust header compressor (ROHC) thus helps reducing in number of bits to transmit over radio medium. ROHC is a well-known algorithm in LTE networks and have been employed by many telecommunication vendors. The PDCP [37-38] is located in the radio protocol stack in LTE air interface on the top of Radio Link Control (RLC) layer and responsible for integrity, protection of data transmitted, ciphering and in sequence delivery at the transmitter end. While at receiver end, PDCP is responsible for deciphering and decompression processes.

Radio Link Control (RLC): is responsible for segmentation, identical detection, retransmission handling, and in order delivery to higher layer. RLC delivers services to the PDCP in the form of radio bearers.

Medium Access Control (MAC): is responsible for multiplexing of logical channels, hybrid Automatic Repeat Request (ARQ) retransmission, downlink and uplink scheduling at BS. The MAC provide services to RLC in the form of logical channels.

Physical Layer (PHY): responsible for modulation/demodulation, coding/decoding, multi antenna mapping and many other physical layer functions. PHY layer provides services to MAC layer in the form of transport channels.

Since this research work also consider few aspects of both MAC and PHY layers therefore both layers further discussed in detail as follows.

2.5 LTE Physical/MAC Layer

LTE provides major enhancements in cellular technology, while designed to meet carrier needs for high speed data, multimedia transport and high capacity voice support. The PHY of LTE is known as highly efficient medium of transmitting both data and control information. It employs advanced technologies including OFDMA as a multiplexing scheme on the downlink, where UEs are allocated with required resources for predetermined time intervals [39]. These resources are called as RBs expanded in both frequency and time dimensions. Resources allocation is handled by a variety of schedulers employed in downlink at the BS which is the part of MAC Layer [40]. Each RB carries both data and control information between BS and mobile UEs. To adequately explain RBs within the context of OFDMA, PHY layer frame structure is described in detail in next section [41].

2.5.1 LTE PHY Layer

LTE PHY layer architecture consist of number of frames, while each frame is 10ms in duration is further subdivided into 10 sub-frames, each being 1ms long. Further each sub-frame is divided into two slots, each sized 0.5ms contains one RB whereas total number of resources depends on transmission bandwidth. In the same context, each RB (sized 180 kHz) consists of a 72 Resource Elements (RE) which is the smallest resource unit. There are 12 subchannels and 6 to 7 symbols in each RB. In this view LTE uses OFDMA for data transmission over narrowband carriers of 180kHz (1 RB) instead of spreading single signal over the whole 5 MHz carrier bandwidth. For example, in HSPA with 20MHz the overall transmission bandwidth consists of 4 subcarriers each with 5 MHz, in contrast OFDMA transmission employee hundreds of subcarriers which transmitted over same radio link to the receiver. The number of subcarriers could be range from few hundreds to the several thousand with subcarrier spacing ranging from few kHz to a several hundred-kHz. Due to the orthogonality; two subcarriers do not effect from any interference between each other. In LTE, overall bandwidth is range from 1.4, 3, 5 10, 15, 20 MHz while these bandwidths allow 6, 15, 25, 50, 75 and 100 RBs respectively. BSs allocate resources to UEs for data and voice transmission at the cost of their power consumption.

2.5.2 Downlink Physical Channels

LTE PHY layer uses downlink physical channels which determine how data is processed and then mapped at RBs. Physical channels carry both data and control information and mapped to specific transport channel. There is fixed linkage between physical channel types and transport channels types, while there are four transport channels at downlink i.e. Broadcast Channel (BCH), Downlink Shared Channel (DLSCH), Paging Channel (PCH), Multicast Channel (MCH). LTE PHY consists of three physical data channels and three physical control channels. Since this research work is mainly focus on physical downlink control channel (PDCCH) channel, therefore only PDCCH is described as follows [42-43].

- ***PDCCH:*** Physical Downlink Control Channel (PDCCH) used to support efficient data transmission. PDCCH and PDSCH are the two key channels among rest of the four above discussed physical channels. Every sub-frame contains PDCCH signals as well as reference signals. The PDCCH channel carries control information about the data carried in PDSCH in the current sub-frame and contains information about the those RBs used by UEs for uplink data transmission. PDCCH carries Downlink scheduling Control Information (DCI) messages which contain information about the resource allocation, modulation and coding scheme and allow UEs to decode data sent in PDSCH. This research work target PDCCH because it is the main contributor in overhead transmission. Notably as per 3GPP specifications; PDCCH contributes approximately 26% in total transmission overhead caused by control signals. One of the common drawbacks of all control signals is that they occupy capacity and consume power which causes signalling overhead, whereas PDCCH is one of the major signalling overhead's contributor. Among many efficient features of PDCCH there are drawbacks associated with it. Every subframe carry PDCCH signals, while these signals can be configured to occupy 1st, 2nd or 3rd OFDMA symbols in each time slot of each RB. Accordingly, PDCCH's produce approximately 26 percent signalling overhead which contributes in additional energy consumption. However, energy consumption can be reduced to limits this signalling overhead of PDCCH. Due to the above mentioned reason this research mainly focus on reducing PDCCH's overhead signalling thus resulting into reduced energy consumption and increased capacity. Next to this MAC layer is discussed in next section.

2.5.3 Medium Access Control (MAC)

MAC layer consists of five logical control and two data/traffic channels. It is responsible for logical channels multiplexing and mapping them with appropriate transport channel, it also requests some services in the form of transport channels from PHY layer. Further downlink packet scheduling is also part of MAC layer, which control the allocation of shared channel transmission to the UEs depending on channel quality. Packet scheduling at BS occur at every Time to Transmit Interval (TTI) which allow utilization of information on the instantaneous channel quality for each UE [44].

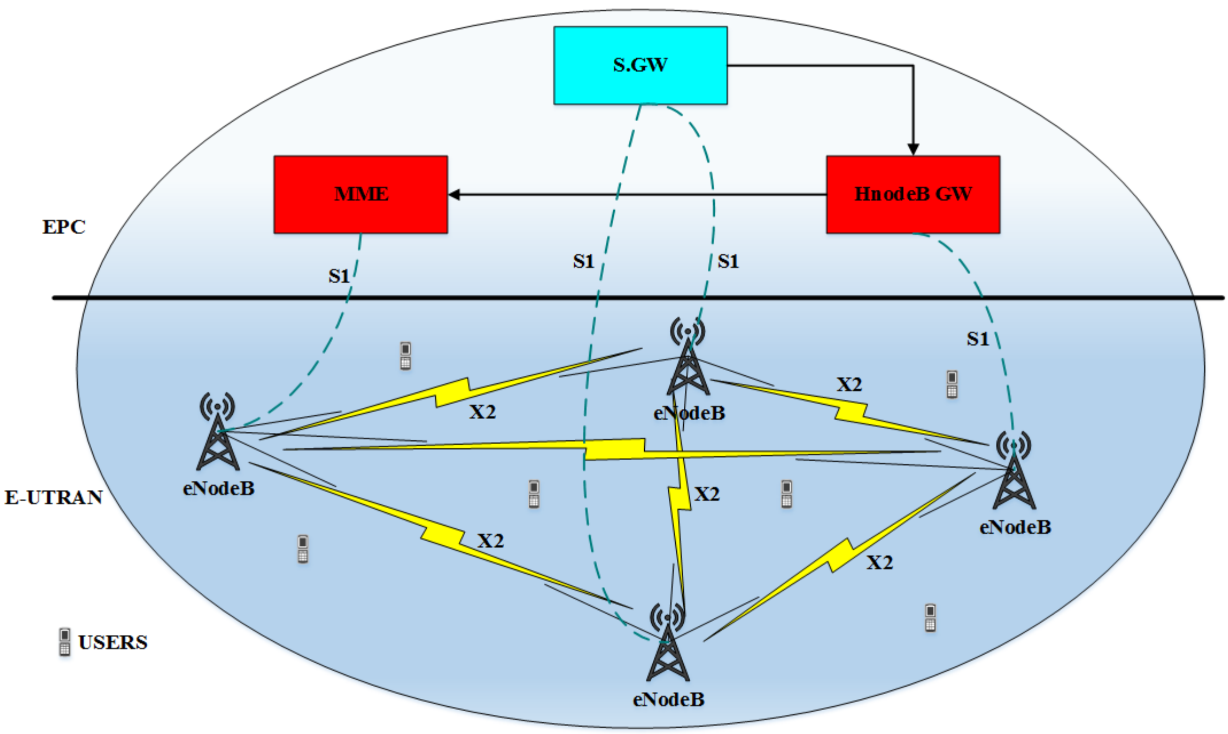
2.6 Reference Signals

LTE uses Reference Signals (RS) for channel estimation, while there are five types of RS, each used for a different purpose as described below. One of the most important is cell specific RS which can be used to calculate the received power of UEs from BS during the handover process [45-46].

- *Cell-specific RS:* Known as common reference signals available for all UEs.
- *UE-specific RS:* Embedded for specific UE and used for demodulation.
- *MBSFN:* Multicast Broadcast Single Frequency Network is used for Multicast or Broadcast operations.
- *Positioning RS:* Embedded in certain positioning sub-frames for UE location measurement.
- *Channel state information RS:* Designed for estimating the downlink channel state.

2.7 Architecture of LTE Networks

Since this chapter is focused on energy management in LTE networks, therefore this section presents a brief overview of the LTE architecture. The 4G systems usually provides low latency, high data rate and packet optimized radio access. Compared to 3G, 4G additionally provide international roaming and compatibility with other legacy networks [47-48]. The 4G systems make use of OFDMA and Single Channel Frequency Division Multiple Access (SC-FDMA) schemes to support flexible bandwidth [49-55]. LTE architecture is generally based on EPC, Universal Terrestrial Radio Access (UTRA), and Universal Terrestrial Radio Access Network (UTRAN), each of which communicates with core network air interfaces and radio access network [56-57]. Figure 2.1 illustrates overall architecture of the LTE networks showing both EPC and evolved UTRAN (E-UTRAN) [58-60] while Table 2.1 summarizes



the core elements of the LTE architecture.

Figure 2.1: Architecture of LTE networks

Table 2.1: LTE networks components

Components	**Description**
Evolved Packet System (EPS)	Provides IP connectivity between end UEs using UTRAN.
MME [61]	Responsible for authorization, security, handover, roaming and mobility of UEs.
S1 Interface [62]	It connects EPC with BSs.
S.GW	EPC terminates at this node. It is connected to EUTRAN through S1 interfaces. Each UE is allocated with unique S.GW which is responsible for handover, packet routing and forwarding functions.
PDN-GW	PDN-GW provides UEs with access to packet data network by allocating IP addresses. It is also responsible for secure connection with untrusted devices from non-4G networks.
HnodeB	Femtocells [63] are employed to improve seamless connectivity in coverage holes.
eNodeB (BS)	Also known as BS that serves the UEs.
HnodeB GW	Provides connection to the core network.
X2 Interface [64]	Provides communication between two BSs.

2.8 Current Issues in LTE networks

Though LTE has proven to be a promising technology, it is a complex network and there is one of the most important challenge that need to be carefully addressed for optimum functionality.

2.8.1 BS Energy Efficiency

In LTE networks; BS provides high data rate at the cost of high dynamic transmission power. Since, high transmission power results in increased energy consumption and thereby increases OPEX, energy management has become major challenge in LTE networks to stay profitable and to reduce global warming [65].

2.9 Power Hungry Elements in BS

Each BS in cellular networks consists of Baseband Units (BBU) with one or more transceivers. Each transceiver contains RF part, Power Amplifier (PA) and antennas connected through cables [66-68]. All these components are located very close to each other in a unit called Radio Resource Unit (RRU). PA is the main power hungry element in this unit [69]. Since LTE uses OFDMA [70-72] and normally PA operates at a level that is 6-12 dB lower than the saturation point, this results into lower adjacent channel interference. Power consumption at BS can be categorized as static and dynamic power consumption [73]. Static power consumption belongs to hardware used in BS and remains nearly constant. Dynamic power (also known as communicational power) on the other hand, depends on traffic load between BS and UEs [74-75]. The focus of this chapter is to investigate, classify and critically analyze existing ES techniques to control the dynamic power consumption. In the same line, next section discusses the role and importance of ES in mobile networks.

2.10 Role of ES in Cellular Networks

The augmented power has become major obstacle for environmental and economic aspects [76-77]. Vendors highlighted the raising trend of power consumption due to the increased data traffic. Number of UEs of the mobile networks has 10 percent annual increase across the world with an increase of 25-50 percent in each UE data requirements [78]. Therefore, provision of high data rate demanding services with minimum power consumption has become a major challenge for vendors to stay profitable [79-80]. The ICT is responsible for approximately 10 percent in worldwide power consumption while it is contributing 2 percent in global warming [81-82]. Noteworthy, ICT contribution in global warming will become 3 percent by 2020 [83-84]. Since, BS consumes major part of energy in LTE networks, reducing power consumption at BS could help reducing global warming and OPEX [85]. Vendors choose to deploy automated networks to facilitate ES [86]. The 3GPP has already introduced Self Organized Networks (SON), which increase the level of automation achieved in operation and maintenance, thereby resulting in a decreased OPEX [87]. Apart from other functionalities, SON also provides opportunities for incorporation of enhanced ES techniques that can help achieve reduced OPEX values. Technologies based on the concept of SON (e.g. LTE), can enjoy a 19 percent reduced OPEX due to advanced ES techniques [88]. In the same line various ES schemes have been discussed in next section.

2.11 Classification of ES Schemes

The literature presents considerable amount of research work on energy efficiency in LTE systems. Power consumption at BS can be classified into two main categories: dynamic power consumption (also known as communicational power consumption) and static power consumption (also termed as hardware based energy consumption) as shown in Figure 2.2.

Static Power Consumption: The static power is purely hardware based constant power consumption, which BS needs to cater for necessary operations. The static power consumption can be improved by EE hardware designs and subsequent intelligent deployments. However, this work mainly focus based on dynamic power consumption.

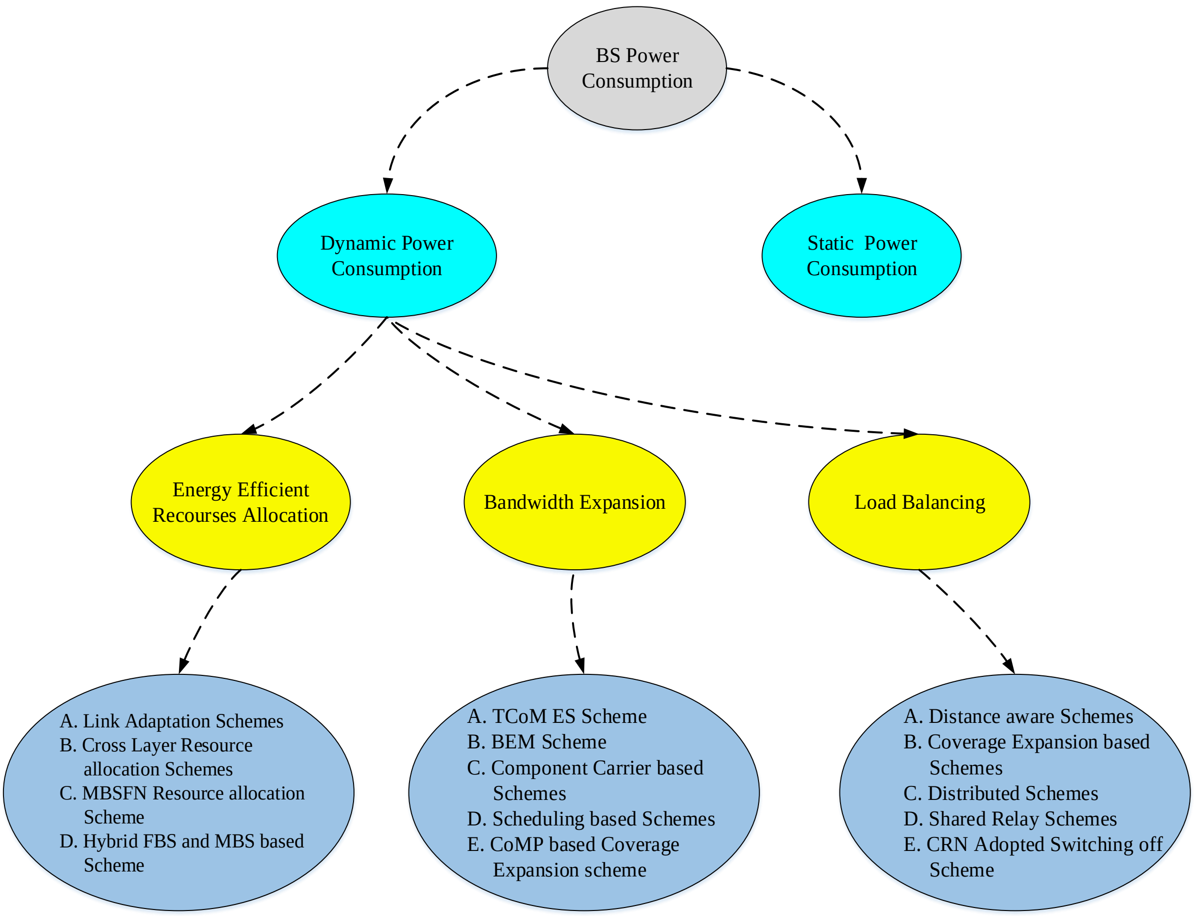


Figure 2.2: Classification of ES Schemes.

Dynamic Power Consumption: The dynamic power consumption depends on BSs downlink transmission while it is directly affected by resources allocation to the UEs. In this view, dynamic power could be reduced by turning off of BS operations during idle states. Therefore, dynamic power management has attracted attention of researchers, whereas it could be classified in to three main categories i.e. EE resources allocation, bandwidth expansion and load balancing as shown in Figure 2.2.

The dynamic (a.k.a. communicational) power consumption can be reduced by appropriate activation and deactivation of BSs transceivers also known as Discontinuous Transmission (DTX) during off peak time periods. The DTX based schemes allocate Multicast and Broadcast Single Frequency Network (MBSFN) sub-frames through traffic load consideration [89-90].

The power aware algorithm analyzes the traffic that cells need to serve, then calculates the amount of resources required and distributes them among the sub frames (SFs) to minimize the power consumption. In lightly loaded conditions, there is a possibility of some frames being not utilized, which could help to achieve improved energy conservation by configuration and turning off of idle frames. The micro cell DTX significantly reduces power consumption during low traffic rate, however it doesn't work during high traffic loads because there are no empty sub frames left.

Aggregation of RBs through carrier aggregation algorithms can also help achieve better ES [91]. This helps in reduced overheads thereby increasing energy conservation. ES can also be achieved through suitable cells coverage expansion and turning off of idle BSs [92]. Importantly, mentioned scheme initially splits cells in two main categories, i.e. cooperative cells and dormant cells. Where, cooperative cells serve associated UEs while dormant cells are turned off during low traffic time periods for ES. The most recent research work has established the idea of integrating Cognitive Radio Networks (CRNs) [93] with LTE infrastructure for improved ES. This predominantly lies in the fact of isolating UEs in two categories (i.e. Pus and SUs). During awake periods, BS transmits PUs data over licensed spectrum while in contrast SUs data is sent over unlicensed spectrum. BSs are switched in to sleep mode right after completion of data packets transmission thus resulting into opportunities for improved power conservation. Distance-aware schemes, which involve switching off of the BS having greater distance from UEs, can also help to obtain better ES [94-95]. These schemes reduce energy consumption by appropriate activation/deactivation of the BS, based on information of varying distance and load. Another dynamic traffic-aware approach is introduced in [96], which uses time varying traffic information for energy conservation. Each BS divides its cell in different number of sectors, then switch off appropriate sector (with low traffic) providing power saving opportunities [96]. Centralized and distributed schemes which engage UE migration also help achieve better ES [97-98]. Centralized schemes select highest loaded BS through analysing traffic information and determine if it could accommodate more UEs. Considering selected BS, if available bandwidth is greater than the capacity required to serve neighbour cell, UEs with lowest load traffic will then be shifted towards the heavily loaded BS resulting into switching off of lightly loaded BS for reduced energy consumption. Compared to centralised, distributed schemes in contrast, select pair of BSs and then determine the ES state of each BS. Initially, schemes activate ES on particular BS, which examines neighbour cells list, and select one BS with lowest load forming a pair. The BS preferred to keep powered ON is the one that could accommodate more UEs. Another work in [99] shares relay between different operators thus resulting into ES. In [100] authors introduced an energy-efficient link adaptation scheme that combines the traditional link adaptation with power control, thereby resulting into improved energy efficiency at the BS. This scheme uses BSs transmitted power as a new feedback parameter and predicts an optimal set of parameters in order to maximize the BSs energy efficiency and satisfy the Block Error Rate (BLER) constraint for the channel state. Another interesting scheme is presented in [101], which suggests an energy-efficient resource allocation scheme that operates in multi-cells OFDMA-based LTE networks. This method combines dynamic RB allocation with energy-efficient power allocation and reduces the overall BSs power consumption. Bandwidth expansion scheme with load balancing is introduced in [102] which employs the idea of moving UEs from overlapping area of lightly loaded cell to the heavily loaded cell. The Time Compression Mode (TCoM) is presented in [103], which saves power by reducing control signals overheads transmission. RBs are compressed together in TCoM, either in time or frequency domain by usage of higher order modulation. ES is achieved through reduction in overhead signalling by appropriately turning off of the unused RBs [103]. Next to this, intelligent resource allocation and power control can also help reduce dynamic power consumption thus resulting into improved energy efficiency. Noteworthy, EE scheme while deployed at every BS allocates lower transmit power to suitable resources in line with the associated Signal to Noise plus interference (SINR) ratio [104]. EE BSs deployment too has helped for improved energy conservation [105].

A lot of research work has been carried out to develop different ES Schemes, which help to reduce dynamic power consumption. However, increasing trends of OPEX and global warming indicate that there is always needed to do more research work to achieve enhanced ES systems for future wireless systems. Based on discussion above, broad classification of the ES schemes is presented in Figure 2.2. while detailed insight into individual schemes are provided in the following sections.

2.11.1 EE Resource Allocation

In order to transport UE data across wireless medium, wireless cellular systems employee various control channels which segregate dissimilar types of data and transport them across radio access network in orderly routine. LTE consist of physical channels, transport channels and logical channels. Further, physical channels consist of Physical Broadcast Channel (PBCH), Master Information Block (MIB) and PDCCH. Intelligent switching on and off of these control channels can result in increased ES. Some EE schemes in EE resource allocation category are explained below.

2.11.1.1 Link Adaptation Schemes

LTE provides high data rate through the effective resources utilization in available bandwidth. The Channel Quality Indicator (CQI), Precoding Matrix Indicator (PMI) and Rank Indicator (RI) parameters play key role in efficient use of resources. PMI determines which precoding matrix should be used for downlink transmission while RI presents the number of layers that should be used for downlink transmission. CQI is reported from UEs to the BS that contains information about the supported Modulation and Coding Schemes

(MCS). CQI plays major role in selection of MCS at downlink in BS while CQI value ranges from 0 to 15. Higher value of CQI indicates use of higher modulation scheme while BS can use higher coding rate for increased energy efficiency [100]. An EE link adaptation scheme, which combines traditional link adaptation with power control resulting into improved energy efficiency at BS is presented in [100]. This scheme uses BS transmitted power as a new feedback parameter and predicts optimal parameters that maximize the BS energy efficiency and satisfy the Block Error Rate (BLER) constraint which is used for demodulation tests in multipath conditions during radio link monitoring. This scheme can be best described with the help of LTE based downlink transmission model shown in Figure 2.3. UE estimates channel gain between BS and itself to calculate the parameters RI, PMI, CQI and transmit power. These parameters are then feedback to BS through feedback channel as shown in Figure 2.3. The BS uses feedback received from UEs as input parameter to adjust its transmission power; where RI helps to determine the code word, CQI helps to select MCS scheme for each transmission, and PMI is used by BS to select the precoding matrix.

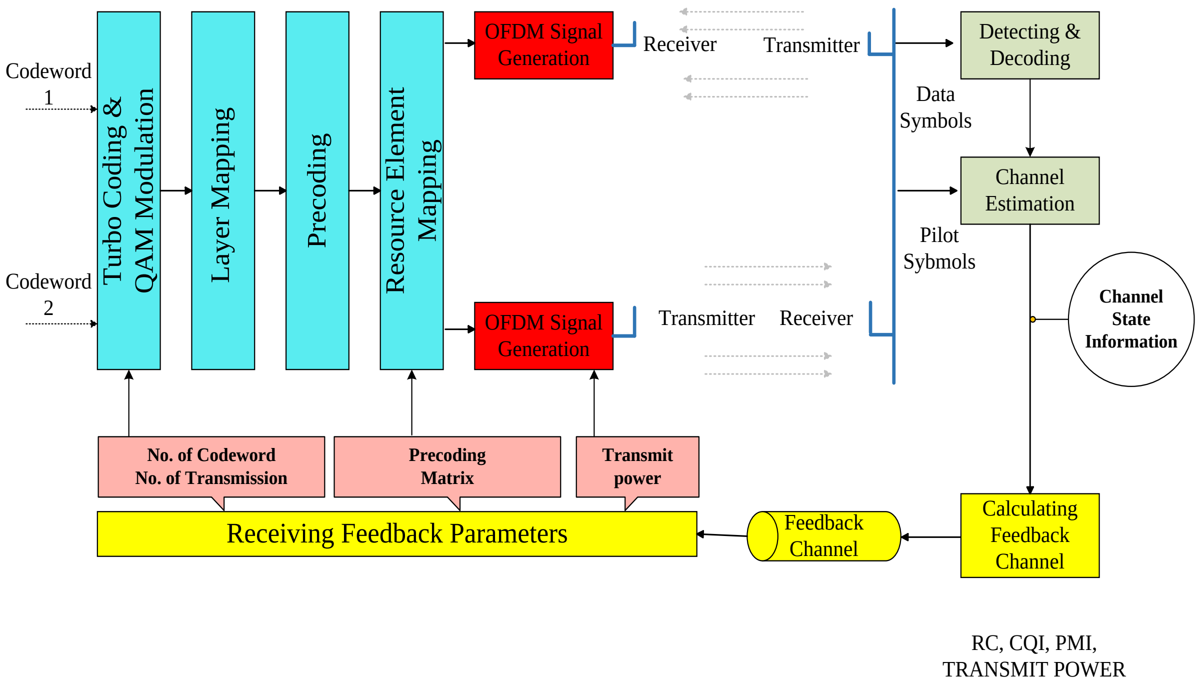


Figure 2.3: Link Adaptation Scheme based downlink transmission.

2.11.1.2 Cross Layer Resource Allocation Schemes

A cross layer based EE resource allocation scheme for multi-cells OFDMA based LTE networks is presented in [101]. This technique encompasses PHY and MAC layers combining dynamic RB allocation at MAC layer with EE power allocation at PHY layer thus resulting in reduced overall power consumption by the BS. Dynamic RB allocation is based on feedback (energy efficiency indicator) that is used to adjust scheduling process. This method also promotes the UEs fairness through allocating equal resources to all UEs either with good and bad quality channels.

2.11.1.3 MBSFN Resource Allocation Scheme

The MBSFN predicts future traffic load that needs to be served in the next frame, this predicted load is used to calculate the required RBs while turning off the unused resources.

The future load prediction is made using previously served load information exchanged between BSs through X2 interface (standard interface used for BS communication in LTE). An interesting MBSFN based ES scheme in [90] configures MBSFN sub-frames that helps to provide and setup transmitter switching-off periods. Additionally, this method estimates the resources required to serve the predictive load for effective resource allocation resulting into enhanced power saving by turning off the idle resources. Based on LTE specifications, six out of ten sub-frames can be configured as MBSFN (Figure 2.4). Importantly MBSFN sub-frames carry less RSs compared to the standard sub-frame. Therefore, in case no data is available, MBSFN sub-frames can be turned off resulting into reduced energy consumption.

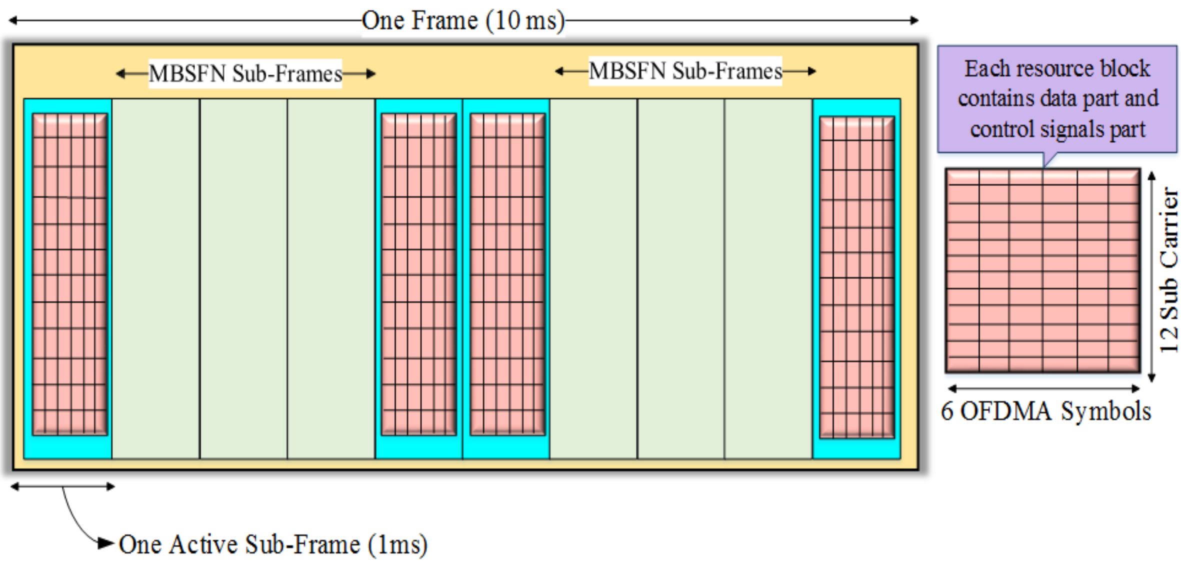


Figure 2.4: MBSFN based Frame architecture.

2.11.1.4 Hybrid FBS and MBS Based Schemes

The use of Femto Basestations (FBS) has proven to be promising technology to cover those areas where Macro Basestations (MBS) are limited. In the same context, work presented in

[104] introduces power control based RBS allocation scheme in LTE network with MBS and FBS, which employ the concept of Almost Blank Sub frame (ABS) and Reduced Power Blocks (RBs) to allocate reduced transmission power to resource blocks thereby resulting in to reduced downlink power consumption. Said scheme is recommended for two tier heterogeneous networks with MBS and few FBSs as shown in Figure 2.5. The main idea lies in the fact that varying transmit power levels can be assigned to different resources thus resulting into reduced BS power consumption. The level of transmit power is measured through SINR, thus if UE SINR is higher than predefined threshold then they are allocated with lower transmit power, while higher power is assign to UEs with lower SINR. Since SINR values changes rapidly, accordingly estimation of transmit power also changes continuously. Next to this Breathing technique is introduced for RB allocation which divided UEs in two classes, i.e. (Inhale and Exhale). UEs are arranged in ascending order in Inhale class in relation to the required transmit power and are mapped with RBs in sequence. On the other hand, Exhale class involves sorting of UEs in descending order of their transmission power value, [104].

2.11.2 Bandwidth Expansion Schemes

The EE LTE networks can also be realized through bandwidth expansion. Several proposed techniques employing bandwidth expansion for improved energy efficiency are presented below.

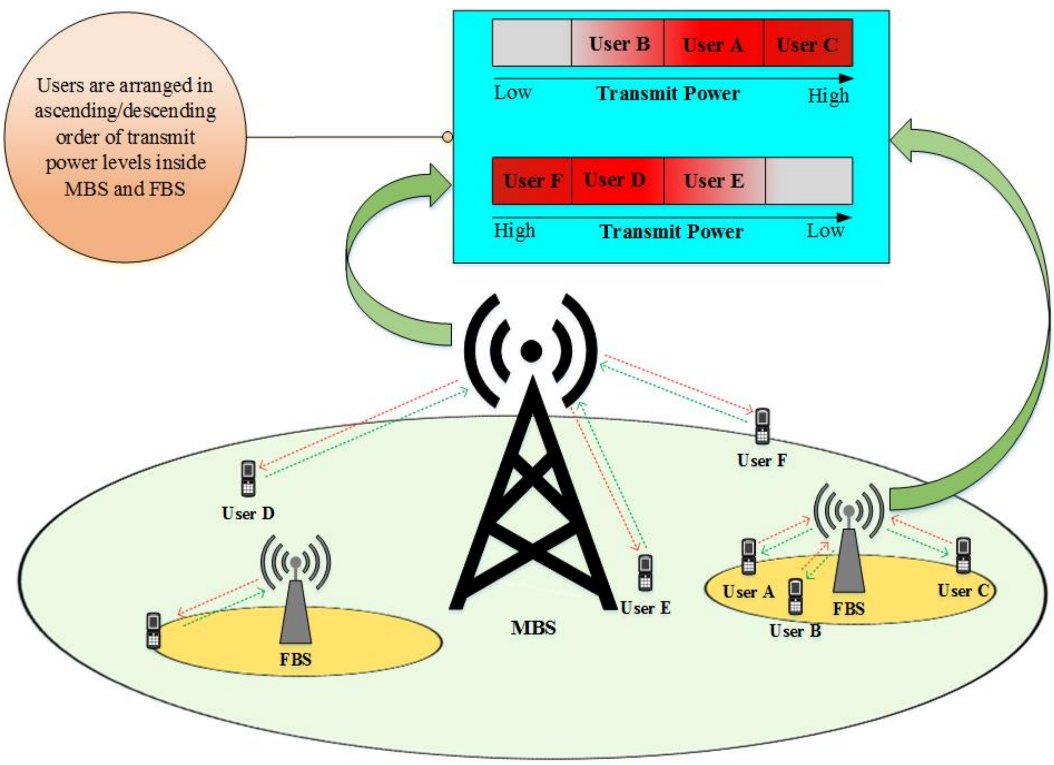


Figure 2.5: Hybrid FBS and MBS based ES scheme

2.11.2.1 Time Compression (TCoM) Scheme

The 10 ms frame in OFDMA consists of 10 subframes. Each subframe includes two slots of 0.5 ms each and each time slot consists of 12 subcarriers and 7 symbols as shown in Figure 2.6. Subcarriers of each symbol can be allocated to multiple UEs thereby making efficient use of radio resources. TCoM reduces power consumption caused by the usage of higher order modulation schemes in OFDMA through decrease in control channel overhead [103]. RBs in TCoM are compressed together and ES is achieved through reduced overhead signalling by appropriately turning off unused RBs during idle state. The time and frequency implementations of TCoM do not differ in performance because changes in either length or bandwidth of a transmission have the same impact on the transmitters energy. A compression factor to represent the number of RBs to be pooled together is introduced in [103]. It also uses Shannons capacity to derive required SINR. TCoM is found to be around 26 percent more EE compared to LTE benchmark standard.

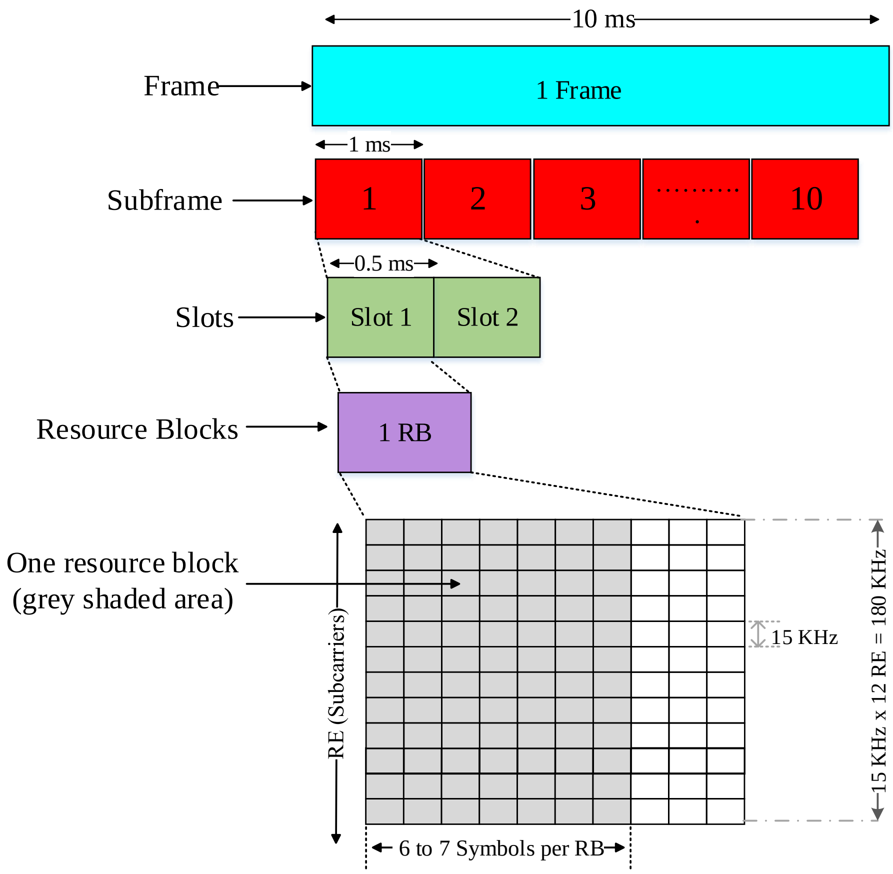


Figure 2.6: OFDMA frame architecture.

2.11.2.2 Bandwidth Expansion Mode (BEM) Scheme

Another Bandwidth Expansion Scheme (BEM) is described in [102]. This method is based on the concept that when the network is lightly loaded (larger number of RBs are free), in this scenario bandwidth allocation can be increased to reduce power consumption at BS. In LTE systems, minimum resource allocation is one RB while allocation is done by schedulers. Work in [102] is specially recommended for low loaded networks, because extra RBs that are idle during off peak traffic helps in bandwidth expansion. BEM addresses two important factors; Energy Efficiency (EE) and Mobility Load Balancing (MLB) in networks. This work proposes an effective EE resource allocation optimization model by employing a low complexity method called EE Virtual Bandwidth Expansion Mode (EE-VBEM). The concept of Virtual Load Balancing (VLB) that distributes some of the traffic (UEs) from highly loaded cells to the lightly loaded cells is used as shown in Figure 2.7. The EE-VBEM consists of two major parts: 1) EE Resource Allocation Optimization Model**;** 2) Low Complexity Method to achieve 1. Firstly, all BSs exchange load information of neighbouring cells through X2 Interface. Based on this information; each BS determines if there is a need of load balancing. In case load balancing is required, VLB automatically start shifting UEs from overlapping area to lightly loaded BS. BEM then calculates the required RBs for each UE using minimum required data rate and UE channel quality. Once RB calculation is done, the BEM prioritize the UEs according to the SINR value. Higher SINR indicates higher BEM priority for the UE and vice versa. After priority assignment, RBs are allocated to the UEs. BEM saves energy by allocating extra resources at the expense of reduced overall capacity of the BSs [102].

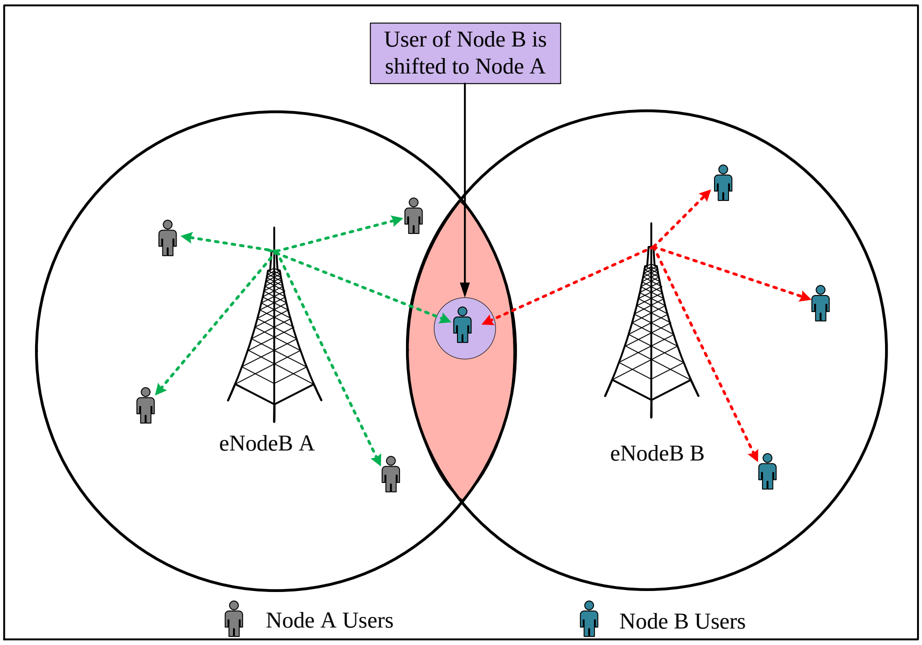


Figure 2.7: UE migration from serving to target cell.

2.11.2.3 Component Carrier based Schemes

Carrier Aggregation is well known technology used in LTE networks for the effective use of bandwidth. Each aggregated carrier is known as Component Carrier (CC) which can have bandwidth ranging from 1.4, 3, 5, 10, 15 or 20 MHz, while maximum of 5 carriers can be aggregated at a time. Carrier aggregation can be achieved through three methods as shown in Figure 2.8. The simplest method is known as intra-band contiguous; which uses contiguous carrier aggregation at the same frequency band. Second method is known as non-contiguous intra band carrier aggregation in which CC operates at same frequency band but have gaps as shown in Figure 2.8. Third method is non-contiguous inter band carrier aggregation in which carriers operate at different frequency bands. To achieve an EE communication in the LTE networks, more CCs can be jointly utilized in a BS for enhanced ES opportunities.

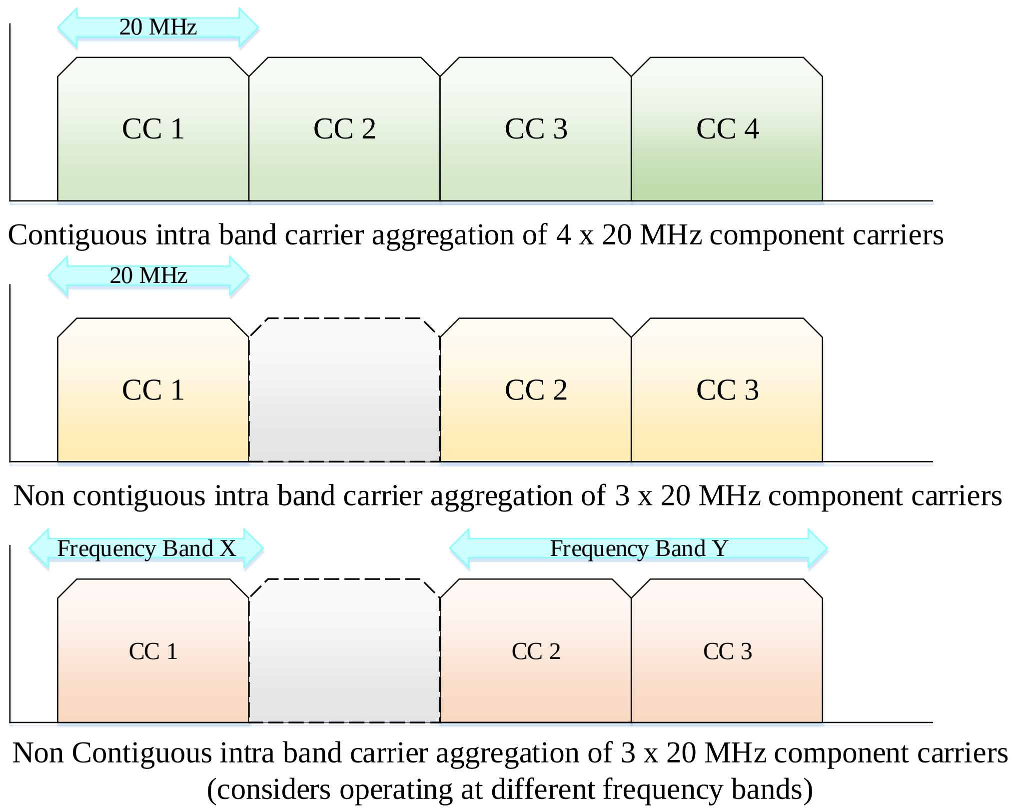


Figure 2.8: Carrier Aggregation.

In [91], authors recommended OFDMA based multiple CC technique for EE transmission that uses two CCs for data transmission. The main idea is to transmit only necessary CCs thus providing opportunities for appropriate deactivation of idle CCs to reduce the power consumption. The ES scheme in [91] works in downlink in BS and support both real and non-real time traffic simultaneously as shown in Figure 2.9. The ES scheme consists of 2 CCs operating at same frequency band and can be jointly utilized in BS for data transmission. The two CCs are called Primary Component Carrier (PCC) and Secondary Component Carrier (SCC), respectively. Normal data transmission uses PCC while SCC is only used during high traffic conditions. During transmission, UEs data packets are transmitted to the session level where they are classified as Real Time (RT) or Non-Real-Time (NRT) by the classifier and forwarded to RT and NRT Queues, respectively (Figure 2.9). The data packets then wait in transmission queue to be served by the proposed ES scheme, which consists of two algorithms. First algorithm allocates radio resources, while second algorithm is used for the appropriate activation/deactivation of the SCC. The first algorithm further contains two sub-algorithms called Bandwidth Allocation Algorithm (BAA) and RB Allocation Algorithm (RBAA), respectively. All these algorithms are executed at the beginning of every sub frame and jointly provides ES opportunities at BS.

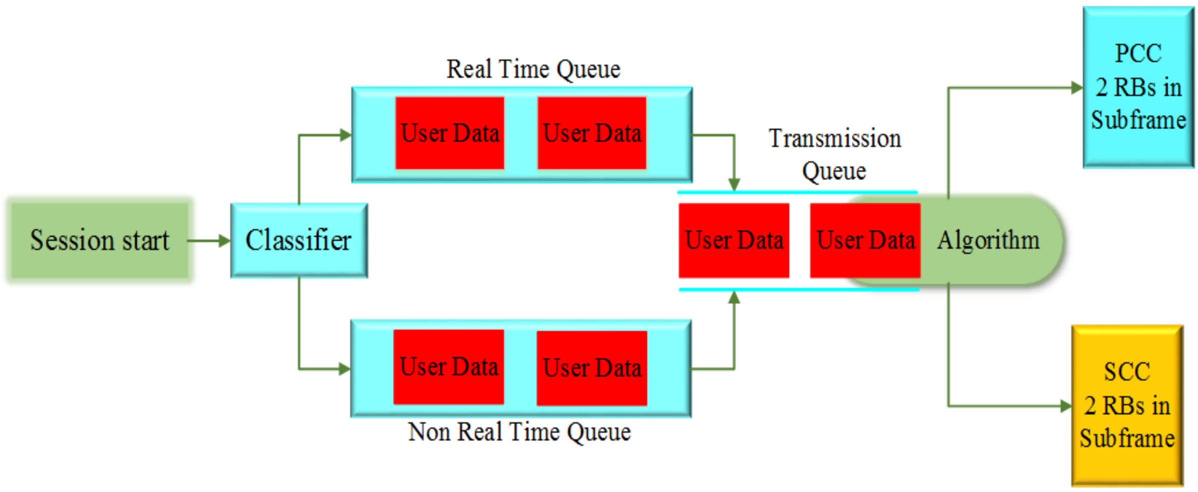


Figure 2.9: Component Carrier based ES Scheme.

2.11.2.4 Scheduling based Schemes

Videv et al. have presented an EE scheduling scheme in [106]. The method is based on bandwidth expansion through allocation of extra resources to the UEs and uses lower order modulation schemes for ES. This scheme reduces power consumption by 44 percent while maintaining throughput and QoS constraints. It uses energy-aware scoring scheduler, which considers best channel conditions and allocates additional resources to the UEs. The scheduler allocates resources by following the integer factor defined for bandwidth expansion. This method is effective only for networks where traffic is low and more free resources are available to be allocated to the UEs. This scheme provides ES at the cost of overall system capacity and therefore, not effective in practical real-time environment.

2.11.2.5 CoMP Based Coverage Expansion

Work in [92] uses Coordinated Multiple Point (CoMP) for improved ES. CoMP expands cell coverage thus resulting into better expansion compared to antenna adjustments and transmission power measurements. Proposed work employs link budget and SINR as input parameters and then divides networks in clusters on the basis of equivalent cell principle with distributed method (Figure 2.10). Cells in this scheme are divided in two main categories, i.e. cooperative and dormant cells, which is decided by Joint Processing (JP) cooperative cell selection model. During off peak traffic time periods, cooperative cells expand their coverage to serve dormant cells which are turned off for energy saving purposes.

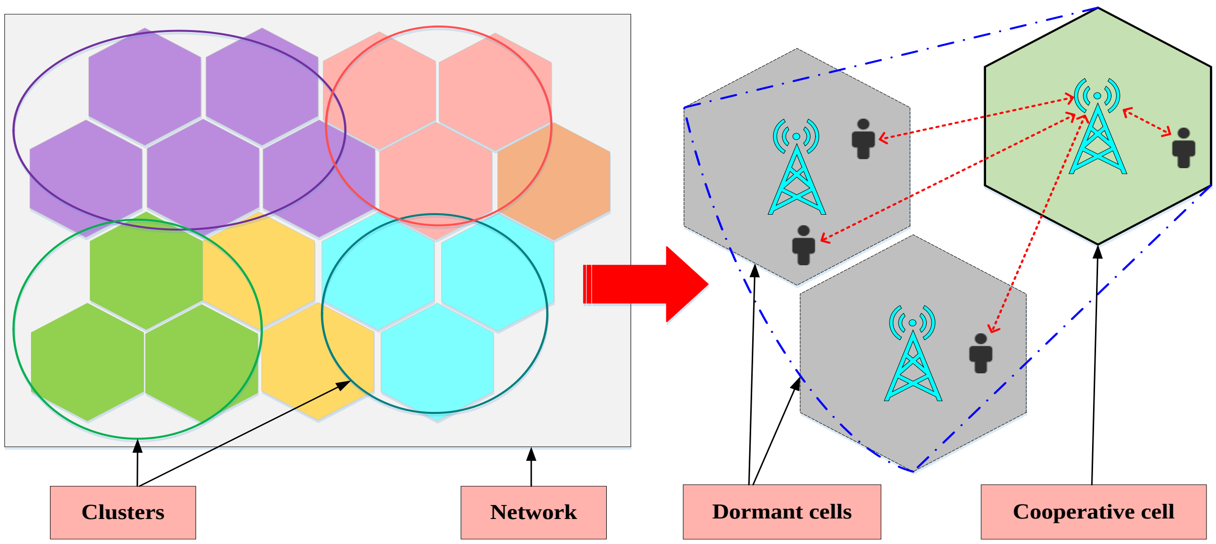


Figure 2.10: CoMP based Coverage Expansion

2.11.3 Load Balancing Schemes

Research has shown that traffic load varies significantly at the BSs and a lot of energy is wasted during low load operation. Load Balancing is a part of Radio Resource Management (RRM). The term *'Load Balancing'* presents any method that could be used to transfer load from highly loaded cells to lightly loaded neighbour cells for the efficient use of radio resources. The users distribution and traffic flow is irregular in cells, which can cause an unbalanced load condition in the network. In wireless cellular networks with unequal traffic load distribution, some of the UEs at the edges of cells can be transferred from highly loaded cells to the lightly loaded cells thereby providing opportunities for efficient resources utilization. When UEs detect that neighbour cells can provide better signal quality than its current serving BS, they are handed over to that neighbour cell. During load balancing, if the cell is desirable or already in ES mode and it is selected as a candidate for load balancing from a nearby heavily loaded cell, then there exist two options. To prioritize the load balance without considering the ES, and secondly focus is made only to prioritize the ES. In the second case, UEs are not allowed to be handed over to the cells, which are desirable, or already in ES mode and the heavy loaded cell has to find another neighbour cell for load balancing. In this case, edge UEs may not be served efficiently but power saving could be improved. Following discuss load balancing related ES schemes in detail.

2.11.3.1 Distance Aware Schemes

Work in [94] has introduced distance aware schemes that involve switching off of BS having greater distance from UEs. This work reduces energy consumption by appropriate activation/deactivation of BS through information of varying distance and load. Each BS in 7 cells base cluster calculates its average distance from associated UEs and adjacent cells UEs as shown in Figure 2.11. Since the larger average distance between BS and UEs leads to the higher power consumption, appropriate BS (with larger average distance) is selected for switching OFF. If the bandwidth requirements to serve associated UEs are less than the total available capacity supported by adjacent cells, then the selected BS is switched off and traffic is allocated to the neighbour cells resulting in a reduced power consumption. Moreover, the BSs in sleep mode can be activated if network becomes busy due to high volume of traffic. ES scheme aims to turn off as much BSs as possible without any degradation of QoS. This scheme divides the day in two zones, a night zone (7PM to 7AM) and a day zone (8AM to 6PM). Turning off the BS is performed during night zone to achieve ES during 12 hours of low traffic load conditions. The BS is switched ON during the day zone when traffic load increases and network becomes busy. In high traffic load conditions, many BSs should remain switched ON in order to serve the UEs appropriately without affecting the QoS. ES scheme proposed in [94] significantly reduces power consumption by deactivating BSs while neighour cells can send activation instruction back to the BS in sleep mode through X2 interface.

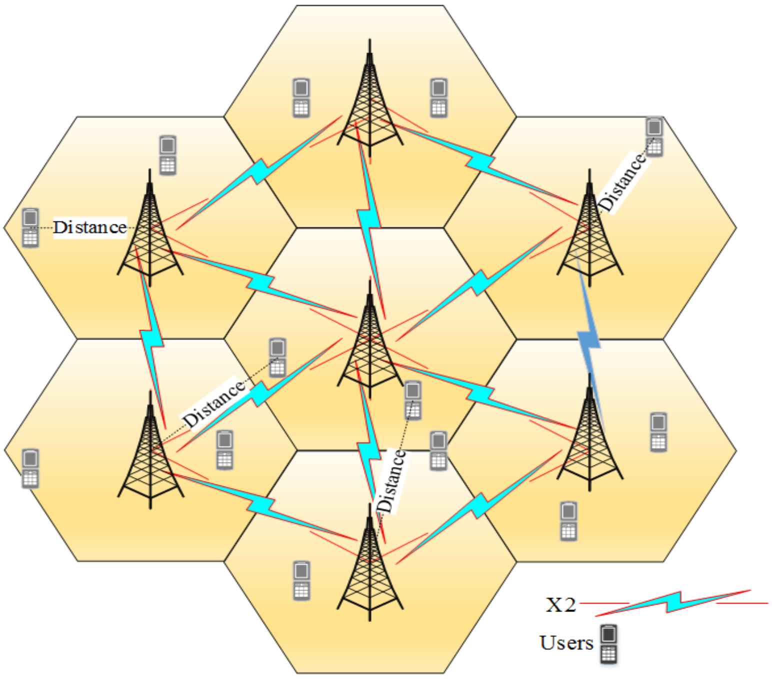


Figure 2.11: Distance aware based BSs communication.

2.11.3.2 Coverage Expansion based Schemes

A centralized ES algorithm is proposed in [97] that provides ES by turning off the lightly loaded BSs. This scheme is based on the idea of shifting the traffic towards highest loaded BS using load and coverage information of the network and switch off lightly loaded BS.

The main idea lies in the fact that all UEs of lightly loaded BS are served by neighbour busiest BS, thus permits lightly loaded BS to turn OFF for ES. Initially neighbour BS sectorize its coverage, then extends coverage of appropriate sector through transmission power adjustment and reconfiguration of antenna as shown in Figure 2.12. The extended sector coverage helps BS to serve UEs of lightly loaded BS being turned off. Proposed algorithm while deployed at every BS, sectorize and extend its coverage for ES purposes. It uses two algorithms; first one monitors network for load information while second operates on individual BS and manage its sectorization and transmission expansion process. Initially, based on load information, centralized algorithm selects busiest BS and analyze its resources availability. If selected BS has enough resources to serve neighbour BSs' UEs, then one of its sector transmission coverage is expanded to serve UEs of the neighour cell being switched off for ES as shown in Figure 2.12 [97].

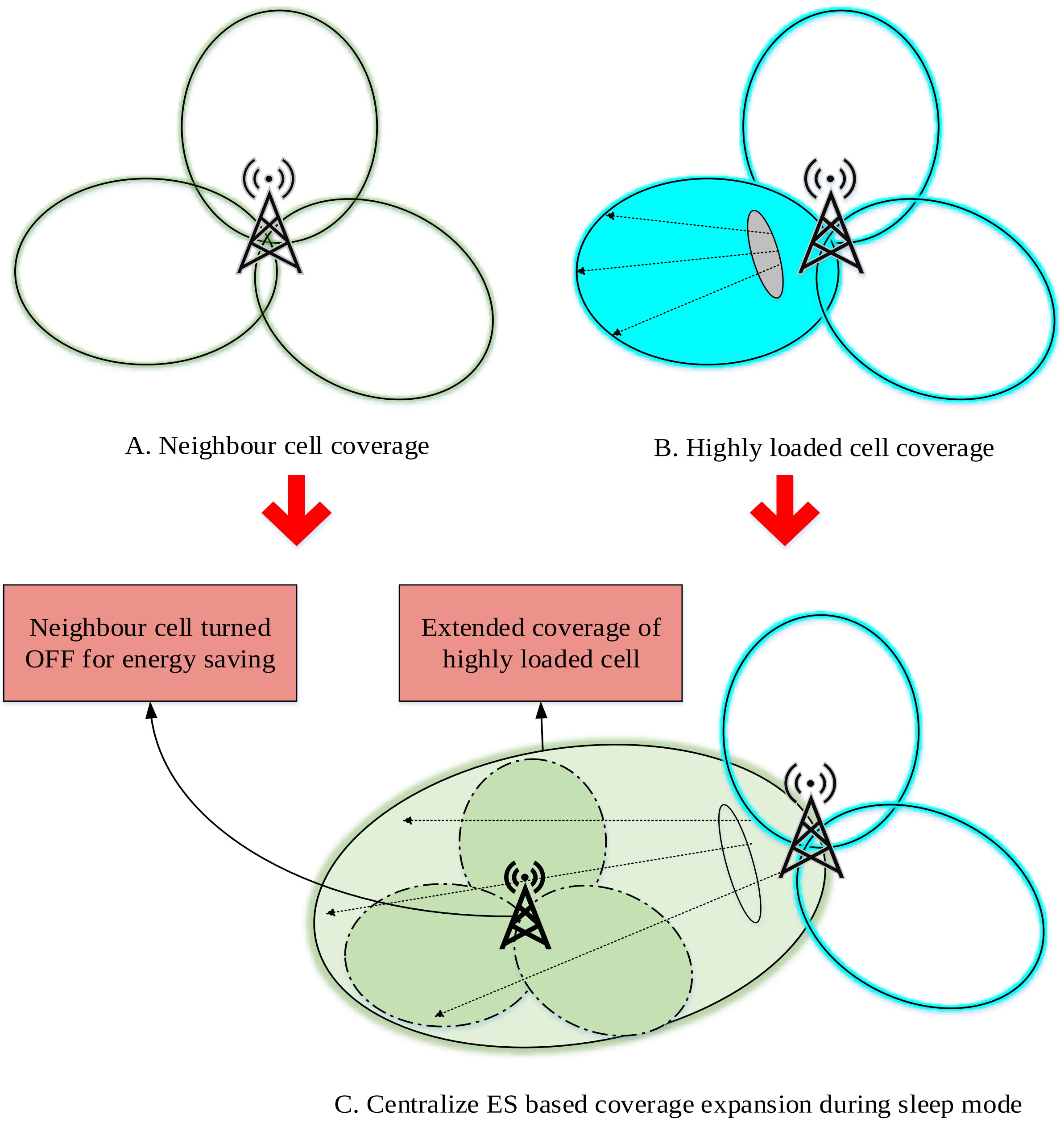


Figure 2.12: BS Coverage Expansion for ES.

2.11.3.3 Distributed Schemes

In [96], a distributed self-organized sectorization of BSs is presented for EE communication. Based on the varying load information, each BS reconfigures itself in real time thus utilizes minimum number of sectors for ES while promising adequate QoS. Since each BS dynamically reconfigures itself and no correspondence is required with neighbour BSs, this scheme is inherently distributed and self-organized. Each BS is implemented with traffic aware algorithm for continuous reconfiguration of sectors depending on time varying load. The objective of traffic aware algorithm is to regulate sectorization and minimize the number of sectors in each BS, while maintaining necessary signal power required for each UE and other QoS constraints. During the low traffic durations, fewer number of sectors are sufficient to serve BS UEs so the unused sectors are turned off to achieve ES as shown in Figure 2.13. Meanwhile. QoS constraints are maintained by considering parameters of call blocking and cell coverage in the specific limits. This scheme links budget analysis for the estimation of required number of RBs for each UE while using both time-inhomogeous and time-homogenous traffic models for performance analysis. It also employs interference-managing arrangements to handle inter-cell interference and significantly reduces overall system dynamic power consumption by turning off the unused sectors in each BS (Figure 2.13). However, one of the major disadvantages of this technique is that a sector can be turned off only if it serves not a single UE even in low traffic durations.

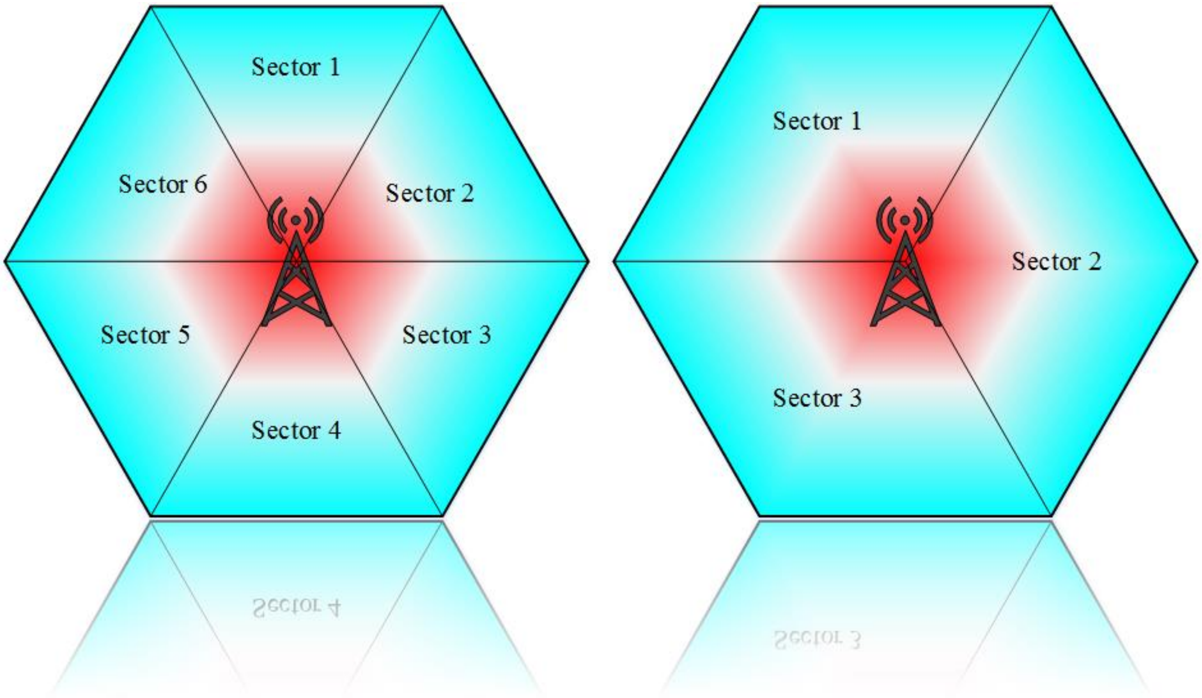


Figure 2.13: Distributed Schemes - Sectorization in Base Stations.

2.11.3.4 Shared Relay Based Schemes

Authors have proposed shared relay based load balancing ES scheme for the LTE networks in [99]. The operators or service providers share their network resources to accommodate additional UEs and support their demand of increased voice and data services through load balancing. This scheme however, needs reasonable investment in the network infrastructure and is based on two assumptions. First assumption states that two different network operators jointly provide coverage to the service area through service level agreement, which allows UEs to communicate with operators through load balancing algorithm. Second assumption says that a centralized SON algorithm is used for optimization of communication between UEs for ES. It lays foundation for a relay based shared network based on two LTE networks belonging to two different operators having their own BSs. UEs of both operators can freely communicate with any BS regardless of their operator. BSs of both operators are connected through backhaul link, which is monitored and controlled by a remote entity called RAN. Having information of load and channel conditions, SON algorithm calculates Reference Signal Received Power (RSRP) of both BSs for each user. Once RSRP has been calculated, the UE is then allocated to the BS having better RSRP for it. However, if RSRP of both BSs is same then UEs prefer to communicate with their own operator BS because both operators prefer to utilize their own resources first. This scheme reduces power consumption from 15 to 20 percent with the help of SON based load balancing.

2.11.3.5 CRN Adopted Switching Off BS

The work presented in [93] incorporates CRN with LTE and turns off BSs for ES purposes. Proposed algorithm employs three modes of operation, namely sleep, awake and listening modes respectively (Figure 2.14). During awake mode, Primary UEs (PUs) data is transmitted using pre-emptive priority while secondary UEs (SUs) data is sent using unused remaining spectrum. Once all packets have been transmitted and buffer becomes empty, the BS is turned in to sleep mode for ES. Importantly arrival of PUs data can shift BS from sleep mode straight back to awake mode. Otherwise BS remains in sleep mode to conserve energy and shifts to listening mode upon expiry of sleep mode timer. The BS listens to data traffic in listening mode before it repeats the whole cycle.

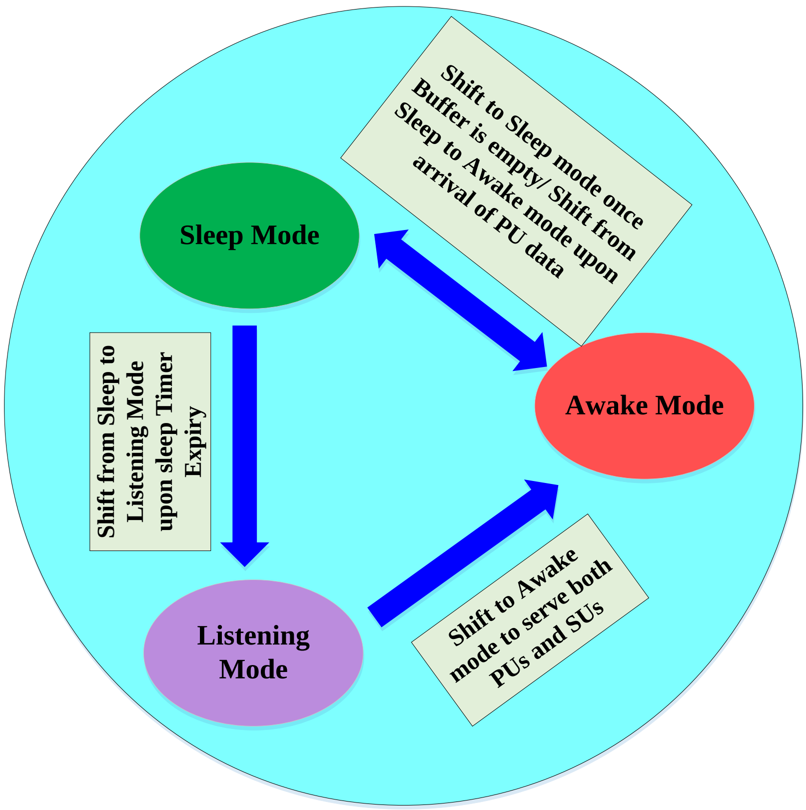


Figure 2.14: State diagram for CRN based energy saving

2.12 Discussion and Critical Analysis

Table 2.2 critically compares existing ES schemes in terms of their pros and cons followed by detailed discussion and analysis.

Table 2.2: Critical Analysis of Existing ES Schemes

ES Schemes	Advantages	Disadvantages
Distance Aware [94]	• Power saving up to 30 percent as compared with always ON network.	• Runs during limited time frame 8:00 PM – 8:00 AM. • No power saving during peak traffic time period.
Dynamic Distance aware	• Power saving up to 70 percent as compared with	• Exchange of information overhead between cells every

[95]	always ON network. • Low probability of blocking. • Runs every hour.	hour. • Low power saving during 7PM to 11PM.
Micro DTX scheme [89]	• Power saving up to 61 percent as compared to the cell without any DTX • No need to power off whole BS • Uses MBSFN sub-frames for power saving. • It creates empty transmission intervals during which PA can be deactivated.	• Longer sleep mode increase the delays; 10 to 20 seconds in going back in active mode. • Increased number of MBSFN sub-frames decreases the capacity and bandwidth. • In LTE rel-8, information could change at system broadcast channel only once in every six minutes.
Enhanced DTX scheme [89]	• Power saving up to 89 percent as compared with cell without any DTX. • Only synchronization and other secondary signals transmitted.	• Increased number of MBSFN sub-frames decreases the capacity and bandwidth • In LTE rel-8, information could change at system broadcast channel only once every six minutes.
EE bandwidth expansion scheme [106]	• Save power up to 44 percent • Effective for lightly loaded network	• Reduce the actual capacity or bandwidth. • As traffic load increase, bandwidth decreases.
Centralized Algorithm [98]	• Uses load information scope from entire network. • More effective with lower number of UEs.	• Lower transition cost with low bandwidth requirements • Higher worst case complexity due to the binary heaps
TCoM [103]	• Provide ES up to 26 percent as compare to always ON System.	• Not effective ES at the cell edges. • Suffer from capacity limitation.

	• Deactivation of RBs is very effective ES Technique	
EE Link Adaptation Scheme [100]	• Only effective for the UEs closer to the BS	• Limited reduction • Increase feedback overhead
BEM [102]	• Significantly reduce power consumption at BS in low load cells. • Distribute UEs only from overlapping area between two cells thus reduces Overhead. • Allow the use of lower order modulation schemes, which consume less power.	• Not suitable for highly loaded cells. • ES in trade off with more bandwidth used. • Distribute UEs to those cells that are already desirable for ES mode, thus reduce the power saving opportunities in overall network.
Component Carrier Based EE Scheme [91]	• Support both real and non-real-time traffic simultaneously. • Reduce power consumption by 50 percent as compared to always ON CCs network.	• Only considers two component carriers. • Session blocking increases the delay in high traffic period.
Energy Efficient BS deployment [105]	• Provide Static hardware base ES.	• Scheme doesn't provide further ES opportunities, once BSs have deployed.
Power Aware allocation of MBSFN sub-frames [90]	• Uses two power saving concepts • Deactivates the unused sub-frames • Allocate RBs as much as required depending on load	• Increased delays • Only few sub-frames can be switch off because control signals require capacity in few sub-frames

Coverage Based Scheme [97]	• Significantly reduce power consumption. • Recommended for lightly load network. • Only one partition of BS could be expended rather than full BS coverage area.	• Execution of multiple algorithms increases processing computation. • Challenging for BS to use one sector to provide coverage to full area of neighbour BS. • Load information overhead
Sector Based Scheme [96]	• SON based ES scheme. • Distributed in nature; each BS provide ES without communicating with other BSs • Divide coverage in different number of sector depending on load.	• Additional processing computation for sectorization of coverage of BS. • Even existence of single user in each sector will fail and reduces ES opportunities for BS. • Challenging for BS to manage varying sectors in their coverage.
Relay Based Scheme [99]	• Significantly reduce power consumption from 15 to 20 percent. • UEs can freely access recourses of two different operators. • Does not require load information exchange through X2 interface	• Difficult for two operators to work together • Allocation of resources to the UEs of other operator may causes capacity limitation for their own associated UEs.

Table 2.2 shows that distance aware scheme [94] operates for 12 hours and save energy up to 30 percent as compared to always on network during night zone. Since traffic load is high in daytime, distance aware schemes fail to turn off BSs during day time and are only effective in

night zone when traffic load is low. Dynamic distance aware approach achieves ES up to 70 percent in comparison to always on network and operates every hour in contrast to distance aware scheme [95]. Since each BS is required to exchange load information every hour with other neighbor cells, it results in an increased overhead in the network. DTX is one of the most interesting ES schemes. Main advantage of DTX is that it targets operational ES where there is no need of turning off whole BS and only unused RBs are switched off [89, 90]. On the other hand, main disadvantage of DTX is the long sleep mode of unused RBs that increases delay time required by RBs to go back to active mode. Distributed schemes also contribute in ES in LTE networks by effectively migrating UEs to the neighbour cells [97, 98]. In these types of schemes, BSs keep exchanging load information with each other resulting in an increased traffic information overhead. Bandwidth expansion is also used to achieve 44 percent of ES in lightly loaded networks. However, allocation of extra RBs results into reduced available capacity of the BS and thus not very effective during peak hours' time period [106]. A combination of load balancing with bandwidth expansion is also used to reduce power consumption in the network [102]. However, this scheme could migrate UEs to those cells that are already desirable for ES mode thus reducing ES opportunities in overall network. The centralized schemes also provide ES but suffer from high traffic load similar to the distributed scheme. The TCoM scheme provides 26 percent ES by cutting down control channels signalling [103]. Its main idea is similar to the bandwidth expansion; however, it reduces control channel overhead by transmitting two RBs jointly to a single user. TCoM suffers from the drawback of being not effective at cell edges and requires a reduced overall system capacity. The EE link adaption scheme is only effective for the UEs located closer to the BS and saves 9.4 percent of energy while increasing the feedback overhead in the network [100]. Carrier aggregation approach is also used for ES reducing power consumption by 50 percent as compared to always on network [91]. One of the disadvantages of this scheme is session blocking which may increase the delay during high traffic time period.

Coverage expansion is also used as a means to realize ES in the LTE networks [97]. It is however very complicated for the BS to make partitions to expand their transmission power and provide coverage to full neighbour BS using one partition. On the other hand, execution of two algorithms to implement this scheme also increases overall computation overhead. Division of the BS in different sectors and turning off unused or free sectors is also employed to attain ES [96]. This scheme however only works for a completely free sector and existence of even a single user would not allow the BS to turn off that sector. A shared relay ES scheme based on the idea of sharing resources of two different operators is proposed in [99]. However, it is very difficult for two different operators to work and integrate their operations under a shared environment. Table 2.3 summarizes the performance of the discussed ES schemes in relation to other QoS issues.

Table 2.3: QoS factors involved in ES schemes.

ES Scheme	QoS Issues				
	Lightly loaded	**Heavily loaded**	**Reduced capacity**	**Increased delay**	**Increased Overhead**
Distance Aware [94]	✓	X	X	X	✓
Dynamic Distance Aware [95]	✓	X	X	X	✓
Micro DTX scheme [89]	✓	✓	X	✓	X
Bandwidth expansion [106]	✓	X	✓	X	X
Centralized Algorithm [98]	✓	X	X	X	✓
TCoM [103]	✓	✓	X	X	X
EE Link Adaptation [100]	✓	✓	✓	X	✓
Component Carrier [91]	✓	✓	✓	X	X
EE BS deployment [105]	✓	✓	X	X	X
Power Aware MBSFN [90]	✓	✓	✓	✓	X
Coverage Based Scheme [97]	✓	X	X	✓	✓
Sector Based Scheme [96]	✓	X	X	✓	X
Relay Based Scheme [99]	✓	✓	X	✓	✓

In line with previous sections, Table 2.4 presents detailed open research issues learnt from critical analysis of existing ES schemes. This can be useful to further improved research work.

Table 2.4: Open Research Issues.

ES Scheme	**Open Research Areas**
Distance Aware [94]	ES can be extended for 24 hours including daytime.
Dynamic Distance aware [95]	Load information overhead could be reduced for enhanced system performance. Whereas ES could be extended to daytime.
Micro DTX scheme [89]	Increased delay could be reduced for better performance.
Enhanced DTX scheme [89]	Capacity limitation could be explored as an open research issue.
Centralized Algorithm [98]	Complex system due to the binary heaps could be explored for a better performing ES scheme.
TCoM [103]	ES could be further improved at cell edges for enhanced system performance.
EE Link Adaptation Scheme [100]	Feedback overhead could be considered as an open research issue.
BEM [102]	Further enhancement can be done offering ES in peak load hours.
Component Carrier Based EE Scheme [91]	More component carriers can be considered in future research work.
EE BS deployment [105]	ES could be extended towards dynamic part of an enhanced system.
Power Aware MBSFN sub-frames [90]	Capacity limitations can be studied as an open research issue.

2.13 Summary

Due to the increased global warming and worldwide climate change, energy consumption has become major hurdle. The ICT contributes approximately 2 percent in global warming, while major part is attributed to telecommunication in ICT. In cellular networks, energy consumption is effected from growing mobiles UEs and their data requirements. Moreover, further deployment of additional and enhanced BSs to fulfill ever growing UEs requirement also adds in ICT contribution. Therefore, increasing trend of energy consumption has become major challenge for vendors thus affecting both economical and environmental aspects. The rapid increase in energy consumption not only increases OPEX but also effects climate change. Research work has proven that BSs in LTE networks consume a lot of dynamic power during idle state, which could be saved by appropriate turning off of BSs. The reduced power consumption enhances the LTE system performance through cutting down the OPEX and carbon emission thus also helping the vendors to have high profile in green communication. This chapter has provided the detailed discussion on existing ES schemes developed for LTE networks. Critical analysis of the schemes has been presented before open research issues are discussed. The chapter is a comprehensive account of the existing ES schemes for LTE networks and can help researchers to understand current taste of art, open research issues to come up with innovative solutions resulting in optimized system performance. In the same context novel ES scheme is proposed, on the bases of above discussed open research issues, in the next chapter.

Chapter 3

3. Joint Resource Blocks Switching Off and Bandwidth Expansion for ES in LTE

3.1 Introduction

In chapter 2 numerous existing ES schemes, their practicality, advantages and disadvantages were discussed. Further detailed critical analysis of these ES schemes was also described. In the same context based on the open research issues and critical analysis in chapter 2, novel ES scheme is proposed in chapter 3. This chapter firstly presents OPEX background which is followed by introduction and working of proposed ES scheme. Then detailed information about system model and simulation is provided. Proposed ES scheme is analysed through the investigation of various performance related parameters. Initially reduced power consumption is examined then its impact on operators OPEX is discussed to validate proposed scheme.

In LTE networks; data hungry UEs engage radio resources over long periods of time thus resulting into higher energy consumption by BSs. Increased energy consumption due to higher data rates directly increases OPEX thereby results into reduced economic benefits, i.e. profitability of vendors. Point to be noted that it is very challenging for vendors to increase their price plan due to competition with other vendors in market. Increased packaging plan would result into UEs migration to the other operators. Therefore, profitability must be increased through alternative methods i.e. energy efficiency in existing network infrastructure. In the same context, a novel joint resource block switching off and bandwidth expansion based energy efficiency scheme is proposed in this chapter. In addition to ES performance related findings, OPEX correlated results specifically demonstrate the economic benefits achieved through the usage of proposed ES scheme thus helping vendors to stay profitable.

OPEX is one of the most important factors for vendors/operators to stay profitable, whereas power consumption is key element of OPEX. A lot of research work has been carried out to reduce power consumption in LTE networks. Some of the existing ES schemes work on static part, while others work on dynamic power. Even though considerable research work has been done in switching OFF/ON of BSs, however most of them have drawbacks related to coverage and interference. Apart from developments of ES schemes, it is also important to evaluate the impact of schemes on OPEX and Capital Expenditure (CAPEX). In the same context authors in [107] presents combined micro and femtocell deployment scenario which minimizes CAPEX/OPEX. The research work concluded that proposed combination of micro and femtocell deployments is cost effective and sustainable in term of high data rate. SDN presents self-organized management system for networks, which reduces labour cost thus resulting into reduced OPEX (i.e. money saved from cutting off labour) [108]. The reduced labour cost, through the employment of SDN, directly adds in profitability. Another work in [109-110] compares CAPEX of SDN with other switched networks. Further research work related to OPEX and CAPEX in highlighted in [111-112], where techno-economic modelling is used to evaluate the performance and feasibility of solutions proposed for cellular networks. Even though research has been done on CAPEX and OPEX in term of self-organized networks, however existing work mostly limits itself and investigate OPEX in relation to top level configuration arrangements. Most of the ES schemes discussed above and in chapter 2 offer ES but in light loaded networks only and do not work efficiently during high traffic load. Therefore, despite existing research, there is strong need to develop an ES scheme in LTE networks which span across different layers to provide ES during both lightly and heavily loaded network. In this context, a novel ES scheme is proposed in this chapter which reduces dynamic power consumption at downlink BS by employing RBs switching off and bandwidth expansion through time compression resulting in reduced PDCCH signaling. The novel feature of proposed scheme lies in the fact that it offers ES by merging bandwidth expansion with RBs turning OFF. Proposed scheme reduces PDCCHs overhead through extended bandwidth, which reduces power consumption and additionally turn off idle resources thus provides enhanced ES opportunities. The achieved ES impact on OPEX is analysed through comparing performance analysis parameters (dynamic power consumption, OPEX and profitability) with standard typical LTE network.

3.2 Importance of OPEX

Cellular communication service providers need to deploy thousands of BSs to cover large geographical areas. Considering operators in Europe; approximately 20,000 BSs deployment were considered for provision of adequate QoS [113]. Largely, vendors OPEX can be classified or calculated as; 1) site rents; 2) backhaul rents; 3) energy consumption cost (bills); 4) marketing cost [114]. Data provided from vendors, marketing reports and literature review proves that average OPEX and CAPEX for operating LTE networks is approximately £200,000/km^2 (annual cost) [113]. The impact of power consumption in relation to radio frequency access on OPEX depends on different factors, e.g. data rate, number of UEs, coverage area, etc. In modern and competitive world, due to the increase in number of UEs and their data requirements, it has become challenging for vendors to fulfill those requirements. These trends further lead towards increased OPEX thus resulting into increasingly reduced profits. As shown in Figure 3.1, there are three main aspects which must be considered by vendors to survive in competitive markets; 1) Economical benefits; 2) Environmental Effects; 3) Technological Advancements [115]. The economical benefits include profitability and UEs satisfactions, while environment impacts consider CO_2 emissions and power consumption. The technological advancements consist of data rate, resources efficiency and capacity of system to accommodate increasingly higher number of UEs.

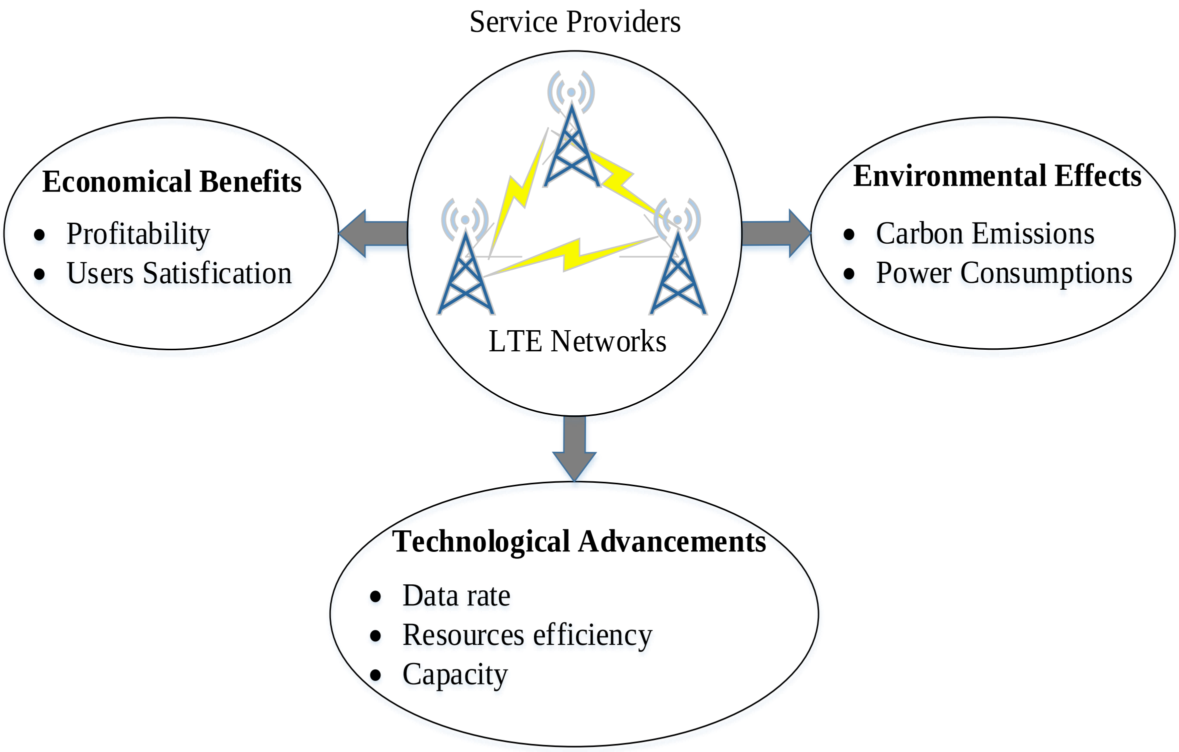
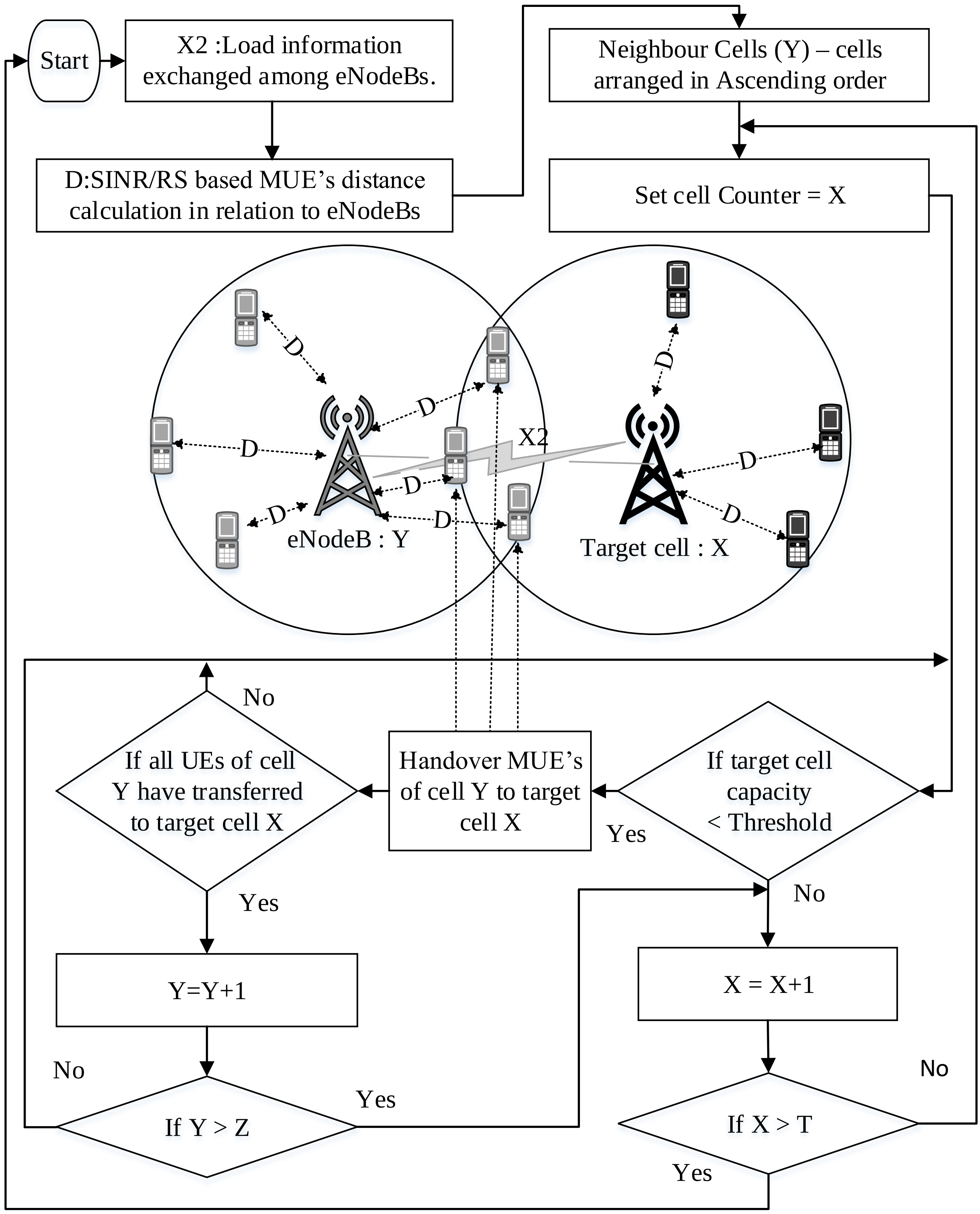


Figure 3.1: Service Providers and Profitability

3.3 Proposed ES Scheme

The proposed scheme while implemented at every BS enable them to achieve load balancing among themselves by relocating UEs from overlapping areas to the target cell as shown in Figure 3.2 and giving the serving cells BSs an opportunity to switch off RBs and attain increased ES. Proposed ES scheme combines the idea of bandwidth expansion and switching off RBs. In this view, employing the concept of bandwidth expansion; compared to benchmark, proposed scheme combines two RBs per UE thereby resulting into reduced PDCCH overhead transmission. As explained in chapter 2, in LTE network each UE is allocated with minimum of one RB which contains data and control signals. It also carries PDCCH signals (required at the receiver end) which contains control information about data part in RB. The PDCCH signals consume power and responsible for 26% signals overhead. Recalling OFDMA from chapter 2, RBs are spread in time and frequency domain. In the same context, our proposed ES scheme merge two RBs together through time compression to form one super RB thus cutting down PDCCH signals in 2^{nd} RB. Since one super RB (formed by combining 2 RBs together) is allocated to single UE therefore freed REs of 2^{nd} RB from PDCCH can also be used for data transmission or turn off for ES. By doing so, it improves energy conservation through reduced PDCCH overhead signals and better system capacity. Enhancement in system capacity helps even further towards load balancing, thus addressing the problem of BS capacity limitation during high traffic periods. The 2^{nd} part of our proposed ES scheme is switching off RBs. Accordingly, a BS in proposed scheme could accommodate more UEs from the overlapping area of neighbouring cells and turn off freed RBs right after handover thereby further increasing ES opportunities.

Figure 3.2 shows two cells (Target Cell X and Neighbour/Serving Cell Y) to elaborate working of proposed scheme. In densely deployed LTE networks, there could be numerous serving and target cells in large clusters, while each cell has six neighbour cells as shown in Figure 3.3. Referring Figure 3.2, ‘Y’ presents serving cells among selected target cell X while ‘Z’ describes total number of neighbour cells ‘Y’ in List. Further ‘X’ presents target cell and ‘T’ presents total number of target cells. Accordingly in proposed scheme the counter for target cells X can vary from X to T, whereas neighbour cells counter varies from Y to Z. Each BS exchanges load information with neighbour cells through X2 interface. If target cell X capacity is available, then handover is carried out between cell X and neighbours cells Y. After each handover, target cell X checks its resources availability before proceeding towards next UE in overlapping areas. Once UEs in overlapping area have been handed to the target cell X, then neighbour (serving cell) turn off its freed RBs which save idle power consumption. This process continues until all neighbour cells (Figure 3.3) have relocated their UEs from overlapping to the target cell X. Importantly proposed scheme iteratively works through neighbour cells (Y) and target cell accordingly (Figure 3.2). Table 3.1 provides the description for notations used in Figure 3.2.



Y= Neighbour cells among selected target cell X ; X= Target cell
Z= Total number of neighbour cells Y in list ; T= Total number of target cells

Figure 3.2: Proposed ES Scheme

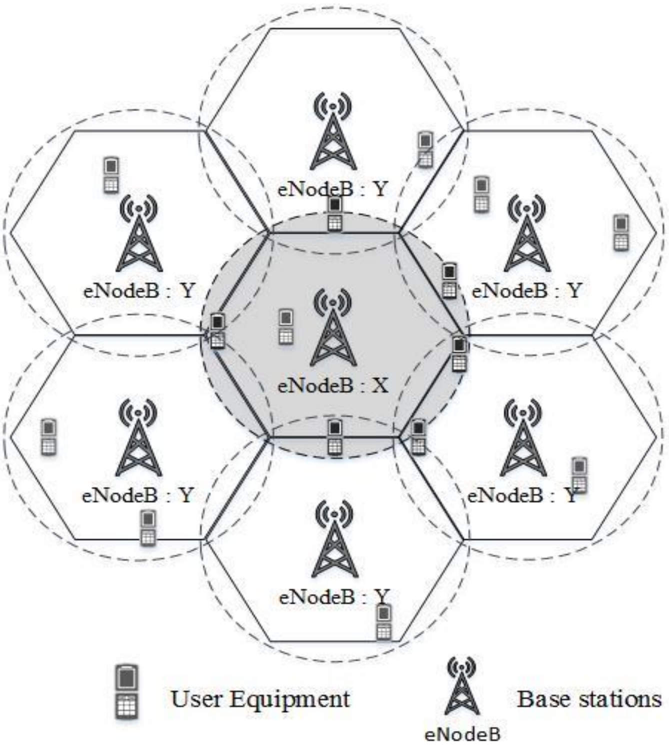


Figure 3.3: System Model

Table 3.1: Notations Description

Y	Neighbour/Serving cells among selected target cell X
Z	Total number of neighbour cells Y in list
X	Target cells
T	Total number of target cells
Capacity	Avaliable RBs in current cell X
Threshold	Indicator of resources avaliability

3.3.1 RBs Switching OFF

Considering 3GPP specification for handover process in LTE networks [116], when UE enters in overlapping area, they receive cell specific RS from target cell which is used to calculate RSRP of target cell X. In parallel UEs also calculate RSRP value of serving cell Y.

In order to understand the working of proposed ES scheme. Initially serving and target cells must be defined, thus initially one cell is selected which becomes serving cell for all its associated UEs. Then any one UE is selected within the coverage of chosen serving cell. Further depending on UE mobility direction, any one of 6 neighbour cells around serving cell can become target cell for that specific UE. Thus, firstly selected cell is named as serving cell Y while 2nd cell named as target cell X for specific UE. Notably two key parameters (Offset & Hysteresis) are used to poorer RSRP of target cell (Figure 3.4). Handover is triggered through A3 event which indicate that RSRP value of target cell has become greater then serving cell as shown in Figure 3.4. The role of hysteresis in A3 event is to worsen target cells RSRP value than the actual value (Equation 3.1) to ensure seamless connectivity.

$$RSRP_X \geq RSRP_Y + Hysteresis \tag{3.1}$$

$RSRP_X$ presents RSRP value of target cell X and $RSRP_Y$ presents RSRP value of current (serving) cell Y. In proposed scheme, idle resources of serving cells are turned off after successful handover of UEs to the target cell. The turning off resources thus results into reduced power consumption. RBs switching off implementation pseudo code is provided in Algorithm 3.1.

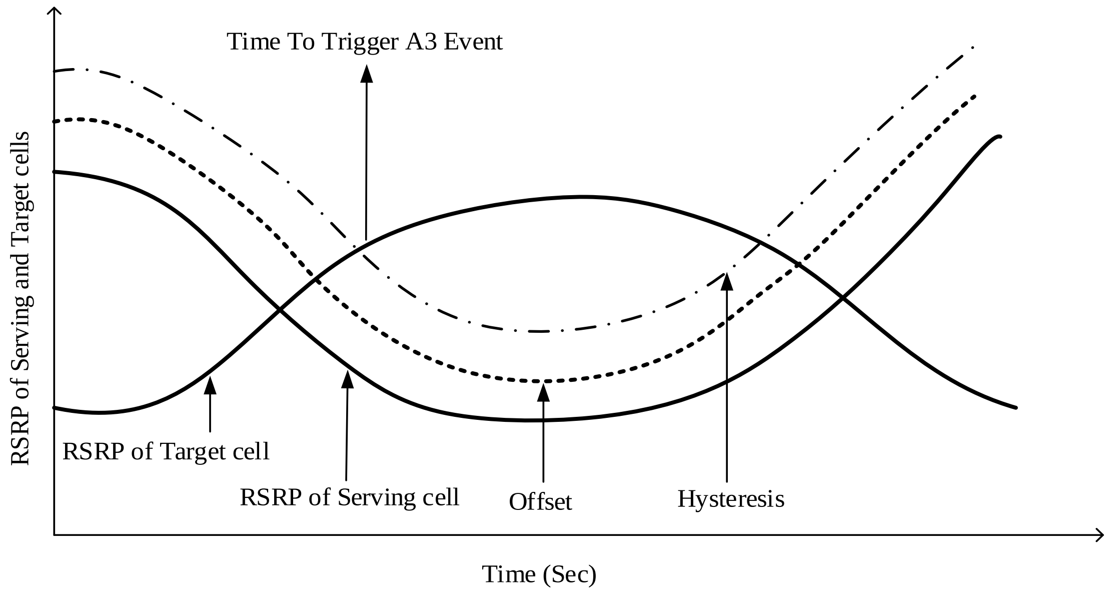


Figure 3.4: A3 event to trigger handover

3.3.2 Bandwidth Expansion

Each RB carries two parts, UE data part and PDCCH signals with RS. Our scheme combines two RBs to expand bandwidth through time compression and allocates these joint RBs to single user thus reducing PDCCHs overhead. Considering 3GPP link budget at downlink, the maximum overhead due to PDCCH is about 26 percent which is transmitted using the fraction of time slot at constant pre-set of radio frequency power. Hence the dynamic energy cost at BS can be calculated as [103], equation 3.2.

$$EC\_BEN_{Pdc} = M.\ TM\ [(1 - \mu_{Pdc})EN_{Data} + \ \mu_{Pdc}.EN_{Pdc}] \qquad (3.2)$$

EC_BEN_{Pdc}, is the energy required for transmission of RBs in benchmark system. M is total number of allocated RBs, while TM is transmission duration. μ_{Pdc} represents PDCCHs overhead. $EN_{Data}$is amount of power required for data transmission, and EN_{Pdc} accounts for

PDCCH overheads transmission power. On the other hand, our scheme expands the bandwidth using time compression factor ($\mathcal{B} = 2$), hence pooling together two RBs which increases the size of sub-frame. Therefore proposed scheme saves considerable energy due to removal of control overhead. Equation 3.2 thus can be rewritten as:

$$EC\_Proposed_{Pdc} = M.\ TM\ [(\mathcal{B}.EN_{Data})(1 - \mu_{Pdc}) + \mu_{Pdc}.EN_{Pdc}] \qquad (3.3)$$

Where $EC\_Proposed_{Pdc}$ is energy consumed after time compression. $\mathcal{B}.EN_{Data}$ is the power required for data transmission after bandwidth expansion.

Algorithm 3.1: RBs Switching OFF

Referring to Algorithm in Figure 3.2:

1. *Get T; Get Z;* U_Y *represent UEs of Y*

2. Set cell counter = X // X: Set of centre cells;

3. Set cell counter = Y // Y: Set of neighbour cel

4. ***For*** *each X → │T│* ***do****, ∀X→T*

5. ***For*** *each Y →│Z│* ***do****, ∀Y →Z*

6.***IF*** ($RSRP_{U_Y} < THRESHOLD_Y \in Y$)*// threshold of* Y

7. ***then*** *Measure* $RSRP_X$ *for* $X \in U_Y$ *// Calculate X's* $RSRP$

8. *Information of* U_Y *exchanged between* X *&&* Y

9. ***IF*** $X_{CAPACITY} < THRESHOLD_{CAPACITY}$

10. X *acknowledge the availability of resources to*U_Y & Y

11. ***then*** $U_Y \leftarrow belongs\ to\ overlapping\ area\ of\ Y$

12. Y *send HO request* → U_Y *// HO: Handover*

13. U_Y *send HO confirmation* → Y

14. *HO* ∀ $U_Y \in Y \rightarrow X$

15. *Y send data packet information* → *X*

16. *Y turn off unused RBs of* ∀ U_Y *handover to X*

17. *Y = Y + 1; move to next neighbour cell*

18. ***While*** *(Y ≳ Z) when all neighbour cells have served*

19. ***do*** *X = X + 1; move to next centre cell in cluster*

20. ***Endwhile***

21. **Else** ***IF*** $(X_{CAPACITY} \geq \ THRESHOLD)$

22. *X = X + 1; move to next centre cell X*

23. ***End IF***

24. ***End IF***

25. ***End For***

26. ***While*** *(X ≳ T) when all centre cells have been served*

27. **do** *Stop/Terminate:*

28. ***Endwhile***

29. ***End For***

Since two RBs jointly transmitted to single user; thereby it reduces the PDCCHs signaling $(\mu_{Pdc}.EN_{Pdc})$, hence following holds true for enhanced ES.

$$\mathcal{B} = 2: EC_{Proposed_{Pdc}} must\ be < EC\_BEN_{Pdc}.\mathcal{B}$$

Above mentioned statement compares network level dynamic power consumed by all RBs in benchmark and proposed ES scheme. From SINR calculation formula, the required RF transmission power (EN_{Data}) for RB *i* can be calculated as:

$$\mathcal{R}_i' = \frac{O' + J_i}{S_{pq}} (\mathcal{Z}_i) \quad (3.4)$$

While $\mathcal{Z}_i$ is required target SINR for RBi, O' is the noise floor, S_{pq} is path gain between BS (q) and UE (p), and J_i is interference at RBi. Using equations (3.2) & (3.4) the total transmission power required to deliver the payload on $\mathcal{B}$ for benchmark system can be calculated as:

$$TP_{Benchmark} = TM \sum_{i=1}^{\mathcal{B}} \left[\left\{ (1 - \mu_{Pdc}) \times \frac{O' + J_i}{S_{pq}} (\mathcal{Z}_i) \right\} + \mu_{Pdc} . EN_{Pdc} \right] \quad (3.5)$$

Equation (3.5) calculates power consumed by two RBs only in benchmark in comparison with one super RB in proposed ES scheme therefore bandwidth expansion factor $\mathcal{B}$ is used in equation (3.5). Further total transmission power required to deliver the total number of RBs (M) in benchmark system can be calculated by replacing $\mathcal{B}$ with M in equation (3.5). While M presents total number of RBs in benchmark system which is differ from proposed ES scheme based network due to the bandwidth expansion. The total transmission power required to deliver the total number of RBs (M') in proposed scheme can be calculated using equations (3.3) and (3.4):

$$TP_{Proposed} = TM \sum_{i=1}^{M'} \left[\left\{ \mathcal{B} \left(\frac{O' + J_i}{S_{pq}} (\mathcal{Z}_i) \right) \times (1 - \mu_{Pdc}) \right\} + \mu_{Pdc} . EN_{Pdc} \right] \quad (3.6)$$

Equation (3.5) and (3.6) are used to calculate total transmission power in benchmark and proposed scheme to analyse the impact of bandwidth expansion for ES. Since our ES scheme merge two RBs together, therefore bandwidth expansion factor $\mathcal{B} = 2$ is used in equation (3.6). The core purpose of $\mathcal{B}$ is to calculate power consumed by extended super RB. Since in our proposed scheme, 2^{nd} RB does not contain PDCCH signal therefore it remains in data part in equation (3.6).

3.4 System Model

MATLAB platform is used in all simulations carried out throughout this thesis. The system model considers densely deployed scenario consisting of 7 cells which are further extended to 21 in next chapters for advanced performance analysis. There is only one BS per cell covering up to 1000 meters in radius with overlapping area with neighbour cells. All BSs communications with each other through X2 interface as per 3GPP specifications. The BS maximum transmission power is 46 dBm while carrier frequency is 2.14 GHz. The system bandwidth is 20 MHz with total 100 RBs uniformly distributed over total number of cells in cluster. The UEs are uniformly generated while placed in coverage area of each cell using random distribution. Initially 10 UEs per cell used for preliminary analysis while they increased to 50 in advance simulations carried out in next chapters. Two mobility models (straight walking and random way points) are used in system model. Due to the simplicity, straight walking model is used in initial results while random way point is employed in next chapters to analyse system performance under realistic UE mobility. The UEs speed is set at 40km/h in both models which is then changed in subsequent simulations in following chapters. The performance of propose ES scheme is analysed through the comparisons of dynamic power consumption at downlink transmission in BS. All simulation assumptions, parameters and models are selected in line with 3GPP specifications [56]. In the same context, initially LTE simulator and MATLAB is presented in next section which is then followed by various models and other important parameters used in this chapter.

3.4.1 LTE Simulator Platform

The aim of this research is to invent and implement novel ES scheme at BS in LTE networks and then investigate its impact on OPEX and CO_2 emission. To achieve these objectives, MATLAB is used for all simulations. The LTE Vienna Simulator [117] is used in this research as it provides realistic scenarios for LTE networks. Importantly Vienna simulator is only used as a standard LTE network, while proposed novel ES schemes and numerous performance analysis results are imported in this simulator. Hybrid ES scheme is implemented at downlink in BSs while densely deployed scenarios are considered to investigate its performance. LTE simulator consist of RAN, UEs distribution, mobility models and BSs. Following presents core building blocks of LTE Vienna simulator platform.

3.4.1.1 LTE Vienna System Level Simulator

The LTE Vienna Simulator is MATLAB based open source platform which allow reproducibility while found appropriate for performance and comparative analysis of novel ES schemes.

3.4.1.2 Validation of Simulator

The simulation parameters are nominated as stated by 3GPP based technical specifications [56]. Proposed novel ES schemes are implemented and analysed in accurate LTE scenario while its performance is validated through comparative analysis with standard and other state of the art in the presence standard 3GPP based parameters.

The system model consist of LTE network topology is a densely-deployed scenario (based on 3GPP specifications [56]) which initially consist of 7 cells with overlapping neighbour cells (Figure 3.3). However number of cells are increased in simulations carried out in next chapters. Each cell has radius of around 1000 meters while consist of 1 BS and 10 mobile UEs randomly distributed within the coverage area. Network model consists of core network also known as EPC, UEs and E-UTRAN [118].

3.4.2 Power Model

To interlink power consumption with OPEX, it is important to consider appropriate power model considering all components of the BS. Figure 3.5 presents detailed power consumption model employed in this work.

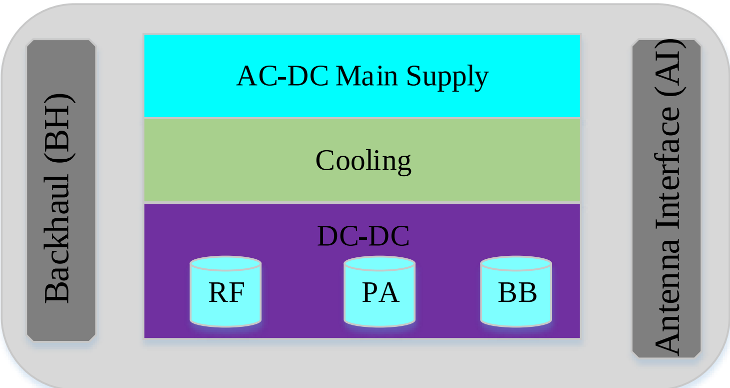


Figure 3.5: Power consumption model.

The backhaul part serves the provision of link between BS and core network. Importantly each BS may consist of multiple transceivers (TRXs) with multiple antennas. Figure 3.5 shows individual TRX consists of PA, antenna interface (AI), base band unit (BB), RF, cooling system, Direct Current (DC) - DC power supply regulator and Alternating Current (AC) - DC power supply. To calculate overall OPEX, the total power consumption of cell must be considered. The total power per BS is calculated as:

$$P_{BS} = P_{Dynamic} + P_{Static} \tag{3.7}$$

Where P_{BS} presents power consumption of each BS, $P_{Dynamic}$ presents dynamic power consumed by PA relying on data rate. P_{Static} describes constant power independent of data load. Since AI directly affects RF therefore it is considered in DC power consumption part. Hence P_{BS} including dynamic power, considering number of antennas can be calculated as [119-120]:

$$P_{BS} = N \left(\frac{P_{Trx}}{R_{eff}} \sqrt{\frac{R\sim}{C_{cell}}} \right) + P_{Static} \tag{3.8}$$

{C_{cell} *for LTE (20 MHz BW;) 43 Mbps/cell*}

In equation (3.8) square root is only used to reduce the length of larger decimals in simulation. However, it does not have any contribution on power consumption and system performance. Further N presents number of antennas, P_{Trx} presents maximum transmission power, R_{eff} describes radio efficiency, which is directly related to traffic load. $R\sim$ presents required data rate, while C_{cell} is maximum cells capacity in relation to RBs, BW presents bandwidth available for each user. Thus C_{cell} for total number of UEs (UE_T) per cell can be calculated as:

$$C_{cell} = BW * UE_T \tag{3.9}$$

Since RBs are equally allocated to the all UEs in cell, thus BW is known. Therefore C_{cell} can be easily calculated by multiplying BW with UE_T as shown in equation (3.9). Further annual energy consumption per BS can be calculated by manipulating equations (3.7) and (3.8) as:

$$P_{Annual} = P_{BS} * H_{Sec} * H_{Hours} * N_{Days} \tag{3.10}$$

Where H_{Sec} presents number of seconds per hour, H_{Hours} presents number of hours and

N_{Days} presents number of day per year. Since proposed scheme allocates two RBs to single user in comparison with benchmark therefore C_{cell} varies in both systems. Equation 3.10 is used to calculate total power consumption per BS.

3.4.3 OPEX and CAPEX calculation

Once power consumption has calculated in previous section, then next step is to calculate OPEX and CAPEX accordingly. In view of network operators, OPEX and CAPEX are calculated in unit km^2 to analyse the effects of reduced power consumption on profitability. Initial CAPEX of each cell (BS) per km^2 can be calculated as equation (3.11) [120]:

$$E_{CAPEX} = Cost_{equipment} + Cost_{Insertion} + Cost_{Backhaul} + Cost_{Spectrum} \tag{3.11}$$

$Cost_{equipment}$ presents equipment's expense, $Cost_{Insertion}$ presents components installation expense, $Cost_{Backhaul}$ is backhaul network installation expense, while $Cost_{Spectrum}$ is cost of spectrum purchased for network operations per BS. Accordingly, $CAPEX$ can be calculated using equation (3.11) while annual OPEX for each BS per km^2 can be calculated as:

$$E_{OPEX} = Cost_{Electricity} + Cost_{Rent} + Cost_{Maintenance} + Cost_{Backhaul} + Cost_{Marketing} \tag{3.12}$$

Equation (3.12) is used to calculate OPEX per BS. Where $Cost_{Rent}$ presents site rent expense, $Cost_{Maintenance}$ presents BSs maintenance expense, $Cost_{Backhaul}$ presents backhaul expense. $Cost_{Marketing}$ presents marketing cost, $Cost_{Electricity}$ is BSs electricity expense which can be calculated by manipulation equation (3.12) and (3.13).

$$Cost_{Electricity} = P_{Annual} * Price_{kWh} \qquad (3.13)$$

Where $Price_{kWh}$ presents price of electricity per unit (kWh). Usually operators consider OPEX as ongoing expenditures while they transform CAPEX cost in to OPEX via loan and repaid instalments. The total annual expense (EXP_{Annual}) of each BS per km^2 can be calculated using equation (3.14).

$$EXP_{Annual} = E_{CAPEX} + E_{OPEX} \qquad (3.14)$$

It is possible for operators to deploy more than one BS per km^2 to ensure reliable QoS in enlarged UEs density. In that case, the total annual expense considering total number of BSs per km^2 must be calculated as:

$$EXP_{km} = \sum_{k=0}^{n} EXP_{Annual} \qquad (3.15)$$

Where k presents each BS and n presents total number of BSs per km^2. However, in this work only one BS per km^2 ($n = 1$) is considered for performance analysis. To get EXP_{km}, initially the $CAPEX$ and $OPEX$ needs to be calculated using equation (3.14) & (3.15). While equation (3.15) used to calculated total annual expense per km^2.

3.5 Performance Analysis

Performance analysis of proposed scheme is done using system level simulations in MATLAB with parameters according to the 3GPP specifications [56] as shown in Table 3.2. Power consumption is calculated at downlink transmission at BS. Proposed scheme is compared with 3GPP specifications based LTE standard network (Benchmark). Table 3.2 also contain all OPEX/CAPEX related parameters used in performance analysis. In order to demonstrate reduced power consumption and OPEX, effectiveness of the proposed scheme, the key performance indicators considered are dynamic power consumption, annum OPEX and CAPEX per km^2.

Table 3.2: OPEX and CAPEX parameters

Parameters	**Value**	**Parameters**	**Value**
Bandwidth	20 MHz	Carrier frequency	2.14 GHz
Traffic model	Full Buffer	Target SINR, $\mathcal{Z}_i$	6.3, 12.1 dB
UE Speed	2.8 m/s	RB per UE	1,2
Time compression	$\mathcal{B} = 2$	BS Max. power	46 dBm
Overhead, μ_{Pdc}	14.99 percent	Total number of cells	7
Coverage Area	10 UEs/cell	Antenna Gain	13dB
Path Loss	Hatta Model	BS per cell	1
CAPEX Parameters / cell			
Cell insertion costs [121, 122]	I_{cost}	£115,000	
Cell equipment costs [121]	E_{cost}	£28,000	
Backhaul Installation costs [123]	BH_{Int_cost}	£8,500	
Spectrum cost per cell [124]	SP_{cost}	£3,295	
Total initial CAPEX per cell	$\boldsymbol{CAPEX}$	**£154,795**	
OPEX Parameters / BS			
Backhaul rental costs [123]	BH_{Rent}	£7600	
Cell site rental cost [121]	S_{Rent}	£10,800	
Maintenance cost per cell [121, 123]	MN_{Cost}	£3900	

Cost of energy (per kWh) [125] BS electricity & other site electricity bills BS electricity in KW	B_{cost} $EC_{BS}.B_{cost}$	£0.14 £6325 [£5020+£1305] £0.14*35857.14 kWh 35857.14kWh=4.1kW
Marketing expense [126-127]	MR_{Mark}	£3257
CAPEX (12 months repayment)		£12900
5 percent interest rate on CAPEX [120]	Int	£479
Total OPEX per cell	$OPEX$	**£45261**
Total expense including **(OPEX and CAPEX) / cell**	$\bar{TE}_{Annual}$	**£20005.6**
Number of days	N_{Days}	365
Number of Hours	H_{Hours}	24

3.5.1 Results and Discussions

Performance analysis results are categorized in three sections. Initially power consumption related results are discussed in power consumption analysis section. Further impact of reduced power consumption on OPEX is presented in 2^{nd} section (OPEX analysis). In this chapter OPEX is analyzed at macro level, however it is further investigated in detail in next chapter 4.

3.5.2 Power Consumption Analysis

In this section, various power consumption related results (i.e. received power, dynamic power consumption, energy consumption gain) are discussed. Further reduced total power consumption is also presented in this section which is in link with following OPEX analysis.

3.5.2.1 *Path Loss (PL) & Received Power*

Path loss (PL) is highly variable entity which depends on, antenna height, receiving terminal location related to obstacles, reflectors and link distance. Figure 3.6 presents calculated PL considering the distance between UE and serving cell. Clearly, PL increases with increase in distance of user from BS.

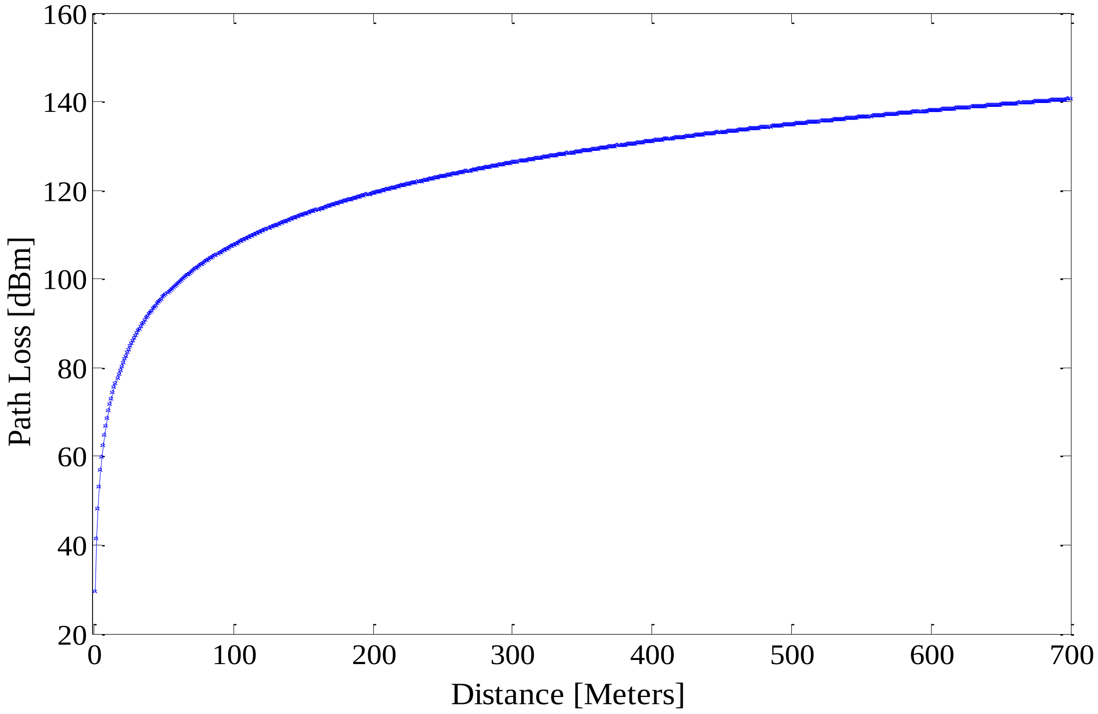


Figure 3.6: UE path loss w.r.t BS

3.5.2.2 *Dynamic Power Consumption with Factor B*

Proposed Scheme employs RBs expansion factor value of $\mathcal{B}$ = 2 & 3 and is compared with benchmark system ($\mathcal{B} = 1$) in Figure 3.7. It is evident that there is direct relationship between power consumption and data rate. Although RB expansion factor of $\mathcal{B}$ = 3 is EE compared to $\mathcal{B}$ = 2, however it significantly reduces overall available capacity per BS, increasing the unaccepted user rate, therefore $\mathcal{B}$ = 2 is considered to be best expansion factor in our scheme. In the same line, Figure 3.8 demonstrates Cumulative Distribution Function (CDF) based plot for the dynamic power consumption in our system with expansion factor ($\mathcal{B}$ = 2) and benchmark. Proposed scheme is around 29 percent efficient while compared to the benchmark. It offers this energy efficiency by employment of joint RBs switching off and bandwidth expansion.

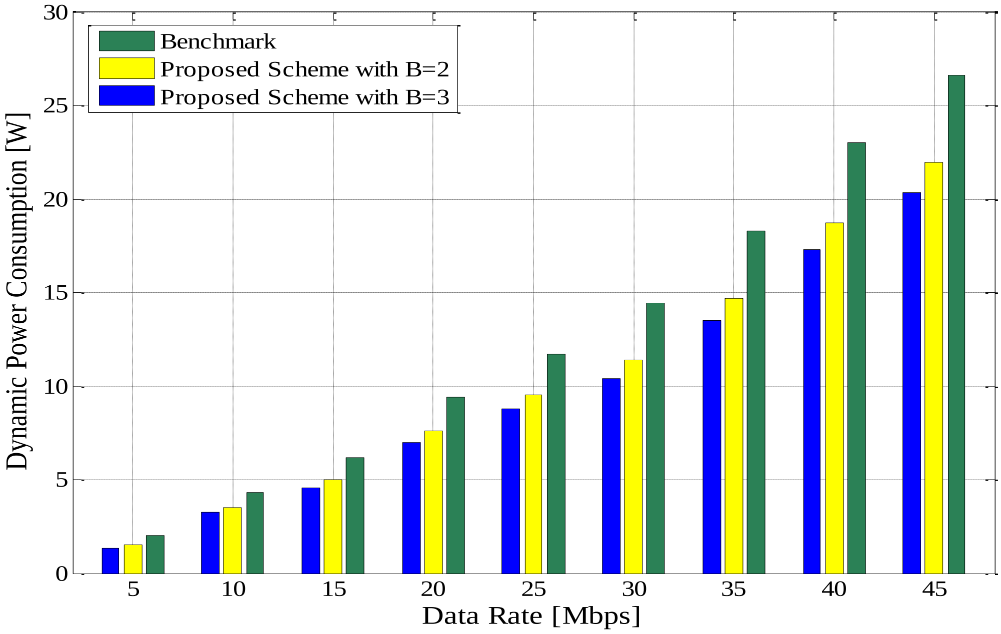


Figure 3.7: Data Rate vs Power Consumption

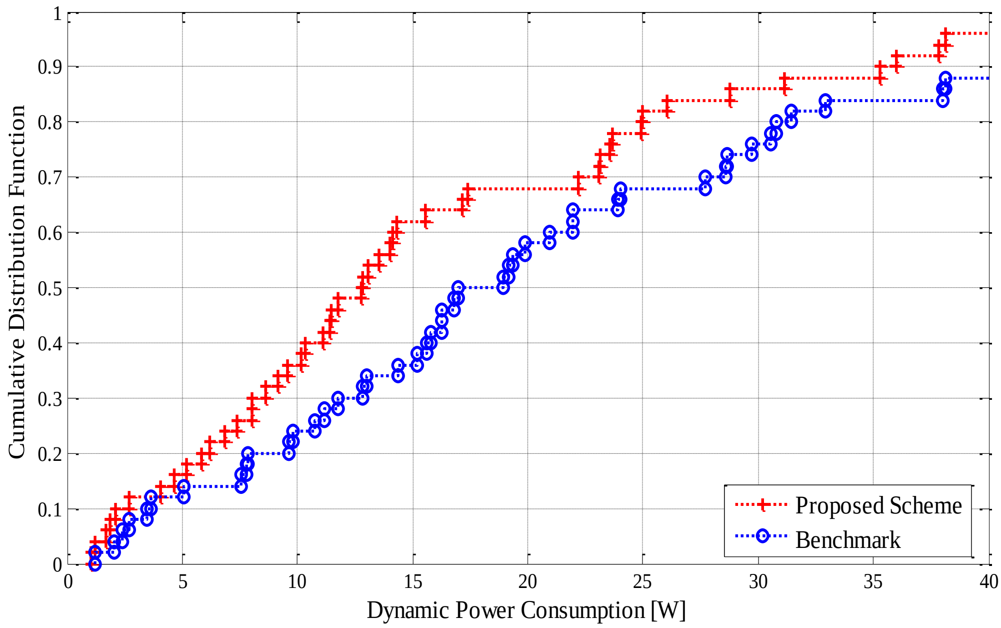


Figure 3.8: Dynamic Power Consumption

As discussed above Figure 3.9 shows that with $\mathcal{B} = 3$, proposed scheme rejects around 40% UEs due to lack of resources which is clearly reduced user satisfaction and undermines QoS, while UEs rejections rate with $\mathcal{B} = 2$ is around 10%. Therefore $\mathcal{B} = 2$ is considered best expansion factor for proposed scheme to keep good balance of ES, overall BS capacity and

UEs acceptance. Therefore, bandwidth expansion factor $\mathcal{B} = 2$ is used in proposed scheme in performance analysis results throughout the thesis. Point to be noted that there is slightly increase in unaccepted UEs at higher data rates in all trends because higher data rate directly reduces overall system capacity to accept inbound UEs.

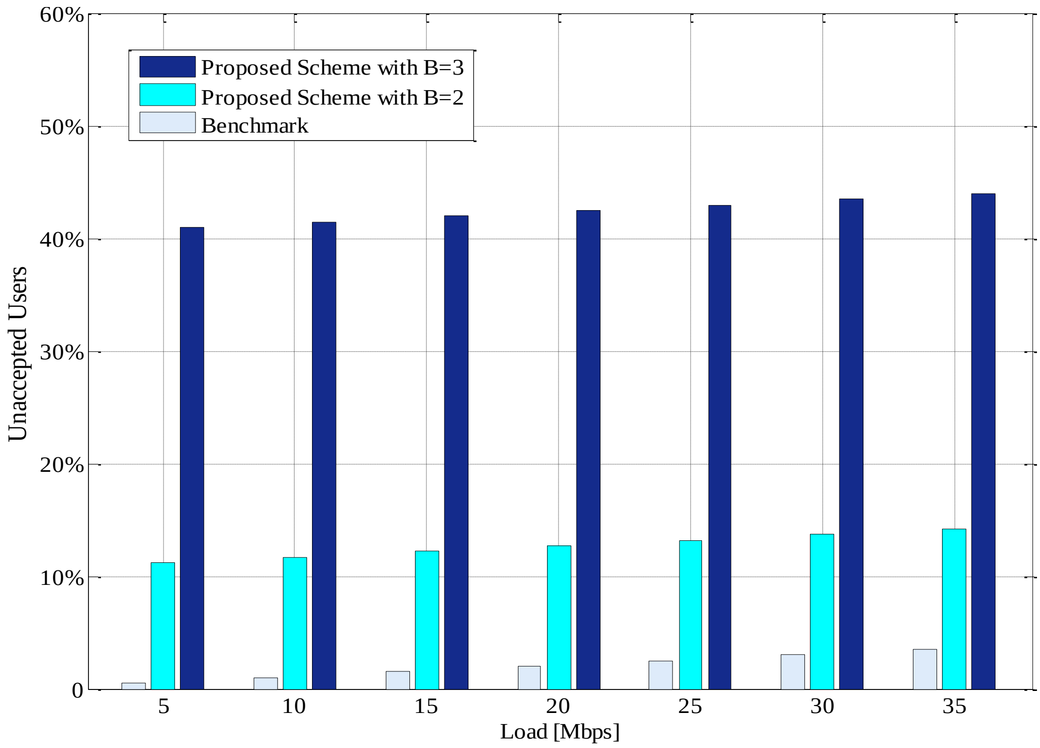


Figure 3.9: Unaccepted UEs

3.5.2.3 Energy Consumption Gain

The reduced power consumption results in to higher Energy Consumption Gain (ECG) while increased power consumption results in to lower ECG. In the same context, ECG is in direct relationship with the ES, therefore 29 percent ES can provide 29 percent improved ECG over Benchmark as shown in Figure 3.10.

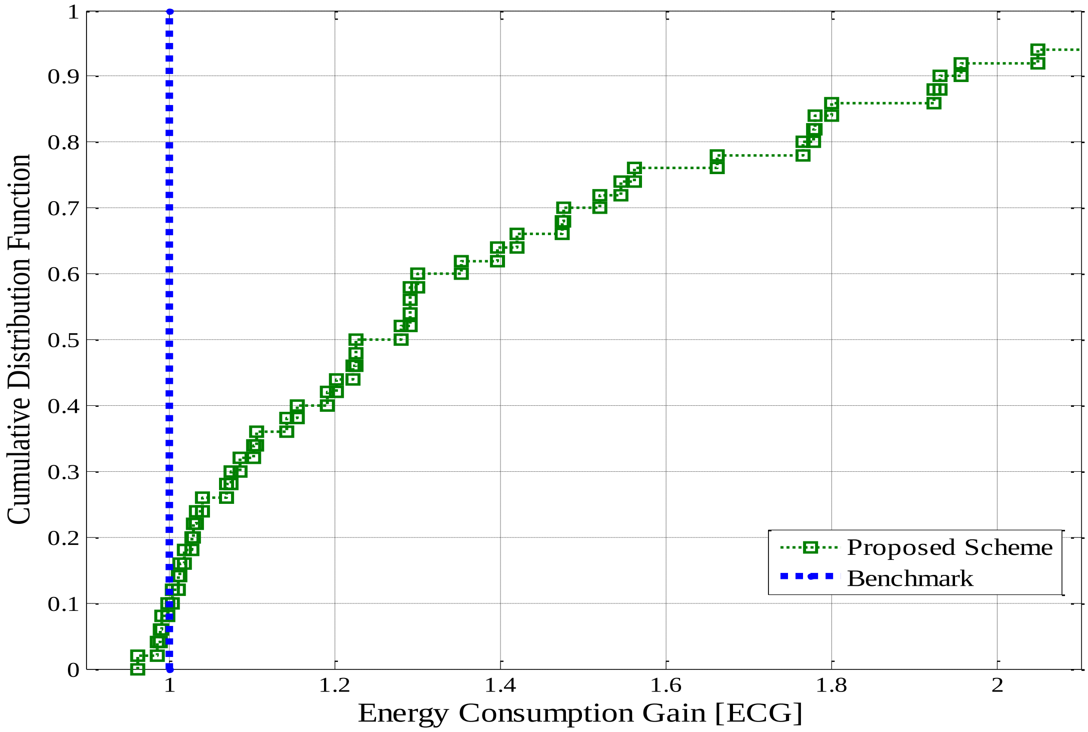


Figure 3.10: Energy Consumption Gain [ECG]

OPEX cost for operating network is main expense for vendors. As explained earlier, the OPEX must be calculated by considering power consumption in kW/ km^2. In the same context, Figure 3.11 compares total power consumption for proposed scheme with the benchmark (typical LTE) system by combining above discussed dynamic power consumption with BSs static power. Again it is evident that power consumption increases with increased data rate. However, on average, proposed scheme was 29 percent EE compared to benchmark system.

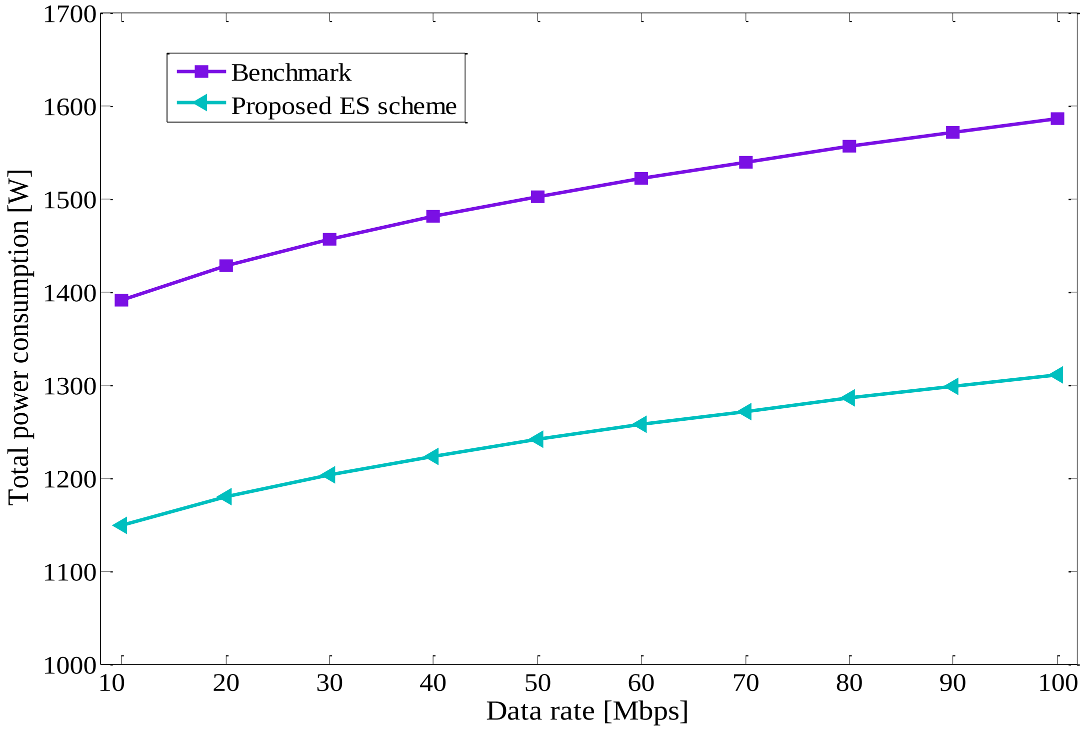


Figure 3.11: Total power consumption

3.5.3 OPEX Analysis

Accordingly, the impact of reduced power consumption is reflected in reduced OPEX. Figure 3.12 presents annual OPEX (per km^2) of benchmark and proposed ES scheme. Results clearly indicate that reduced power consumption in proposed scheme has significant reduction in overall OPEX per year which helps vendors to stay profitable. Accordingly, reduced OPEX through proposed ES scheme would have greater impact on overall profits over full coverage area. Point to be noted that reduced power consumption seems small in view of single BS. However, it will have greater impact on OPEX when full network infrastructure, consisting of thousands of BS, is considered. This will be further investigated in detail in next chapter 4.

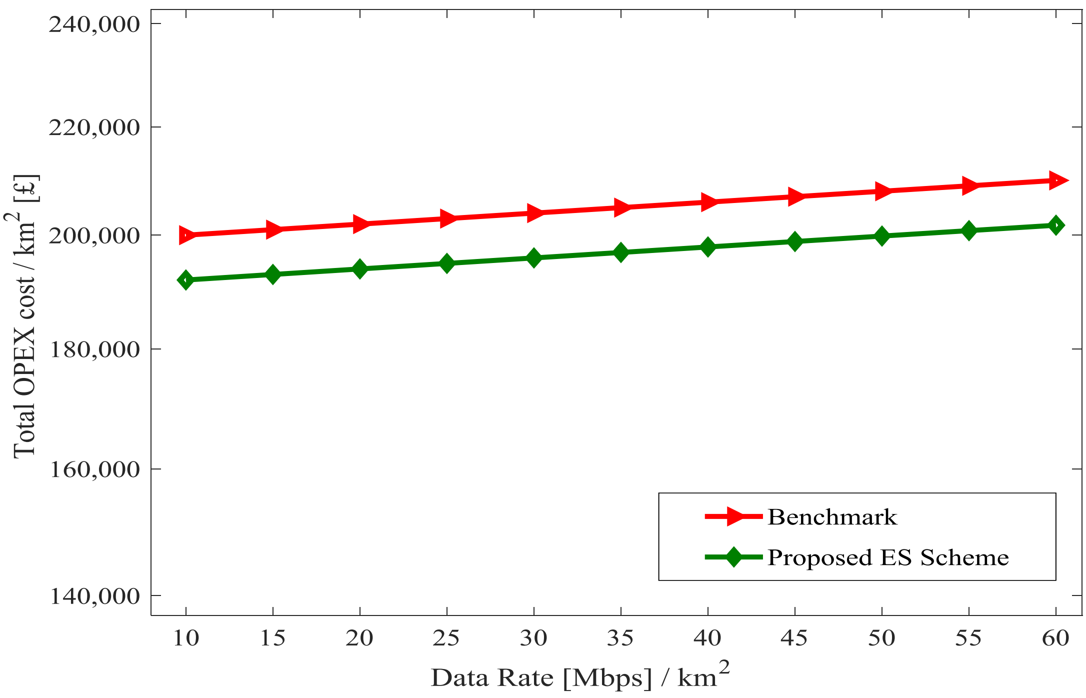


Figure 3.12: Yearly OPEX Analysis

Figure 3.13 presents the complete breakdown of OPEX moreover it also reflects on achieved profit through reduced OPEX. Power consumption contributes approximately 4 percent in overall OPEX, while 29 percent ES through propsed scheme reduces this figure from 4 to 2.9 percent, which results in 1.12 percent increase in vendors profit. Again, achieved profit seems to be small for single BS, however it will significantly increase profit level when all operating BSs are considered in chapter 4.

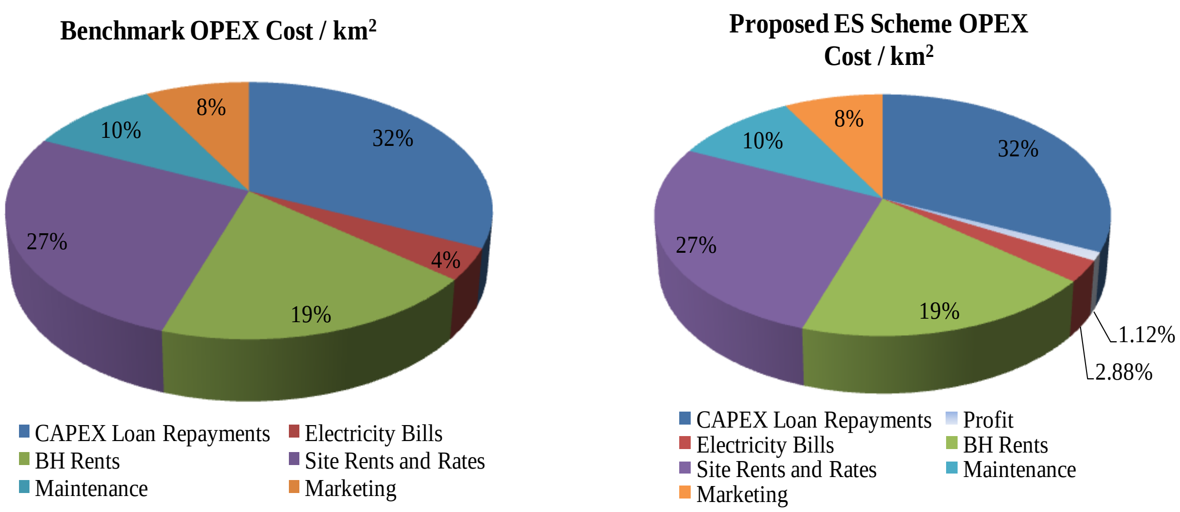


Figure 3.13: Relationship between reduced OPEX and profit gains

3.5.3.1 *Throughput*

As discussed earlier in this chapter that propose ES scheme expand bandwidth by merging two RBs together which results in reduced PDCCH overhead. Thus, the spare REs can be used for data transmission. In the same context proposed scheme uses expansion factor $\mathcal{B} = 2$ which accounts for availability of increased bandwidth results in improved throughput for proposed scheme (6.1 Mbps) as compared to benchmark systems (5.5 Mbps), Figure 3.14.

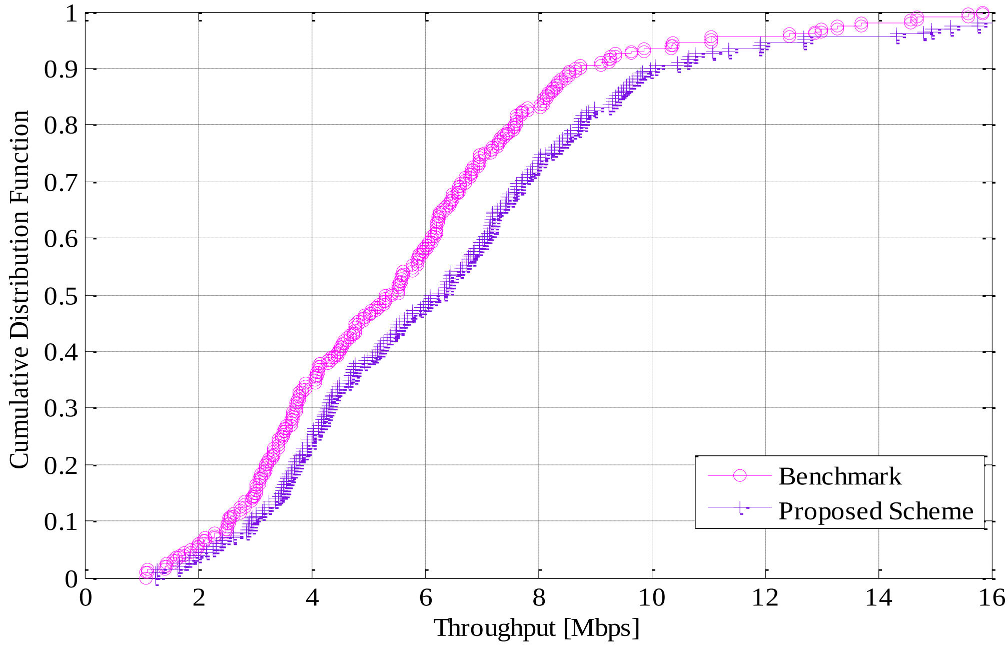


Figure 3.14: Throughput

3.6 Summary

The increased number of UEs and their high data rate significantly affects the economic benefits of vendors. The increased OPEX have become major challenge for future cellular networks. On the bases of critical analysis and open research issues presented in chapter 2, This chapter propose joint RBs switching off and bandwidth expansion ES scheme for LTE networks. The performance of proposed scheme is analyzed using system level simulations for LTE based scenario. This chapter also presents statistical significance of achieved ES scheme in view of annual OPEX. Results proved that 29 percent ES achieved in proposed ES scheme could have significant impact on OPEX. Proposed ES scheme has reduced overall annual OPEX by 1.12 percent per km^2. In view of full geographical area coverage, the 1.12 percent reduction in OPEX per km^2 could provide greater profits. This is carried forward in next chapter for more comprehensive analysis. In chapter 3, OPEX is analyzed undetailed, however next chapter investigate it at very micro level and calculates actual profit achieved through reduced power consumption in presence of real traffic in REHO and LTE standard.

Chapter 4

4. Reduced Early Handover for ES in LTE Networks

4.1 Introduction

In the previous chapter, bandwidth expansion based ES scheme was proposed and analyzed through comparative analysis with LTE standard. Offered ES scheme was based on the idea of bandwidth expansion and turning OFF idle resources. In the same line, this chapter further extends previously proposed ES scheme (in chapter 3) by incorporating the idea of novel early handover and offer complete work by merging both techniques (bandwidth expansion and early handover) together. This chapter introduce a novel reduced early handover (REHO) scheme which combines with formerly proposed ES scheme with reduced early handover to form hybrid system for improved energy conservation in LTE networks.

As already discussed in research question section in chapter 1, the raised power consumption not only affects operators OPEX but also contributes in global warming, i.e. affecting both environmental and economic aspects. In this context, several operators such as Vodafone, Telefonica, Tel-Italia, France telecom have already initiated energy efficiency related research projects to stay progressively profitable and green. Although substantial research work has been carried out for improved energy efficiency, however there is almost no work available which collectively investigates the impact of ES on OPEX, carbon footprint, achieved profitability and overall system efficiency. In this view, this chapter propose novel REHO scheme which results in to increased energy efficiency. In the same line, impact of reduced energy consumption is shown on OPEX, as well as greener aspects are also investigated by inclusion of real life commercial tariffs adopted by one of the mobile operators in the UK. Performance analysis revealed that varying time to trigger (TTT) values significantly impact RLF, ping pong effect as well as call drop ratio (CDR) and Handover ratio (HOR), at changing UEs velocities. Further this chapter investigates and provides a very useful insight for superlative value of TTT for unbiased RLF and Ping Pong, which can help vendors not only to achieve increased energy efficiency, but also maintain other salient performance parameters within acceptable limits. The work also achieves the fact that the time difference in terms of TTIs for reduced early handover in REHO, always remain the same irrespective of the value of TTT, thus ensuring that REHO continuously achieves increased energy efficiency compared to LTE standard. System level simulations have been performed to analyse the performance of proposed scheme. Through fine tuning of the handover parameters (hysteresis, Offset and TTT), the proposed REHO embraces the concept of *reduced early handover*, thus resulting into around 7.5 percent lesser energy. The hybrid scheme, when merged with bandwidth expansion introduced in chapter 3, results into about 35 percent ES in relation to benchmark and other state of art systems. Since REHO initiates early handover for turning OFF idle resources, therefore drawback of standard handover is firstly discussed as follow:

4.2 Limitations of Standard Handover

LTE networks guarantee higher data rate in comparison with 3G technology. To ensure UEs seamless connectivity, handover is performed between serving and target cells. All UEs measure signal strength from serving and neighbour cells; in case signal strength of neighbour cell becomes better than the serving cell, UE sends measurement report to serving cell. Serving cell reviews received information and prepares handover. Three key parameters, Hysteresis, Offset and TTT accordingly are used in A3 event to achieve efficient handover process. TTT delays A3 event to ensure more stable signal quality to avoid unnecessary handovers, whereas the role of hysteresis is to further worsen neighbour cell RSRP than actually measured. All TTT, hysteresis and offset ensure steady RSRP of neighbour cell before UE sends measurement report to serving cell requesting handover.

The use of hysteresis, offset and TTT ensures slightly improved RLF, however accordingly results in increased energy consumption. Importantly these parameters force UEs to get closer to the target cell to avoid link failure before handover thus engaging serving cell resources for longer time which adds in overall power consumption and impact augmented OPEX. The standard handover process can be improved by handover early initiation through usage of reduced hysteresis value. This will help serving cells resources to be switched OFF earlier for increased energy efficiency. Accordingly, this is the basis of proposed REHO scheme as described below.

4.3 Reduced Early Handover Scheme

The REHO scheme employs reduced early handover in terms of TTIs and mainly focuses on appropriate turning off idle RBs for increased ES. To ensure practicality, REHO amends standard handover procedure through the usage of reduced minimum hysteresis (1 dBm compared to LTE standard value of 4 dBm) which helps initiate early handovers as shown in Figure 4.1. REHO while deployed at every BS enables them to handover all UEs from overlapping areas of serving cells to the target cells thus enabling serving cells to switch off freed (Idle) resources for ES. Figure 4.1a presents two cells (serving and target) to explain the operation of REHO scheme. The UEs while heading towards target cell T receive cell specific RSs both from serving cell S and target cell T which is used by UEs to calculate RSRP, subsequently enabling them to decide and trigger handover. Standard handover with usual hysteresis values is presented by blue dotted circle, whereas red dotted circle represents reduced early handover, i.e. the main feature of REHO scheme. The time difference between standard and early handover, helps resources of serving cell to become free early so they could be turned off ΔT earlier for increased ES. Notably ΔT is calculated in terms of TTIs. Figure 4.1b represents turning off of resources in time domain. This fact is proved through system simulation in section 4.4.

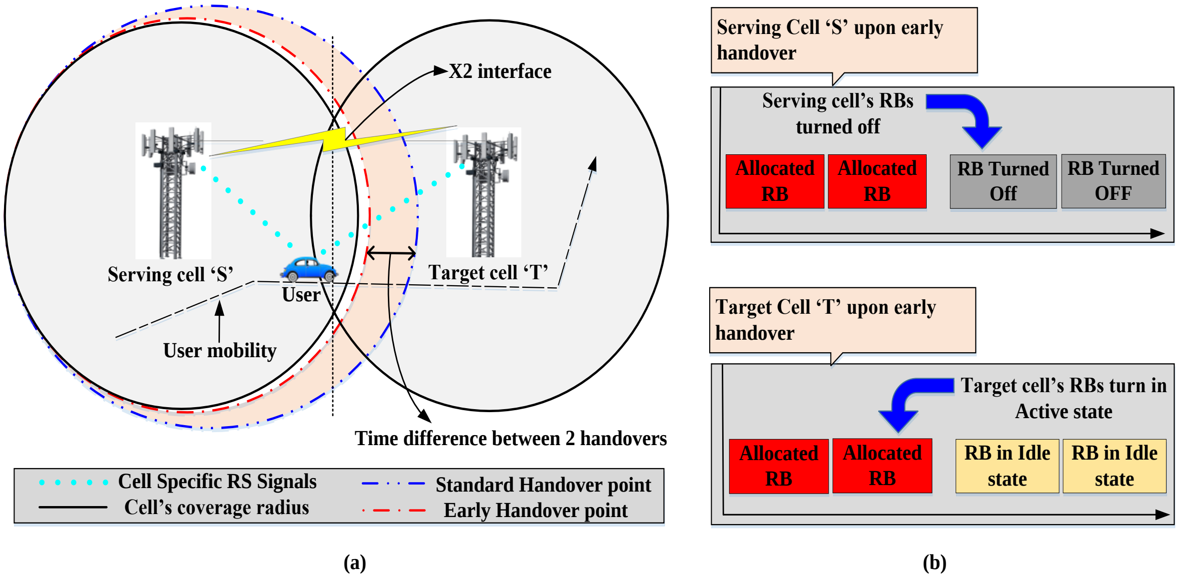


Figure 4.1: REHO scheme; a) Early handover Initiation; b) Turning off resources in time domain

Referring to Figure 4.1, considering UE in cell *S* moving towards cell *T*, its received power from cell *S* could be represented as $\mathrm{P_{ra}}$ (Equation 4.1).

$$P_{ra} = P_a - PL_a + G_{total} \tag{4.1}$$

Where P_a is the transmit power of cell *S*, PL_a is path loss, whereas G_{total} is the antenna gain. RSRP of total number of RSs received per TTIs can be calculated as:

$$RSRP_a = \sum_{i=1}^{n} (P_{ra})/n \tag{4.2}$$

Where n is the total number of RSs received from cell *S* (serving cell). On the same lines equations 4.3 and 4.4 respectively gives the received power and RSRP for the same UE from target (neighbor) cell *T*.

$$P_{rb} = P_b - PL_b + G_{total} \tag{4.3}$$

$$RSRP_b = \sum_{i=1}^{n} (P_{rb})/n \tag{4.4}$$

Where n is the total number of RSs received from cell *T* (neighbour cell). Referring to Figure (4.1), when UE reaches at intersection line, its distance from both cells *S* and *T* becomes equal. When UEs move away from cell S and reaches near target cell T, Hysteresis (Hy) and the $Offset$ is used to make serving cells RSRP ($RSRP_a$) better than actual measured. RLF is one of the most important factors to be considered in handover process. Both early and late handover can result into RLF. RLF can occur in early handover if the signals received from candidate (target) cell are weak enough to sustain the link. While if handover is triggered too late, radio link could get failed too due to the weak signals strength from serving cell. Since proposed REHO is aimed at energy conservation, therefore it considered early handover. TTT and offset are important factors to be considered in reduced RLF while performing early handover. The chosen minimum value of offset (i.e. 3 dB) in this work is to ensure acceptable levels of RLF. Compared to standard 3GPP handover, the phenomenon of reduced early handover provides opportunity to turn off idle resources at early stage, resulting into increased ES. Referring to Figure 4.2, UE of a serving cell moving towards target cell whereas the time I taken by UE to reach at the point where standard handover will take place is given as (Equation 4.5):

$$TM = D_s/V \tag{4.5}$$

Point to be noted that TM presents time from the boundary of target cell, in overlapping area of serving cell, to the handover point. Where V is speed of UE, and D_s is distance covered. While in proposed hybrid scheme, handover is initiated at early stage, i.e. ΔT duration (Figure 4.2):

$$\Delta T = TM - TM^{\tilde{}} \tag{4.6}$$

While $TM^{\tilde{}}$ represents the time spent by UE to reach at early stage of handover $(Hy^{\tilde{}})$, and can be calculated as (Note: UE velocity still remains the same as V):

$$TM^{\tilde{}} = D_s^{\tilde{}} \,/\, V \tag{4.7}$$

ΔT is the hallmark of proposed REHO and represents the number of TTI for which the freed resources of serving cell S are switched off due to *reduced early handover* thereby resulting into increased system level energy conservation.

In proposed REHO the hysteresis is shrunk and its minimum value is used to perform *reduced early handover* $(Hy^{\tilde{}})$. Considering equation (4.2) and (4.4), UEs is to be *reduced* *early handed* over to cell T, when equation (4.8) is satisfied.

$$\sum_{i=1}^{n} \frac{(P_{rb})}{n} \geq \sum_{i=1}^{n} [(P_{ra})/n] + Hy^{\sim} + Offset \tag{4.8}$$

Equation (4.8) presents early handover based on REHO. Next section presents system model.

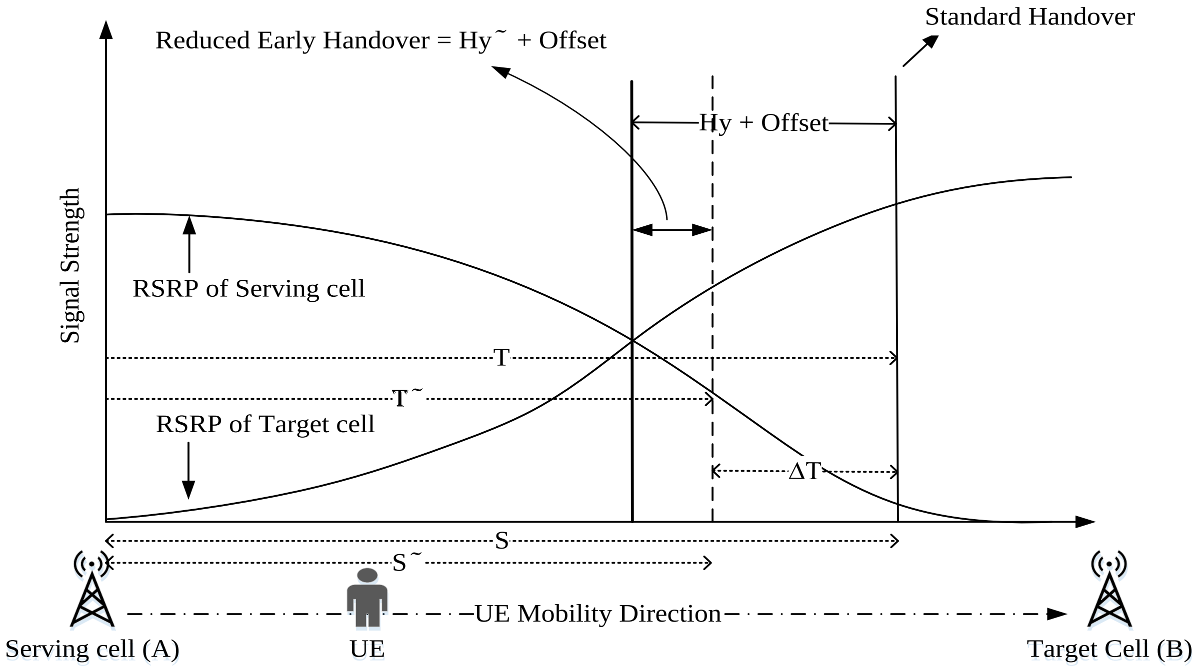


Figure 4.2: Reduced Early Handover

4.4 System Model

MATLAB has been used to perform system level simulations for performance and comparative analysis of the REHO with LTE standard and other state of art. Both straight walking and random waypoint mobility (SWM/RWP) models are incorporated in performance analysis. Noteworthy, the impact of ES on OPEX is investigated by taking into account real life commercial tariffs adopted by mobile operator, Three UK [128].

4.4.1 User Mobility Model

In the previous chapter straight walking model was used. However, in order to provide more realistic UE movement, in this chapter UEs mobility is modelled through random waypoint mobility (RWP) [129-130]. Where each UE initially selects one random point C_0^i as a destination in the coverage area. UE then starts moving towards selected destination C_0^i at velocity [131] S_0^i selected from [S_{Min}, S_{Max}], where S_{Max} is maximum allowed velocity for every single UE. Upon arrival at C_0^i, UE stops for time duration of T_{Pause} and then selects another random point C_1^i before it starts moving towards it. This process continues until the chosen mobility cycle is exhausted. The behaviour of mobility can be best described by mentioned key parameters below.

S_{Max}: *Maximum allowable velocity*

S_{Min}: *Minimum Allowable velocity*

Minimum and Maximum Velocity: $[0 < S_{Min} < S_{Max}]$

T_{Pause}: *The time period user waits at each selected destination.*

The entire range of node destinations in the region R can be given as:

$\{C_j^i\}_{j \in R} = C_1^i, \; C_2^i, \; C_{3,}^i, C_4^i \ldots\ldots\ldots\ldots.. C_n^i$

Where *i* presents specific user while *j* represents different destination points.

4.4.2 Power Consumption

To analyse the impact of power saving on operators OPEX, BSs power consumption per km^2 must be calculated. PA [132] in BS is main power hungry part, around 60 percent, while its power consumption is straightforwardly affected by data rate and resources utilization. Total power consumption per km^2 can be calculated by reusing power model presented in chapter 3 as follows:

$$PC_{km^2} = N * \beta_{c/km^2} \left(\frac{P_{Trx}}{R_{eff}} \sqrt{\frac{R\sim}{C_{cell}}} + E_{cell}^{`} + E_{BC} \right) \quad (4.9)$$

Further annual energy consumption per km^2 can be calculated as:

$$P_{Annual} = PC_{km^2} * H_{Sec} * H_{Hours} * N_{Days} \quad (4.10)$$

Where β_{c/km^2} presents number of cells per km^2 (in this work only one cell per km^2 is considered). E_{BC} presents power consumed by backhaul component, $E_{cell}^{`}$ describes power consumption overhead which is constant power independent of data load. Once total power consumption has been calculated, the next step involves OPEX calculation per km^2.

4.4.3 OPEX and CAPEX

The OPEX and CAPEX values are calculated by reusing their models (E_{OPEX} and E_{CAPEX}) already presented in chapter 3. Notably the BSs electricity bills contribute approximately 4 percent in overall annual expenses, while total annual expense per km^2 can be calculated as [120]:

$$\text{ŢĒ}_{Annual} = \beta_{c/km^2} * \{E_{CAPEX} \frac{Int(1+Int)^{YE}}{(1+Int)^{YE}-1} + E_{OPEX}\} \quad (4.11)$$

ŢĒ_{Annual} presents total annual expense per km^2. Both OPEX and CAPEX are calculated by adding up all above-mentioned expenses as also shown in (Table 4.1). While Int presents interest rate of instalments paid as a loan of CAPEX over years YE. The revenue per UE must be calculated to analyze operator profit, whereas revenue varies depending on UE tariffs, which in turn relies on data rate demanded and UEs density per km^2.

4.4.4 Call Drop Ratio and Handover Ratio

CDR mainly results from weak signal strength between the UEs and BS which in turn is due to increased RLF. Since REHO performs early handover to achieve decreased energy consumption, thus it is important to consider the effect of varying TTT over both CDR and HOR. CDR can be calculated as follows.

$$CDR = \frac{C_{Dropped}}{C_{Finished}} \quad (4.12)$$

$$CDR = \frac{C_{Dropped}}{C_{Dropped} + S_{Successful}} \quad (4.13)$$

$C_{Dropped}$ presents total number of dropped calls, while $S_{Successful}$ is number of successful calls. Similarly HOR can be calculated by equations (4.14) and (4.15) presented below.

$$HOR = \frac{H_{Fail}}{H_{Total}} \tag{4.14}$$

$$HOR = \frac{H_{Fail}}{H_{Successful} + H_{Fail}} \tag{4.15}$$

Where H_{Total} presents total number of handovers including successful handovers (($H_{Sucessful}$) and failed handovers (H_{Fail}). Both CDR and HOR are investigated at varying TTT values in performance analysis section.

4.4.5 Profit calculation Model

The revenue per UE must be calculated to analyze vendors profit, whereas revenue varies depending on UE tariffs, which in turn relies on data rate demanded and UEs density per km^2. The data rate per UE per km^2 can be calculated as:

$$\Gamma_{km^2} = \frac{\acute{R}_{km^2}}{D_{km^2}} \tag{4.16}$$

Γ_{km^2} is data rate(Mbps) per UE which depends on total data rate ($\acute{R}_{km^2}$) per km^2, while D_{km^2} is UE density per km^2. The data rate per UE/month (Γ_{month}) is calculated as:

$$\Gamma_{month} = \Gamma_{km^2} * S_{seconds} * M_{minutes} * H_{Hours} \tag{4.17}$$

$S_{seconds}$ is seconds per minute, $M_{minutes}$ is minutes per hour, H_{Hours} is number of hour per day, whereas Γ_{month} presents data rate/UE/month. The tariff price per UE depending on (Γ_{month}) used to form revenue per UE/year can be calculated as:

$$R_{revenue} = MN * Tariff_{cost} \tag{4.18}$$

MN is number of months per year, while $Tariff_{cost}$ presents price plan per UE. Thus $R_{revenue}$ for total number of UEs per km^2 is calculated as:

$$R`_{revenue} = R_{revenue} * D_{km^2} \tag{4.19}$$

Equation 4.19 is used to calculate vendors revenue per km^2. The vendor profit can be deduced by deducting annual expense (equation 4.11) from the total revenue.

$$P_{profit} = R`_{revenue} - \text{ꞆĒ}_{Annual} \tag{4.20}$$

P_{profit} present operators profit while $R_{revenue}$ presents operators revenue per km^2 which is calculated by considering the total number of UEs per km^2, tariff plan and associated cost which is comprehensively presented in (Table 4.1).

4.4.6 CO_2 Emission Calculation

Most of the telecommunication operators are expectant to reduce power consumption thus resulting in decreased CO_2 emissions. This could also help vendors to have high profile in '*Growing Green'* and enjoy competitive benefits. Additionally, vendors could also get advantage from '*Global carbon credit schemes'*. This scheme allows operators to emit CO_2 while it can also be traded in case of reduced CO_2 emission. Noteworthy, one tonne carbon emission is equal to one carbon credit, while each carbon credit worth of approximately £18 [133]. Thus in addition to growing green, vendors could also benefit from increased profit through reduced CO_2 emission which usually calculated by mobile operators on km^2 basis. Importantly, the amount of emitted CO_2 depends on type of fuel used to generate electricity [134-135]. The annum total power consumption per km^2 is calculated recalling equation (4.10).

$$P_{Annual} = PC_{km^2} * H_{Hours} * N_{Days} \tag{4.21}$$

Accordingly, the approximate volume of CO_2 emitted per km^2 by each fuel type, T_{Approx} can be calculated as:

$$T_{Approx} = P_{Annual} * P_{fuel} * CO_{Em} \tag{4.22}$$

Where P_{fuel} is percentage of the usage of each fuel type, while CO_{Em} presents CO_2 emission in Grams (Table 4.1) produced per kWh. Considering all fuel types (gas, coal, nuclear, renewable and other), total CO_2 emission can be calculated as:

$$T\_CO_2 = \sum_{i=1}^{n_f} T_{Approx} \tag{4.23}$$

T_CO_2 presents total annual CO_2 emission per km^2 while n_f presents the total number of fuel types used in electricity production (in this work $n_f = 5$). Depending on geographical figures, usually operators cover thousands of km^2 to provide adequate services. Accordingly, the total annual CO_2 emission considering full coverage area depending on all deployed BSs can be calculated as:

$$Annual_{Emission} = \sum_{i=1}^{BS_t} T\_CO_2 \tag{4.24}$$

Where BS_t presents total number of BSs to cover full geographical area. The total CO_2 emission interlinked with power consumption is calculated by applying the values of fuel percentage with associated CO_2 production per km^2. Proposed REHO results in atleast 30 percent reduced power consumption, thereby leading towards 30 percent reduced CO_2 emissions.

4.5 REHO Performance Analysis

Using system level parameters (Table 4.1), the proposed scheme is implemented in MATLAB and compared with benchmark (LTE standard network) and other state of the art [136]. A detailed performance evaluation is conducted by calculating dynamic power consumption, energy consumption gain (ECG), RLF, estimating associated OPEX, extracting profit achieved and finally measuring carbon foot prints in both REHO deployed and standard LTE networks. Results indicates that REHO on average offers 33 percent reduced power consumption in comparison with standard LTE handover, while achieved ES significantly impact OPEX. Additionally, reduced OPEX not only adds in profit but also results in considerably reduced carbon footprints, thereby achieving further increase in profits. In order to demonstrate '*Growing Green*' and '*Carbon Credit'* effectiveness of the REHO, the key performance indicators considered are total power consumption, CO_2 emission per km^2 and carbon credit per tonne. While overall system efficiency is also included.

Table 4.1 System Parameters			
Carrier frequency	2.14 GHz	UE mobility	SWM/RWP
Tariff	(Three UK) £360/year [28]	UE velocity V_{Max}	40 km / hour
BS max. power	46 dBm	Number of UEs	50/km^2
Handover hysteresis	1 dBm	Cell coverage radius	1000 m
Carrier frequency	2.14 GHz	Path loss	Hatta Model
BS power consumption parameters			
No. of cells (eNodeBs)	7 (1 BS/cell)	Main supply	18.6 W
PA max. output power	40 W (efficiency 31.1%)	Total $E_{cell}^{\emptyset}$	225 W
RF	13.0 W	E_{BC}	100 W
BB	29.9 W	No. of PAs per antenna	1
DC-DC	13.7 W	No. of antennas	4 x 4 (3GPP based)
Cooling	22.1 W		
CAPEX Parameters / Cell			
Cell insertion costs		I_{cost}	£90 k
Cell equipment costs		E_{cost}	£35 k
Backhaul installation costs		BH_{Int_cost}	£4.2 k
Spectrum cost per cell		SP_{cost}	£3.3 k
Total initial CAPEX per cell		$\boldsymbol{CAPEX}$	**£132.5 k**
Annum OPEX parameters / Cell			
Backhaul rental costs		BH_{Rent}	£8.9 k
Cell site rental cost		S_{Rent}	£12.6 k
Maintenance cost per cell		MN_{Cost}	£4.5 k
Cost of energy (per kWh) BS electricity bill		B_{cost} $EC_{BS}.B_{cost}$	14.00 pence/kWh £1.837 k
Marketing expense		MR_{Mark}	£3.7 k
CAPEX (Repayments)		YE	12 Years x £14.9 k

Interest rate on CAPEX loan	Int	5%
Total annum OPEX per cell	$\boldsymbol{OPEX}$	**£46.4 k**
Number of days	N_{Days}	365
Number of hours	H_{Hours}	24
Total annum expense including (OPEX and CAPEX) / cell	$\bar{TE}_{Annual}$	**£193.19 k**

4.5.1 Results and Discussion

Results are categorized in relevant sections i.e. dynamic power consumption analysis, Overall system efficiency and QoS, green prospects and profitability as follow.

4.5.2 Dynamic Power Consumption

Dynamic power consumption is investigated through the performance analysis of various power consumption related parameters in following section.

4.5.2.1 Comparative Analysis of Dynamic Power

Figure 4.3 compares the proposed ES scheme with the benchmark in terms of average dynamic power consumption. Compared to benchmark, our scheme employs reduced early handover thereby turning off idle/unused RBs resulting in increased energy conservation.

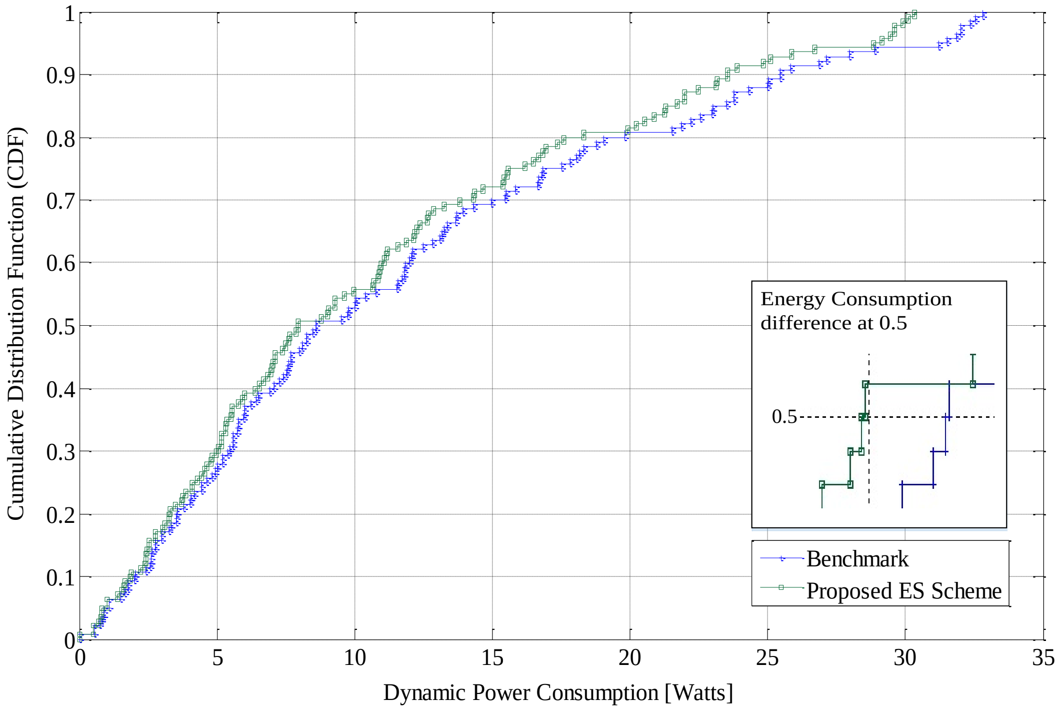


Figure 4.3: Dynamic Power Consumption

Figure 4.4 further compares benchmark and proposed scheme both for straight and RWP mobility models. It is evident that benchmark results into same level of power consumption irrespective of the mobility models. However it is found that SWM favors proposed scheme more (around 7.8 watts consumption) compared to the realistic RWP mobility model (around 8.8 watts). Importantly all the rest of performance analysis results presented in this chapter employ RWP mobility model.

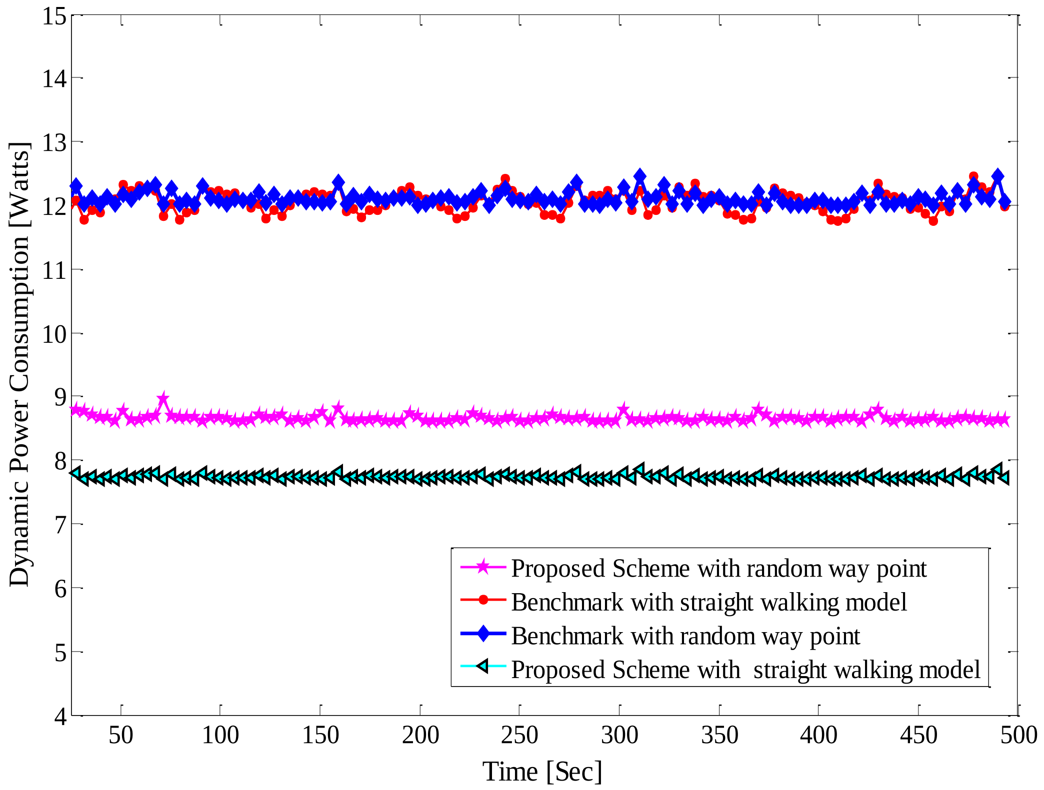


Figure 4.4: Dynamic power consumption with SWM and RWP

Figure 4.5 analyse comparative analysis of REHO with other state of the art [136] and standard system. The traffic aware scheme presented in [136] employs theoretic algorithm and identifies low traffic time periods to turn off BSs. This scheme engages prediction where BSs are turned off on the basis of traffic profile, i.e. their interaction with UEs. This scheme requires neighbour cells BSs to increase their coverage using increased power levels to cater for the need of UEs which otherwise were being looked after by the BSs which have been turned off due to low UE density. However, the location of UEs sometimes inhibits this particular scheme from turning off of BSs, thereby resulting into increased energy consumption. On the other hand, the increased power levels of neighbour cells equally result in increased over all power consumption. Clearly our REHO scheme outperforms the standard and scheme mentioned in [136] in terms of dynamic power consumption.

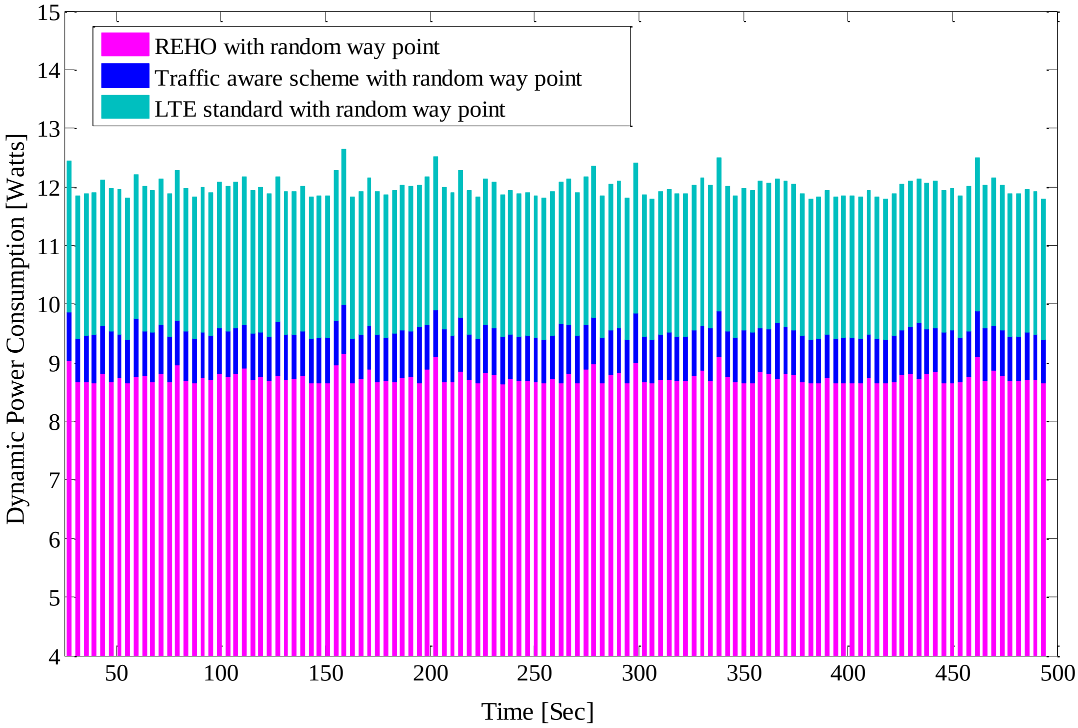


Figure 4.5: Comparative analysis

4.5.2.2 Energy Consumption Gain (ECG)

Figure 4.6 presents ECG. Clearly, the system has achieved higher ECG when employing our hybrid ES scheme compared to the other schemes. This definitely impacts OPEX and help vendors stay profitable.

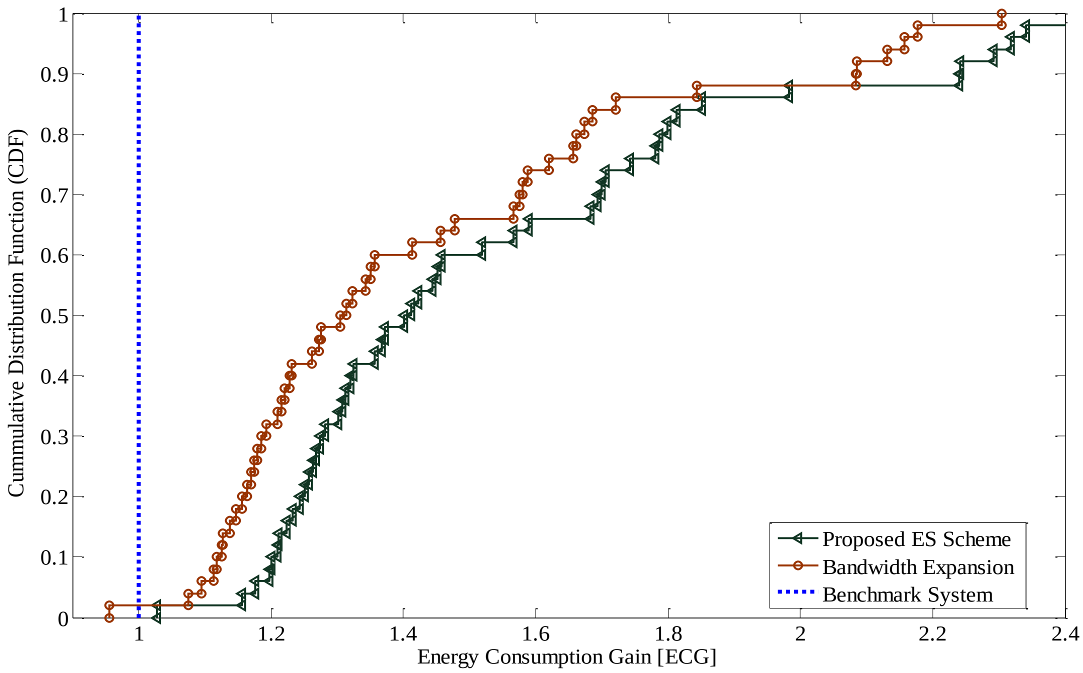


Figure 4.6: Energy Consumption Gain (ECG)

4.5.2.3 Dynamic Power Consumption vs RLF and Offset

The increased ES in proposed REHO scheme is achieved by employing reduced early handover which in turn is obtained by limiting the hysteresis. Figure 4.7 shows the relationship between RLF, power consumption and the offset values. Clearly higher offset values result in reduced RLF and vice versa. However the offset value has to be chosen carefully to impact ES. The offset value selected in our system modeling is 3 dB, which gives a little higher value of RLF (around 5 percent) compared to acceptable RLF values (i.e. 3 percent [137]).

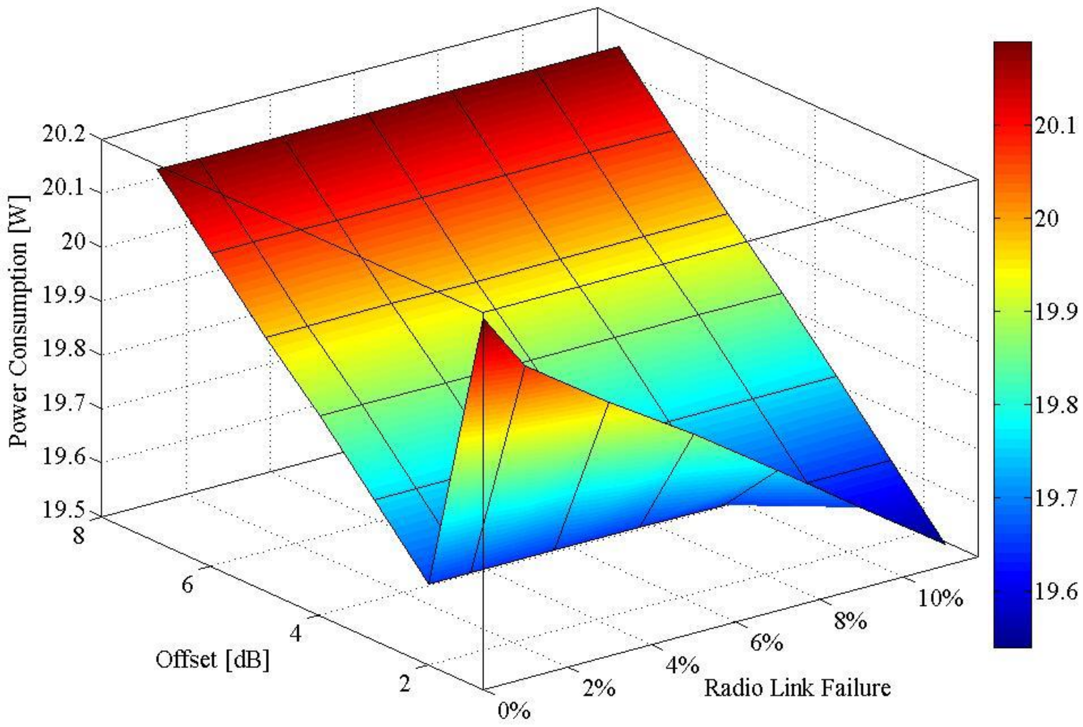


Figure 4.7: Relationship between RLF, Offset and Power Consumption

4.5.2.4 RLF, Ping Pong vs TTT

The ΔT (discussed in detail in next chapter)is hallmark of our REHO scheme which accounts for time difference in terms of TTIs between LTE standard and REHO deployed handovers. It has been found that reduced power consumption in REHO is achieved at the cost of slightly increased RLF. Figure 4.8 inspects average RLF over varying TTT values and UE velocities. Because of the fact that high speed UEs (60 km/h), at any particular value of TTT can get closer to target cell quickly compared to slow speed UEs (20 km/h), thus accordingly they result in lesser RLF both for REHO and LTE standard. Even though increased UE speed results into reduced RLF for REHO, however still at any particular value of TTT, REHO results in higher value of RLF compared to LTE standard (Figure 4.8). This is because of the fact that REHO implements reduced early handover due to the usage of reduced value of hysteresis, i.e. 1 dBm. Figure 4.8 also suggests that varying TTT values also has significant impact on the RLF value, both for REHO and LTE standard. Larger TTT results into reduced RLF compared to shorter TTT. However TTT values larger then 640 ms do not result into significant change in RLF value, both for REHO and LTE deployed networks. The analysis clearly revealed that REHO offers acceptable RLF compared to LTE standard (i.e. around 5%) for UEs velocity of 40 km/h and TTT value of 320 ms; thus the recommnded TTT and UEs velcoity parameters for REHO deployed networks.

Conversely, larger TTT creates more opportunities for late handover thus significnatly impacting the Ping Pong effect as shown in Figure 4.9. It is because of the fact that larger TTT possibly results in weakening of the signal strength between the UE and the BS thus impacting the Ping Pong. Notably Ping Pong effect, at any given value of TTT results in higher values at higher user speeds compared to slow moving UEs because of the fact that high speed UEs can quickly move back and forth resulting into higher values of Ping Pong. Though REHO resulted in slightly higher RLF due to reduced hyesteresis value (Figure 4.8), however at any particular value of TTT, REHO resulted into significantly lower Ping Pong value compared to LTE standard for all UEs velocities. This is because of the fact that REHO intitates reduced early handover thereby resulting into lesser Ping Pong. Higher Ping Pong value further strengthen the fact and justifies the reason for increased LTE energy consumption compared to REHO scheme.

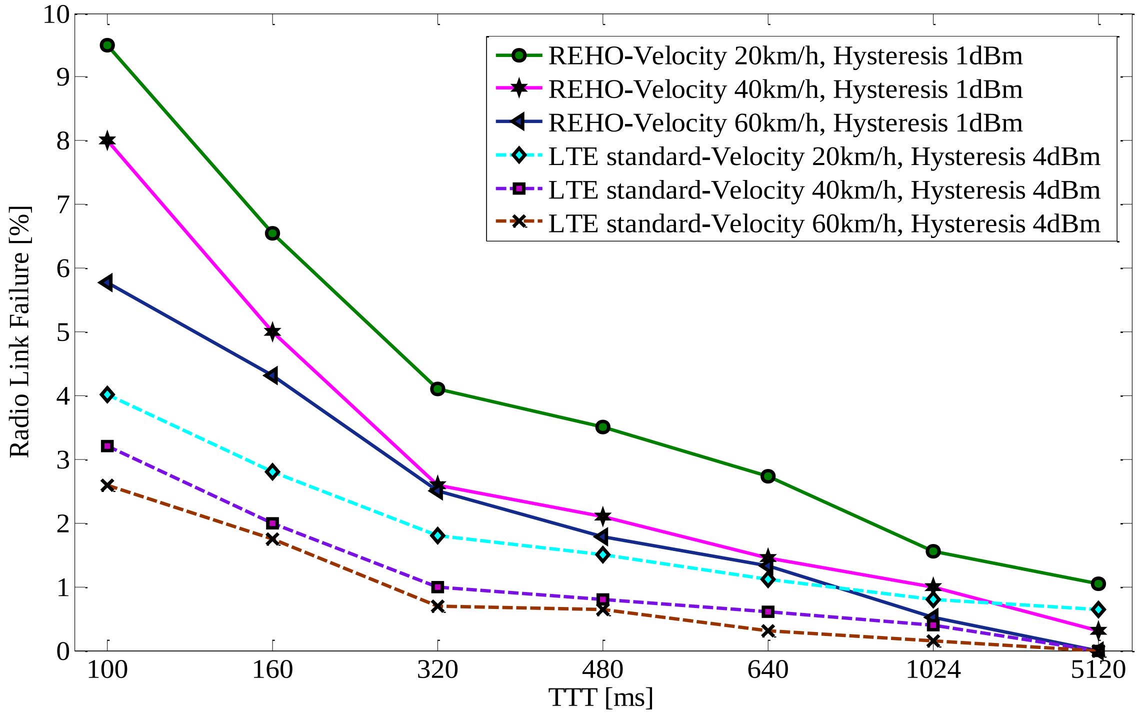


Figure 4.8: Radio Link Failure vs Varying TTT

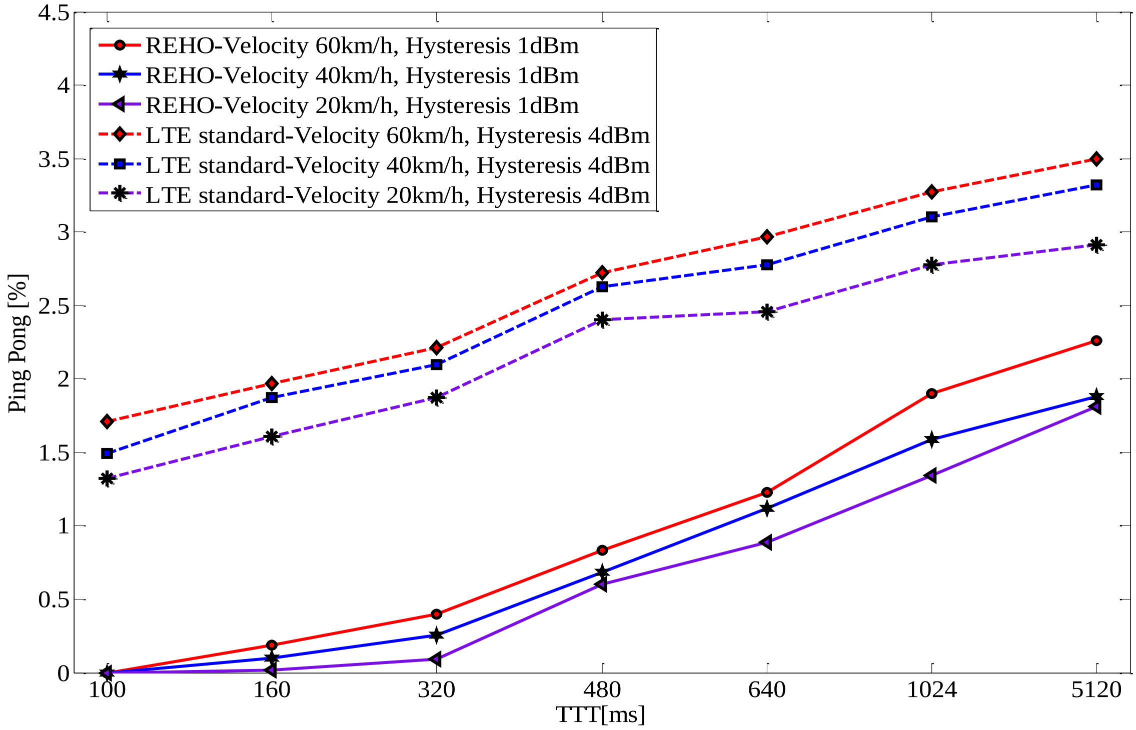


Figure 4.9: Ping Pong vs Varying TTT

4.5.3 Overall System Efficiency and QoS

Following discuss overall system efficiency and QoS related parameters.

4.5.3.1 CDR, HOR & Superlative TTT

The average values of CDR and HOR are calculated over varying TTT with UE velocity of 40 km/h. In line with Figure 4.8 above, where larger values of TTT results into reduced RLF, CDR values are in accordance with RLF values and accordingly exhibit the same behaviour. Higher TTT results in lower CDR and vice versa (Figure 4.10). At any particular value of TTT, further in line with Figure 4.9, even though REHO results in higher CDR value compared to LTE standard, however REHO due to employment of reduced hysteresis value, results in improved HOR values compared to LTE standard (Figure 4.10). Larger TTT further raises the chances of increased handover thereby accordingly resulting into higher HOR values. At the TTT value of 320 ms, the HOR in REHO is around 0.2 while CDR is approximately 0.15 higher than standard LTE network. However, both CDR and HOR are still at acceptable level as per 3GPP specifications.

Figure 4.11 presents value of TTT which keep fair balance between all performance parameters i.e. RLF, ping pong, HOR and CDR. It can be seen that at UE velocity of 40 km/h, TTT value of 320ms is superlative value to initiate REHO based handover which offer significant ES (as shown in Figure 4.5) with acceptable level of vital parameters (RLF around 2.7 %, Ping Pong around 0.3 %).

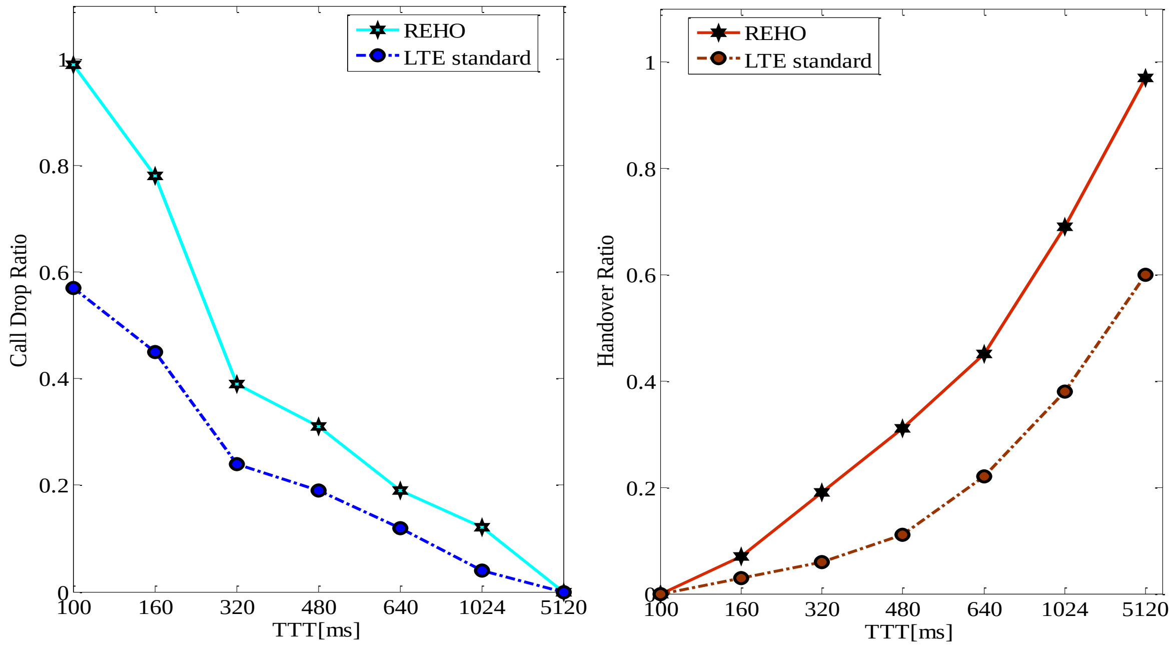


Figure 4.10: CDR & HOR vs TTT

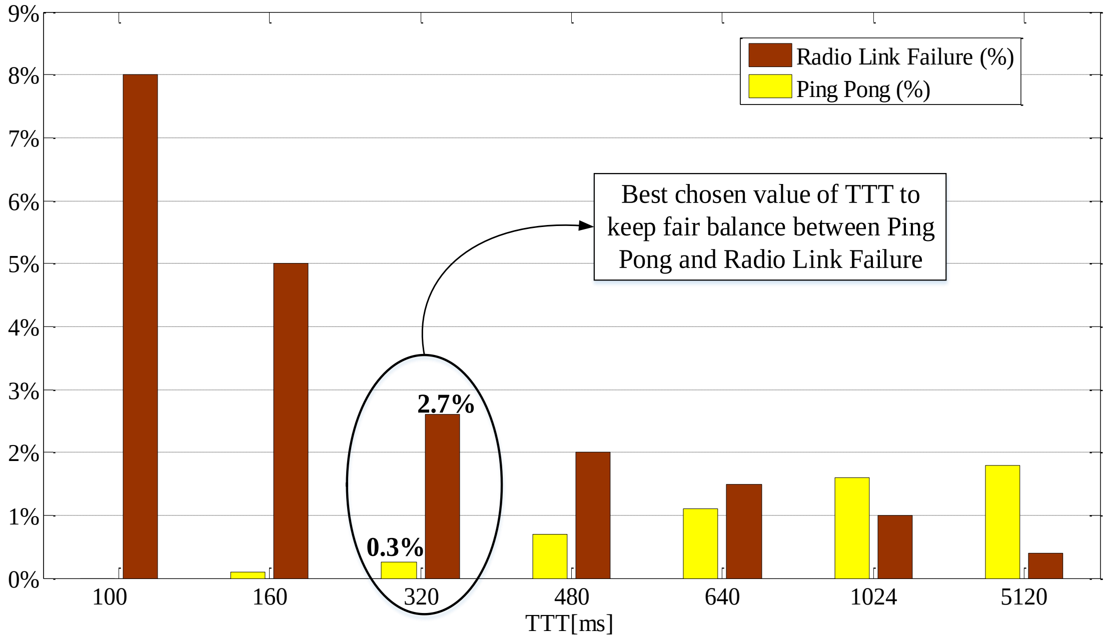


Figure 4.11: Superlative TTT for equitable RLF and Ping pong

4.5.3.2 Delta T (ΔT) vs TTT

Since REHO achieves early handover (ΔT value) compared to LTE standard, Figure 4.12 investigates relationship of ΔT with varying TTT. Importantly change in value of TTT does not effect ΔT because the time difference in terms of TTIs between REHO and LTE standard always remain the same ensuring that REHO always achieves reduced early handover, thereby resulting into reduced energy consumption compared to LTE standard, irrespective of the value of TTT. Point to be noted that the methods employed to estimate the value of ΔT in REHO and LTE standard are further discussed in detail in next chapter 5.

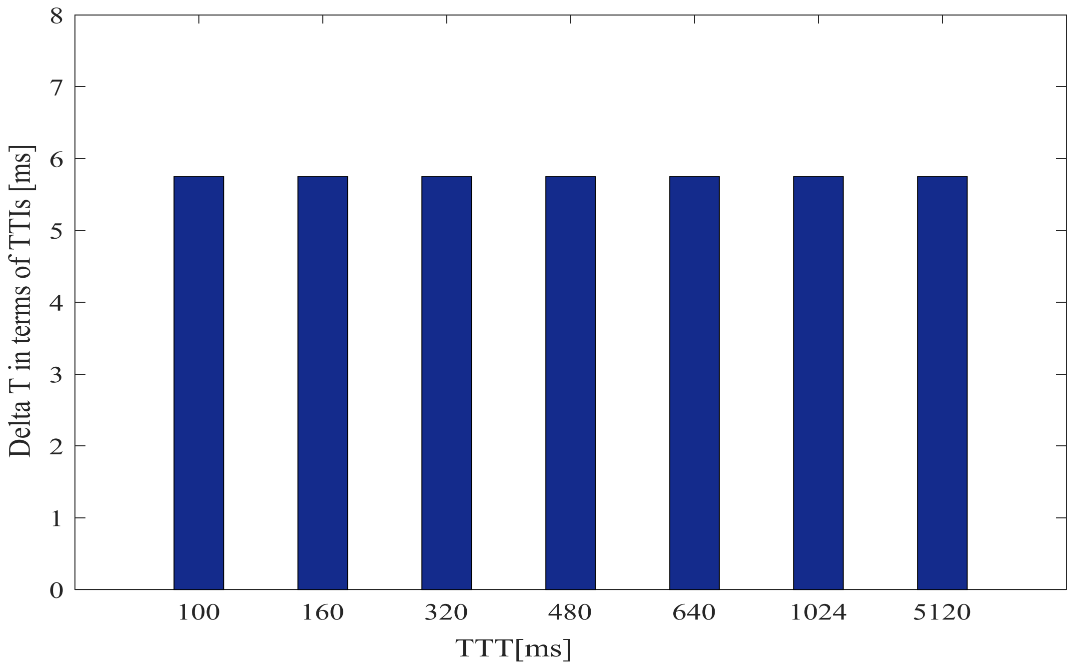


Figure 4.12: Delta T vs TTT

Figure 4.13 compares energy efficiency in relation to number of outbound handovers. In REHO scheme, the handovers initiated from serving cells to target cell are correlated with energy efficiency. Higher handover would lead towards higher opportunities to turn off radio resources thus resulting in to higher energy efficiency in serving cells.

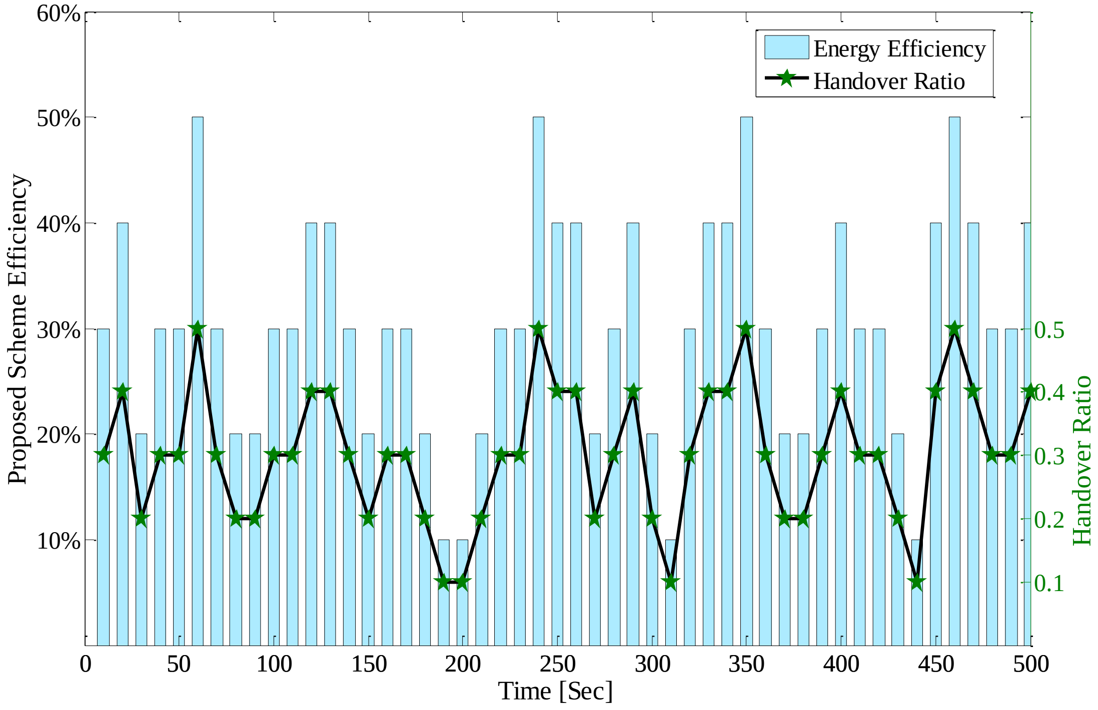


Figure 4.13: Energy efficiency and handover ratio

As mentioned earlier, RLF can be affected not only by early hand over but also by BS capacity limitations. Figure 4.14 plots the relationship between handover ratio and BS capacity for REHO scheme. Results indicate that inbound handover ratio directly impacts cell capacity, i.e. data rate per UE decreases with increased inbound handover ratio and vice versa. It is important to note that results of energy efficiency presented in Figure 4.13 and BS capacity in Figure 4.14 strongly correlate with each other. Even though the proposed REHO scheme results in slightly higher RLF due to reduced early handover, however it still provides significantly improved energy efficiency as a result of reduced power consumption.

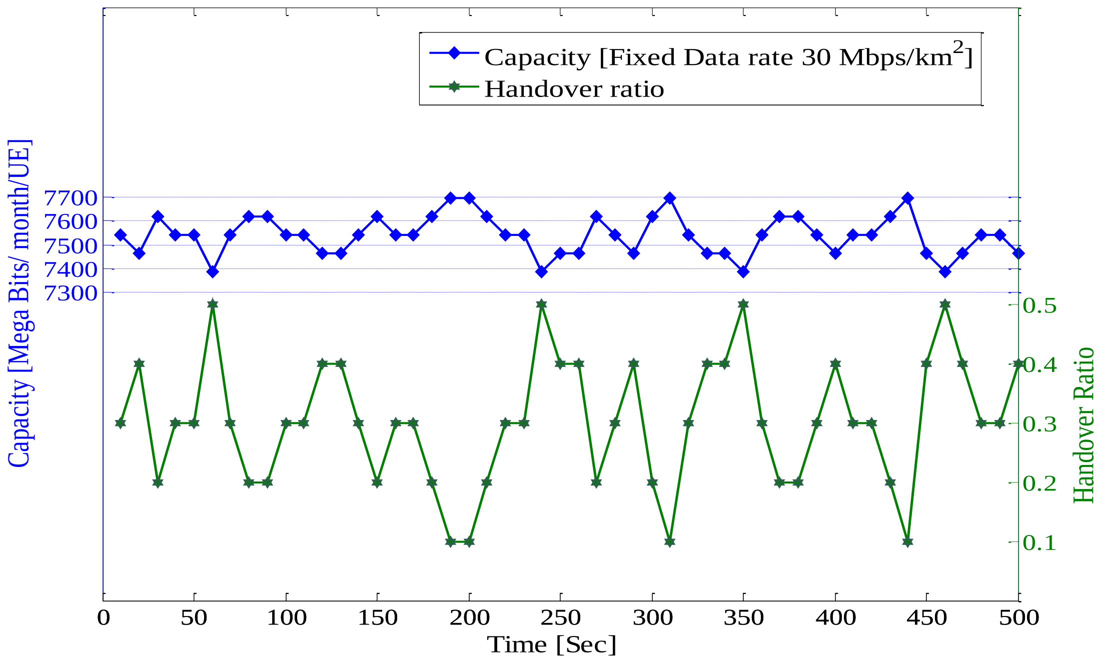


Figure 4.14: Target cell capacity vs handover ratio

4.5.4 Green Prospects

Th green prospects are investigated in line with CO_2 emission and associated carbon credit expense. Particularly one carbon credit is worth £18 (year 2016) [133] which allows operator to emit one tonne carbon [138]. In this view, in addition to growing green, operators could also benefit from carbon credit trade through reduced CO_2 emission, thereby further increasing the profitability. We will now calculate CO_2 emission in line with power consumed in both REHO and standard LTE networks. The CO_2 emission is also measured in km^2 while its amount of emission purely relies on type of fuel used to produce electricity. Figure 4.15 presents different types of fuels currently used in electricity production and describes CO_2 emission (in grams) in line with fuel types. Importantly, gas and coal are main fuels used in electricity production which produces 960 and 443 Grams carbon per kWh respectively [139]. Accordingly, CO_2 emission can be calculated by multiplying total power consumption (kWh) with percentage of each fuel and associated CO_2 grams produced (Figure 4.15). Research has shown that average power consumption of one BS is approximately 1500W, which produces approximately 6 tonnes CO_2. However, the minimum 30 percent reduced power consumption through REHO helps operators cut down CO_2 emission by approximately 1.10 tonnes. Since each tonne is worth £18, therefore operators with 20,000 BSs could benefit approximately £400K from reduced CO_2 emission.

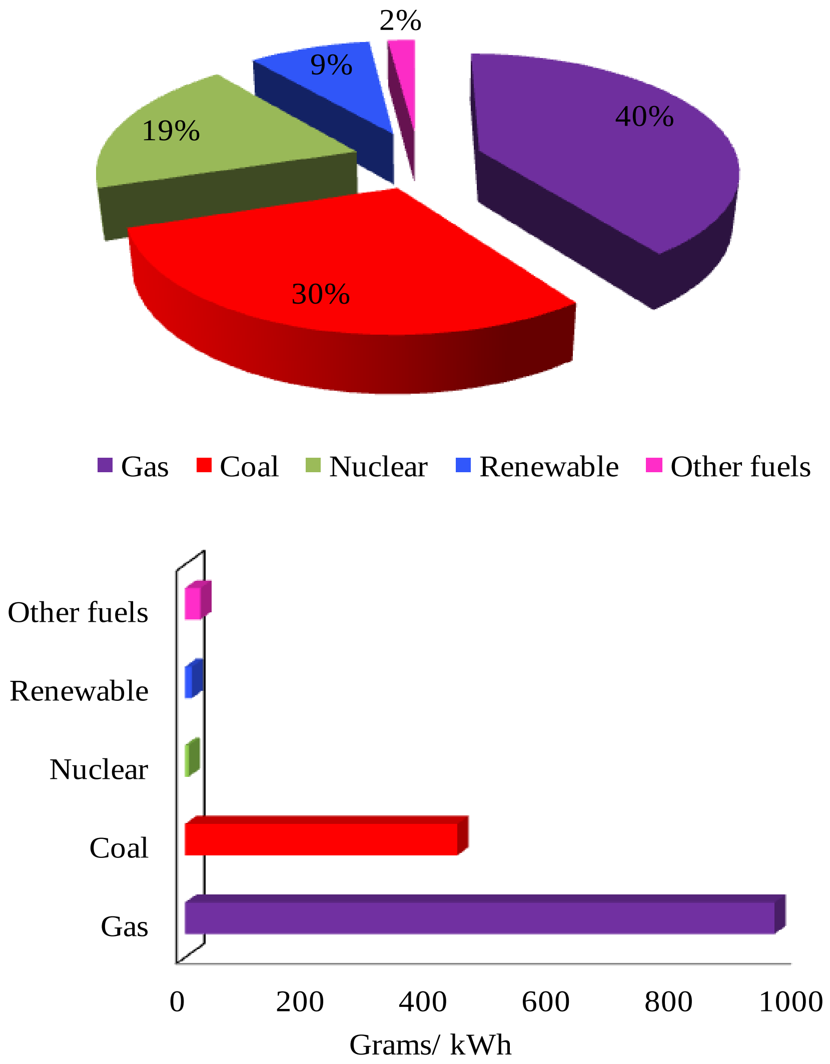


Figure 4.15: Fuels used in electricity production and associated CO_2 emission

4.5.4.1 CO_2 Emission

In line with reduced dynamic power consumption in Figure 4.5. Further CO_2 emission (due to power consumption) per km^2 is presented in Figure 4.16. Clearly it can be seen that standard LTE networks produces approximately 6 tonnes CO_2 per km^2, while in contrast proposed scheme due to reduced power consumption accordingly results in reduced CO_2 emission (approximately 1.12 tonne per BS, Figure 4.16). Importantly there is constant difference in both trends because, average power consumption is used as an input for the estimation of CO_2 emission in both systems. Then average CO_2 emission is calculated over numerous data rates at shown in Figure 4.16. Point to be noted that benchmark reduce power consumption by 35 percent, in the same line average difference is also reflecting in CO_2 emission.

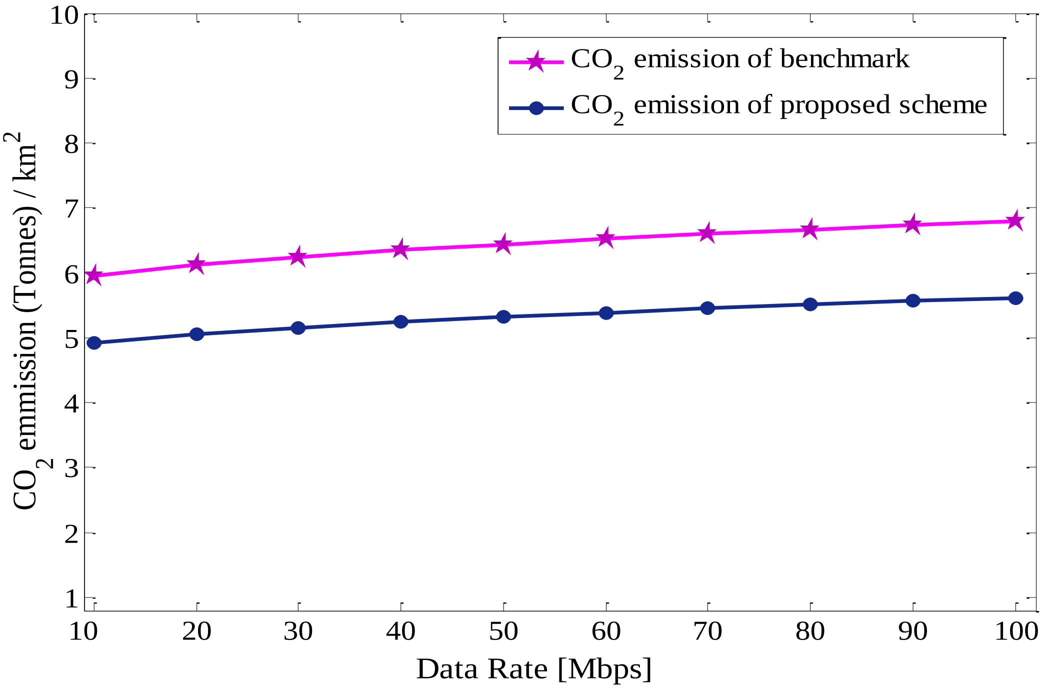


Figure 4.16: CO_2 emission per BS vs data rate

4.5.5 Commercial Impact

Taking into expense related parameters mentioned in Table 4.1, Figure 4.17 analyse reduced OPEX through ES achieved in REHO, which is one of the key objectives because it affects operators profitability. Figure 4.17 compares all OPEX related expenses components both for REHO deployed and standard LTE networks. As already discussed, PA is main power hungry element in each BS responsible for 60 percent of total power consumption, notably REHO scheme cut down this by minimum 30 percent. Accordingly, the total fraction of 4 percent electricity bills expense in standard LTE networks is reduced to 3.28 percent of total OPEX per $km^{2,}$ thereby giving profit of around 0.72 percent in REHO deployed networks as shown in Figure 4.17.

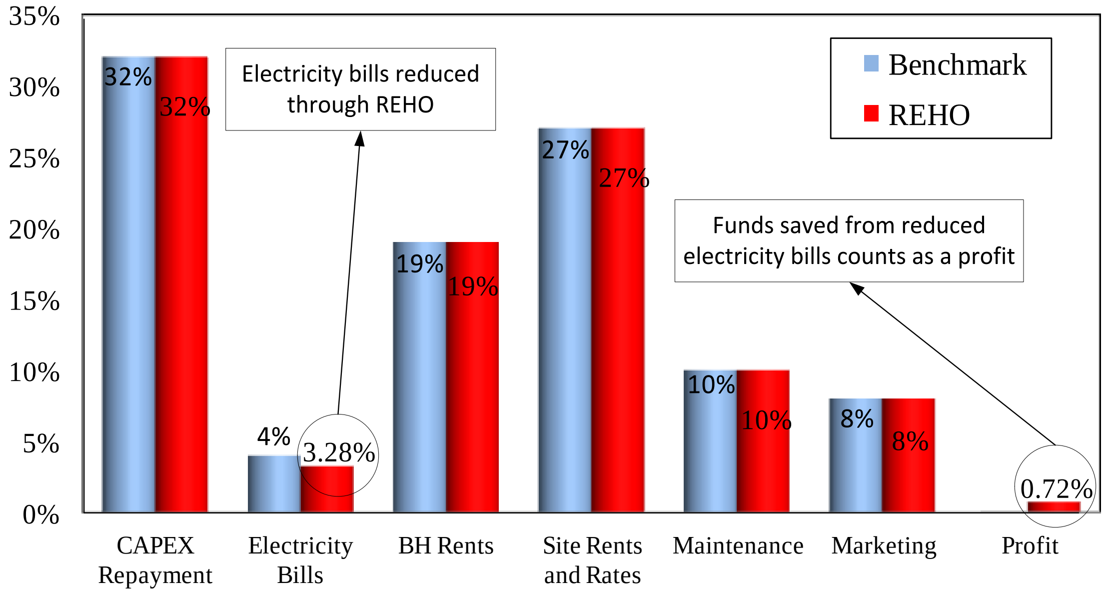


Figure 4.17: OPEX/CAPEX comparative analysis / Km^2

4.5.5.1 Increased Profit through Reduced OPEX

Figure 4.18 provides annual OPEX in terms of money value and compares it with the standard. Again, in line with the results of dynamic power consumption, RWP mobility (as shown in Figure 4.4) accordingly results in slightly higher OPEX value for the REHO scheme compared to SWM. The annual profit is calculated per km^2, based on tariff cost presented in Table 4.1 (profitability in standard LTE and REHO) and one thousand UEs per km^2. Importantly both tariff cost and number of UEs play significant role in OPEX cost and profit. Importantly we have made use of the cheapest tariff in profit calculations; accordingly higher tariff costs will result in to higher profits. Due to reduced OPEX, it can be seen that annual profit in proposed scheme (REHO) is higher as compared to benchmark system (Figure 4.18).

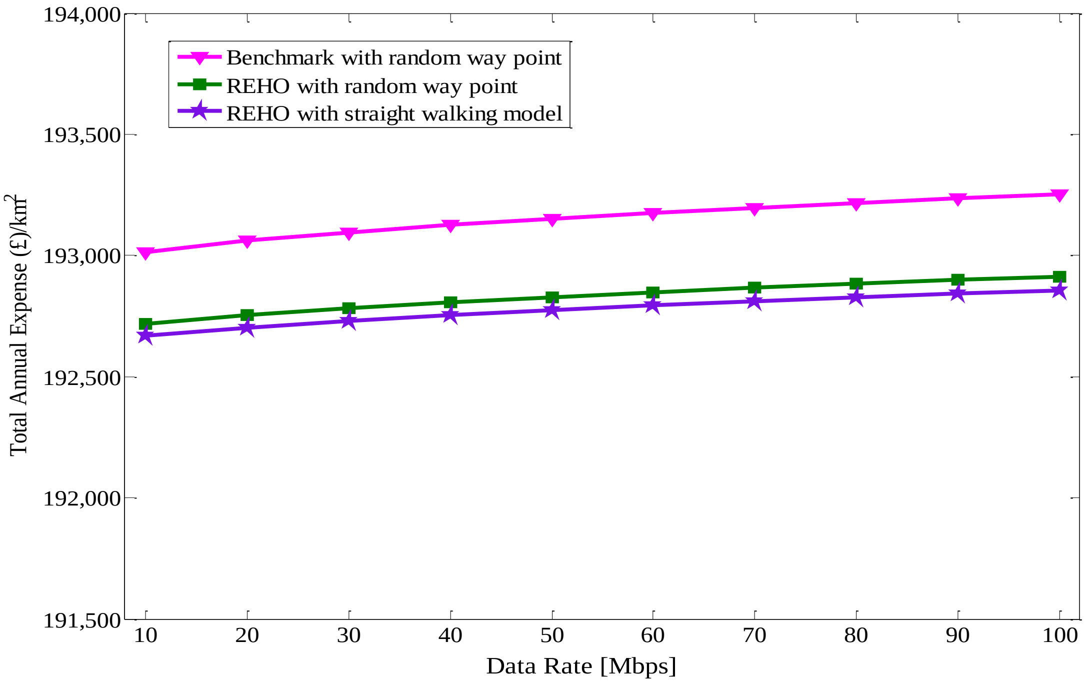


Figure 4.18: Yearly OPEX / Km^2 in GBP

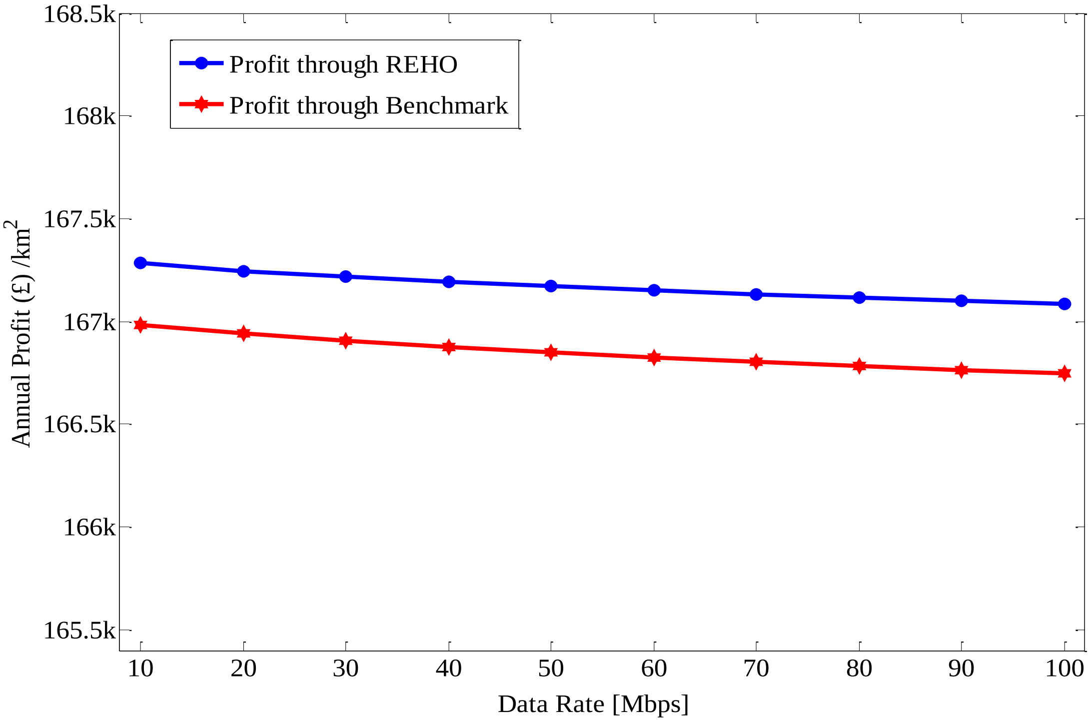


Figure 4.19: Profitability achieved through reduce OPEX / Km^2

Typical European operators usually deploy approximately 20,000 BSs to provide adequate coverage in a country [85]. Importantly, profitability per Km^2 provided in Figure 4.19 above is for one BS (according to our system modelling and system setup). Thus when extended over larger regions, REHO achieves considerable improved profit. Figure 4.20 presents combined profit achieved through reduced OPEX and carbon credit. Clearly, the profitability is directly proportional to number of BSs and will even go higher for extended regions deploying increased number of BSs. It is evident in Figure 4.20 that operators with network infrastructure consisting of 20,000 BSs, through reduced OPEX and carbon foot print, could benefit approximately 6.4 million per year through REHO.

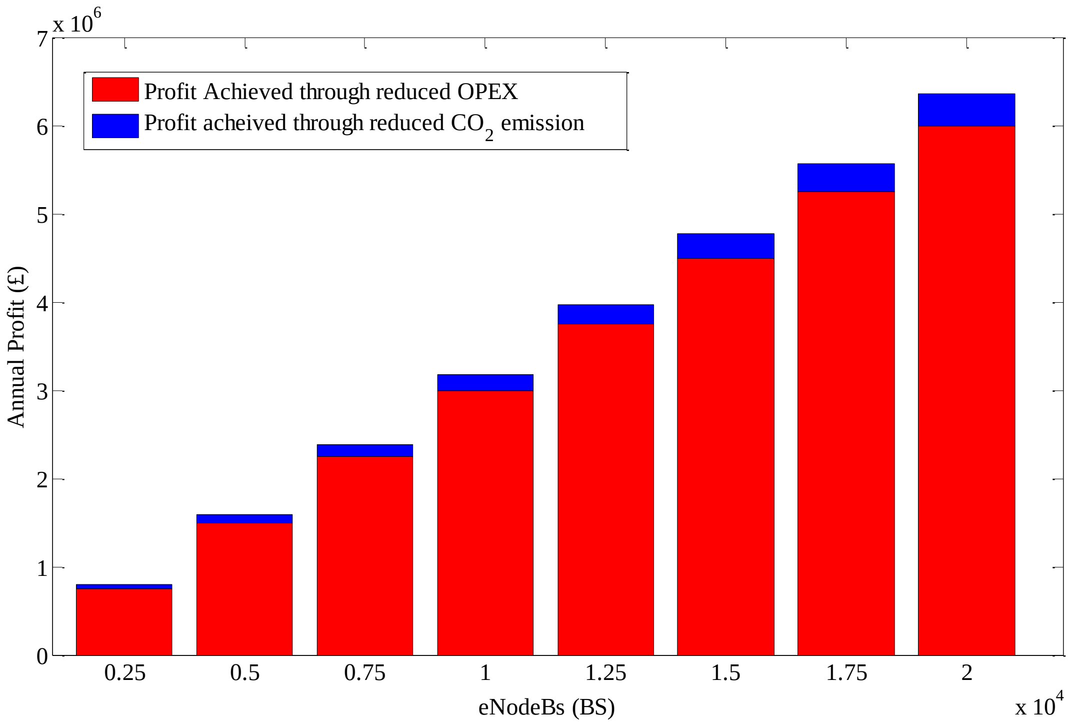


Figure 4.20: Joint profit achieved through reduced OPEX and lower CO_2 foot print

4.6 Summary

This chapter investigates REHO scheme where the spared RBs by early handover of UEs are completely turned off resulting into increased energy efficiency. System level simulations have been performed to performance analyse the scheme and comparative analysis has been made with LTE standard and other state of the art. The REHO scheme has been found EE leading towards reduced OPEX and increased profitability. Moreover, REHO scheme also reduces CO_2 emission thus helps operators stay greener. Among other contributions being made in this work, the major contribution suggests superlative value of TTT (320 ms at UE velocity of 40 km/h) for unbiased RLF and Ping Pong, which can help vendors not only to achieve increased energy efficiency, but also maintain other salient performance parameters within acceptable limits. Since the scheme is implemented and performance analyzed by using 3GPP standard parameters; accordingly the scheme is practically viable and can impact operators profitability significantly thus providing both commercial advantages and environmental benefits.

Chapter 5

5 Energy Efficiency in LTE System through Target Cell Boundary Approximation

5.1 Introduction

In the previous chapter, REHO was proposed through the combination of reduced early handover with bandwidth expansion, which resulted in to enhanced ES up to 35 percent. It was also discussed that ΔT i.e. the time difference between REHO based early and standard handover, is the hallmark of proposed REHO scheme. In the same line, continuing from chapter 4; this chapter thoroughly investigates the phenomenon of early handover by calculating the time difference delta T (ΔT). In this regard, axioms of Euclidean geometry are engaged to estimate the boundary of target cell in the overlapping areas of both serving and target cells. Afterwards, diagonal matrices are being employed to approximate user received power in relation to changing distances, to calculate the value of ΔT to be used to perform early handover in REHO compared to LTE standard. ΔT, calculated in terms of TTIs, results into improved energy efficiency at the cost of slightly increased RLF. The chapter systematically examines REHO and compares it with standard LTE in terms of ES for varying velocity and hysteresis values. The vital finding of the chapter is the non-sensitivity of UEs towards velocity in standard LTE, whereas REHO leads to considerably improved energy efficiency at low velocity thereby making it an advantageous scheme for urbanised densely deployed LTE networks.

Over last few decades; The tremendous growth in smart phones and number of UEs have stepped towards predominant expansions in cellular networks infrastructure as a result demanding enlarged power consumption. In the same perspective, a recent research work has established the idea of integrated CRNs [140] with LTE infrastructure for improved ES, which lies in the fact of isolating UEs in two categories (i.e. primary UEs and secondary

UEs). During awake periods, BS transmits primary UEs packets over licensed spectrum while secondary UEs packets sent over unlicensed spectrum [141] in LTE advanced cellular networks. BSs are switched in to sleep mode right after completion of data packets transmission which results into improved power conservation. ES can also be achieved through suitable cells coverage expansion and turning off of idle BSs [92]. The mentioned scheme initially split cells in two categories i.e. cooperative cells and dormant cells. During off peak traffic period [142], only cooperative cells serve UEs while dormant cells are turned off for ES. Intelligent resources allocation [104] can also help reduce dynamic power consumption where intelligent power control approach is employed in BS resulting into improved energy efficiency. Noteworthy, such EE schemes while deployed at every BS, allocates lower transmit power to the suitable resources according to the associated SINR value resulting in improved energy conservation [143]. Among others, D2D communication based scheme uses EE heterogeneous routing for enhanced energy management [144]. In the same context, the main contribution of this chapter embraces the Euclidean geometry axioms assisted target cell boundary estimation to calculate ΔT. Subsequently the detailed REHO performance analysis includes 1) ΔT calculation in terms of TTIs and relationship with varying hysteresis values, 2) dynamic power consumption relative to varying velocity, 3) analytical and simulation based results to discuss REHO ES with respect to RLF and hysteresis. Finally, analysis of overall efficiency of serving and target cells in relation to inbound handovers and their impact on outage probability and call blocking probability (CBP) is investigated in this chapter.

5.2 Early Handover

Considering 3GPP based standard handover, UEs trigger A3 event when RSRP of target cell becomes better then serving cell. Hysteresis is one of the key parameters which is added in target cell RSRP to make it better than serving cell RSRP. Proposed REHO scheme uses minimum reduced value of hysteresis in target cell RSRP which helps trigger of A3 event earlier then standard, consequently serving cell resources become idle prior and then turned off for ES. The employed system model to estimate ΔT is presented in following section.

5.3 System Model

The system model based on LTE network with E-UTRAN) and EPC [118] accordingly to 3GPP specification [56]. Network is based on densely deployed scenario consisting of 21 cells with overlapping area, where each cell has radius of 1000 meters with 50 mobile UEs randomly distributed over coverage. Table 5.1 presents detailed simulation parameters based on 3GPP Specification, whereas *Pythagorean theorem* and *Diagonal matrix* is employed to identify edges of target cell and measurements of TTIs difference between standard and REHO based early handover.

Table 5.1: Simulation Parameters

Parameter	Value	Parameter	Value
Carrier frequency	2.14 GHz	UE mobility	Random waypoint
Bandwidth	20 MHz	Path loss	Log normal
No. of RBs	100	UE velocity	40 km / hour (11 m/s)
BS max power	46 dBm	Number of UEs	1000/km^2
TTT	160 ms	BS antenna gain	14 dB
No. of cells	21	Noise figure	4 dB
Handover hysteresis	1 dBm -6 dBm	Cell coverage radius	1000 m
PA (Max Transmit power)	40W (efficiency 31.1 percent)	No. of UEs	50 UEs /cell

5.3.1 BS Power Consumption

BS consists of PA, RF, BB, DC to DC, AC to DC, Cooling system and AI [145]. PA in BS is main power hungry part, around 60 percent, while its power consumption is straightforwardly affected by data rate and resources utilization [146]. Figure 5.1 presents breakdown of power consumption by different sections inside the BS.

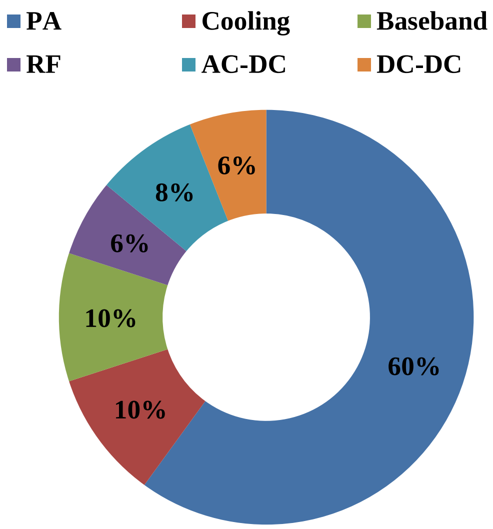


Figure 5.1: Breakdown of BS power consumption

5.3.2 ΔT between REHO and Standard Handover

As shown in Figure 5.2 ΔT presents TTIs difference between REHO deployed early handover and standard handover whereas $TM^{\sim}$ is time essential for UE to reach at early handover point while TM presents time required to reach at standard handover point. This can be calculated by recalling equation (4.6) and (4.7) from chapter 4 as:

$$\Delta T = TM - TM^{\sim} \qquad \begin{pmatrix} TM = \frac{D_s}{V} \\ TM^{\sim} = \frac{D_s{}^{\sim}}{V} \end{pmatrix} \tag{5.1}$$

Where D_s presents distance covered by UE i moving at velocity V to reach standard handover point from target cell boundaries in overlapping area of serving cell, while $D_s{}^{\sim}$ describe the distance covered by UE i moving at velocity V to reach early handover point. In order to find ΔT, the exact boundaries of target cell in overlapping area with serving cell must be identified. Figure 5.2 presents working of serving and target cells with overlapping area (10 percent) as per link budget [147]. To make possible measurement of target cell boundaries and ΔT, initially overlapping area between two cells is measured as follow.

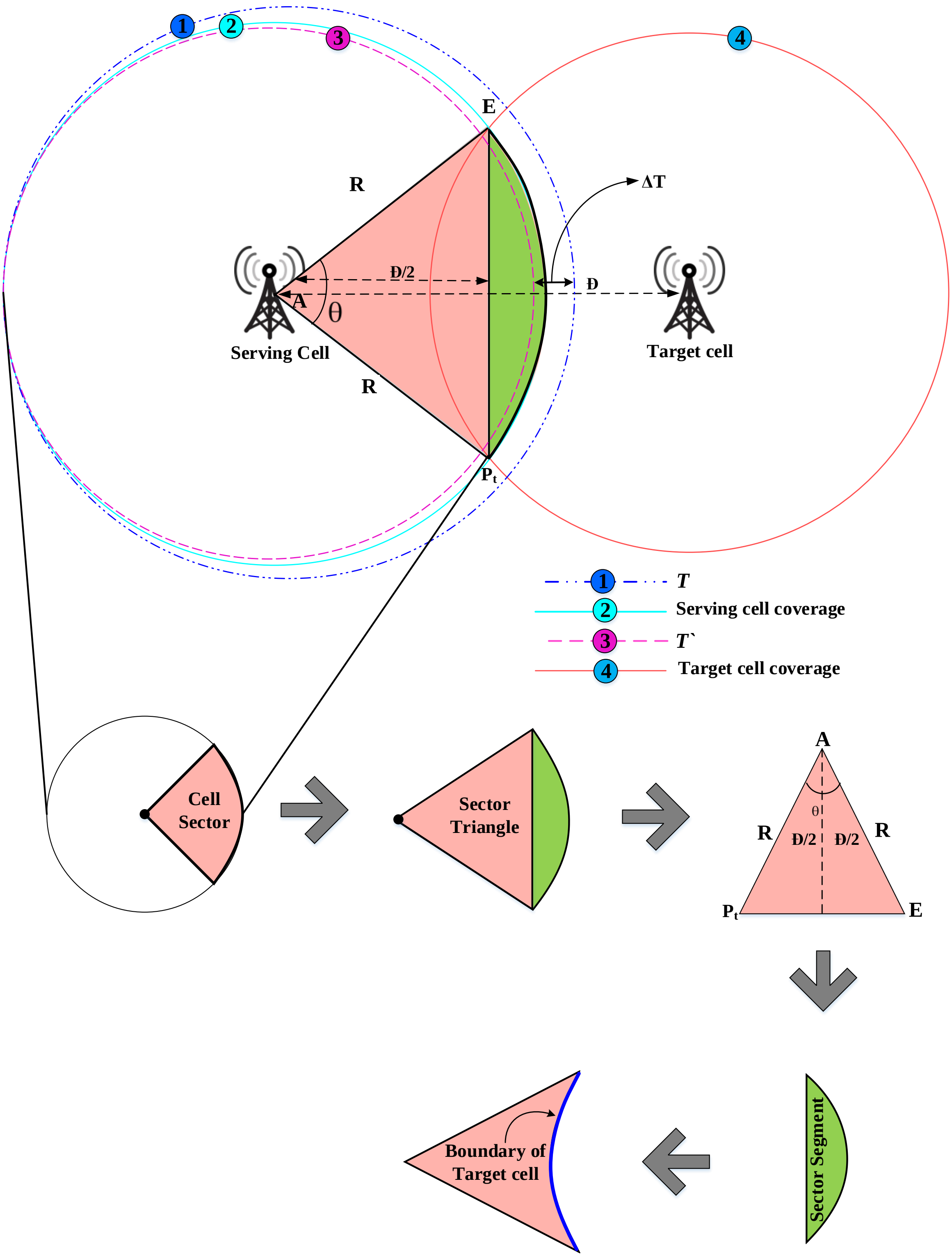


Figure 5.2: REHO - Target cell boundary estimation

5.3.3 Reduced Early Handover Modelling (ΔT Calculation)

Axioms of Euclidean Geometry and Pythagorean theorem [148-149] have been employed to model reduced early handover, i.e. calculation of ΔT. Firstly, serving cell sector which overlaps with the target cell is identified. Subsequently, the segment sector is calculated by subtracting from the area of serving cell sector. Lastly, the sector segment is used to model and estimate the target cell boundary in the overlapping area of serving and target cells. Detailed step wise explanation of the steps is provided in Figure 5.2. Area of sector can be calculated using equation (5.2) as follows.

$$A_{sector,\theta} = \frac{\theta}{2} R^2 \ \ (\theta \textit{ is central angle in radians}) \tag{5.2}$$

Where R is radius of each cell, while θ is a sector angle and can be calculated using axioms of Euclidean geometry. Referring to Figure 5.2, the height of Isosceles triangle (Đ/2) is half of the distance (Đ) between serving and target cells BS [150]. Sector angle θ can thus be calculated as follows.

$$\cos\left(\frac{\theta}{2}\right) = \frac{Đ}{2R} \tag{5.3}$$

Further solving the value of θ as:

$$\theta = \ 2\cos^{-1}\left(\frac{Đ}{2R}\right) \ \ [\, Đ/2 \ \leq \ R] \tag{5.4}$$

Replacing the value of θ in equation (5.2) leads towards calculation of sector area of serving cell (equations 5.5 and 5.6).

$$A_{sector,\theta} = \frac{2\cos^{-1}\left(\frac{Đ}{2R}\right)}{2} R^2 \tag{5.5}$$

$$A_{sector,\theta} = R^2 . \cos^{-1}\left(\frac{Đ}{2R}\right) \tag{5.6}$$

Having known the sector area, sector segment can be found by subtracting triangular area from sector area. Referring to Figure 5.2, area of Isosceles triangle [150] is given by equation (5.7).

$$A_{Triangle} = \frac{1}{2} \beta^{\sim}\mathrm{M} \qquad \text{where} \begin{pmatrix} \beta^{\sim} = P_t E \\ \mathrm{M} = \frac{Đ}{2} \end{pmatrix} \tag{5.7}$$

P_t and E represents base points of triangle and M denotes height respectively. Dividing the Isosceles triangle in two right angle triangles and applying the Pythagorean theorem [148] gives equations (5.8) and (5.9) below.

$$\left(\frac{\beta^{\sim}}{2}\right)^2 + \left(\frac{Đ}{2}\right)^2 = R^2 \tag{5.8}$$

$$\beta^{\sim} = \sqrt{4R^2 - Đ^2} \tag{5.9}$$

Replacing the value of $\beta^{\sim}$ in equation (5.7) gives area of Isosceles triangle below (Equations 5.10 and 5.11).

$$A_{Triangle} = \frac{1}{2}\left(\sqrt{4R^2 - Đ^2}\right)\left(\frac{Đ}{2}\right) \tag{5.10}$$

$$A_{Triangle} = \frac{Đ}{4}\sqrt{4R^2 - Đ^2} \tag{5.11}$$

Sector segment therefore can be calculated by subtracting the area of triangle from the sector area (Equation 5.12).

$$A_{Segment} = A_{sector,\theta} - A_{Triangle} \tag{5.12}$$

Putting the relevant values in equation (5.12) gives as follows.

$$A_{Segment} = \left(R^2.\cos^{-1}\left(\frac{Đ}{2R}\right)\right) - \left(\frac{Đ}{4}\sqrt{4R^2 - Đ^2}\right) \tag{5.13}$$

Equation (5.13) provides the sector segment of serving cell (Figure 5.2). The boundary of target cell in the overlapping area of both serving and target cells can be estimated as follows (Equation 5.14 and 5.15).

$$Boundary_{Target\ cell} = A_{Triangle} - A_{Segment} \tag{5.14}$$

$$Boundary_{Target\ cell} = \left\{\left(\frac{Đ}{4}\sqrt{4R^2 - Đ^2}\right) - \left\{\left(R^2.\cos^{-1}\left(\frac{Đ}{2R}\right)\right) - \left(\frac{Đ}{4}\sqrt{4R^2 - Đ^2}\right)\right\}\right\} \tag{5.15}$$

$Boundary_{Target\ cell}$ represents the distance point from serving cell where UE starts calculating RSRP of the target cell. Having known the boundary, received power of user i located at the boundary of the target cell is calculated using BS transmission power (P_{Trans}) and path loss (PL_i), (equation 5.16 below).

$$P_{i,serving} = P_{Trans,i} - PL_{i,serving} + A_{Total} \tag{5.16}$$

A_{Total} represents antenna gain; this work employs *log normal shadowing* path loss model [151] which is consistent for large scale dense areas (equation 5.17).

$$PL_{i,serving\ d \to d_0} = PL_o + 10\varepsilon\ log_{10}\frac{d}{d_o} + G_i \quad (5.17)$$

G_i presents random shadowing effects measured using *Gaussian distribution*, while ε is path loss exponent and PL_o describes path loss measured at the boundary of target cell (where d_o is associated with ($Boundary_{Target\ cell}$). Accordingly, the path loss at any distance where $d > d_o$ can be calculated using equation (5.17). Equation (5.16) thus can be re-written as follows (equation 5.18).

$$P_{i,serving} = P_{Trans,i} - \left(PL_o + 10\varepsilon\ log_{10}\frac{d}{d_o} + G_i\right) + A_{total} \quad (5.18)$$

So $RSRP_{Serving}$ of the UE i (equation 5.19) located at the boundary of target cell can be calculated by reusing equations (4.1) and (4.2) from chapter 4 and equation (5.18) as follows.

$$RSRP_{Serving} = \left\{P_{Trans,i} - \left(PL_o + 10\varepsilon\ log_{10}\frac{d}{d_o} + G_i\right) + A_{total}\right\} + H_i + Offset_i$$

(5.19)

Importantly d_0 presents the point at start of boundary of target cell. Thus $RSRP_{Serving}$ of UE i from d_0 till boundary of serving cell (i.e. R, Figure 5.2) can be calculated using *Diagonal matrix* as follows [152]. Importantly the Diagonal matrix is used to avoid redundant data.

$$\begin{bmatrix} RSRP_{Ser_0,d_0} & 0 & 0 & 0 & \dots & 0 \\ 0 & RSRP_{Ser_1,d_1} & 0 & 0 & \dots & 0 \\ 0 & 0 & RSRP_{Ser_2,d_2} & 0 & \dots & 0 \\ 0 & 0 & 0 & RSRP_{Ser_3,d_3} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & RSRP_{Ser_R,d_R} \end{bmatrix} \quad (5.20)$$

Once $RSRP_{Serving}$ of serving cell is known, the average difference in RSRP per d is calculated by subtracting received power between any two points (e.g. d_1 to d_0). Accordingly, the received power difference between two points in overlapping area can be calculated as (equation 5.21).

$$Power_{diff} = RSRP_{Ser_1,d_1} - RSRP_{Ser_0,d_0} \tag{5.21}$$

As per link budget the typical difference between d_1 and d_0 is one meter, where Δd presents distance difference between d_1 and d_0. The RSRP of UE i from target cell beyond $Boundary_{Target\ cell}$ can be calculated using equation (5.22).

$$\begin{bmatrix} RSRP_{Tar_0,d_0} & 0 & 0 & 0 & \dots & 0 \\ 0 & RSRP_{Tar_1,d_1} & 0 & 0 & \dots & 0 \\ 0 & 0 & RSRP_{Tar_2,d_2} & 0 & \dots & 0 \\ 0 & 0 & 0 & RSRP_{Tar_3,d_3} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & RSRP_{Tar_R,d_R} \end{bmatrix} \tag{5.22}$$

Importantly, RSRP of both cells becomes equal at point of intersection due to almost same distance of BSs from UE i. However, in standard 3GPP hysteresis is added in serving cell RSRP to make it better then target cell RSRP. Accordingly, $RSRP_{Serving}$ with standard hysteresis can be calculated as (equation 5.23).

$$\begin{bmatrix} RSRP_{Ser_0,d_0} & 0 & 0 & 0 & \dots & 0 \\ 0 & RSRP_{Ser_1,d_1} & 0 & 0 & \dots & 0 \\ 0 & 0 & RSRP_{Ser_2,d_2} & 0 & \dots & 0 \\ 0 & 0 & 0 & RSRP_{Ser_3,d_3} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & RSRP_{Ser_R,d_R} \end{bmatrix} + \begin{bmatrix} H_i \\ H_i \\ H_i \\ H_i \\ \vdots \\ H_i \end{bmatrix} \tag{5.23}$$

Similarly, REHO enabled serving cell RSRP with reduced hysteresis can be calculated as (equation 5.24).

$$\begin{bmatrix} RSRP_{Ser_0,d_0} & 0 & 0 & 0 & \dots & 0 \\ 0 & RSRP_{Ser_1,d_1} & 0 & 0 & \dots & 0 \\ 0 & 0 & RSRP_{Ser_2,d_2} & 0 & \dots & 0 \\ 0 & 0 & 0 & RSRP_{Ser_3,d_3} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & RSRP_{Ser_R,d_R} \end{bmatrix} + \begin{bmatrix} H`_i \\ H`_i \\ H`_i \\ H`_i \\ \vdots \\ H`_i \end{bmatrix}$$

(5.24)

The $H`_i$ in equation (5.24) represents reduced hysteresis value. If $Power_{diff}$ describes power drop during Δd, then H_i in terms of Δd can be represented as (equation 5.25).

$$d_{H_i} = \frac{H_i * \Delta d}{Power_{diff}} \tag{5.25}$$

The d_{H_i} in equation (5.25) is the distance in meters covered by UE until its $RSRP_{Serving}$ becomes better than $RSRP_{Target}$. Knowing the point of intersection (***I***) of both cells and d_{H_i}, the value of TM can be calculated using equation (5.26) below.

$$TM = \frac{D_s}{V} \quad \left(where\ D_s = I + d_{H_i}\right) \tag{5.26}$$

S represents speed while D_s is the distance in meters covered by UE to reach at handover point. However REHO implements early handover by using reduced value of hysteresis ($H`_i$); so accordingly the early handover distance can be calculated as (equation 5.27).

$$d_{H`_i} = \frac{H`_i * \Delta d}{Power_{diff}} \tag{5.27}$$

Subsequently, $TM\tilde{}$ and ΔT can be calculated using equations (5.28) and (5.29) respectively.

$$TM\tilde{} = \frac{D_s\tilde{}}{V} \quad \left(where\ D_s\tilde{} = I + d_{H`_i}\right) \tag{5.28}$$

$$\Delta T = TM - TM\tilde{} \tag{5.29}$$

ΔT, as discussed in equations (5.1) and (5.29) is the time difference in terms of TTIs adopted by REHO to initiate early handover as compared to LTE standard.

5.4 Performance Analysis

REHO is compared with typical 3GPP based LTE systems. According to 3GPP specifications, the system model consists of LTE design based on E-UTRAN and EPC. This work considers densely deployed network topology consisting of 21 cells with overlapping area, where each cell has radius of 1000 meters and 50 mobile UEs randomly distributed. Table I presents detailed system parameters. The performance of REHO is compared with LTE standard in terms of ES, highlighting the non-sensitivity of LTE UEs to velocity as compared to REHO which achieves significant higher ES for slow moving UEs. Detailed performance analysis is presented in the sections below.

5.4.1 Results and discussion

Results are categories in three sections i.e. ES and RLF, Comparative analysis, overall system efficiency

5.4.2 Energy Saving and RLF

ES and RLF related results are discussed as follow.

5.4.2.1 REHO Energy Saving and relationship to Velocity

Figure 5.3 investigates delta T (ΔT) relationship with varying velocity and hysteresis values. Velocity values chosen in our analysis are adopted for densely urbanised areas [153]. Clearly, slow moving UEs (10 km/h) benefit a lot from reduced early handover and result into increased number of TTIs (i.e. higher value of ΔT), thereby creating higher opportunities for RBs to be switched off for longer period of time; subsequently resulting into increased ES for REHO enabled LTE UEs. Conversely, slow moving UEs compared to relatively fast moving UEs (40 km/h), get affected a lot due to late handover, i.e. for values of hysteresis more then the standard value of 4 dBm. Figure 5.4 presents cumulative distribution function plots for dynamic power consumption. In line with Figure 5.3, REHO outperforms standard LTE in terms of power consumption, especially for slow moving UEs at low velocity values. Noteworthy, REHO always implemented reduced value of hysteresis, i.e. 1 dBm compared to standard LTE hysteresis value of 4 dBm. UEs in REHO at velocity of 10 km/h, achieves around 55 percent of ES compared to similar LTE standard UEs. Since TTIs in REHO reduces with increasing velocity (Figure 5.3), accordingly ES is reduced for higher velocity values. However even at maximum velocity value of 40 km/h, REHO results in around 35 percent improved power consumption compared to LTE standard. Figure 5.4 clearly evidences non-sensitivity of LTE standard to UEs velocity, i.e. it does not benefit or affect slow or fast moving UEs at all, thereby making REHO a favourable scheme for densely deployed urbanised networks.

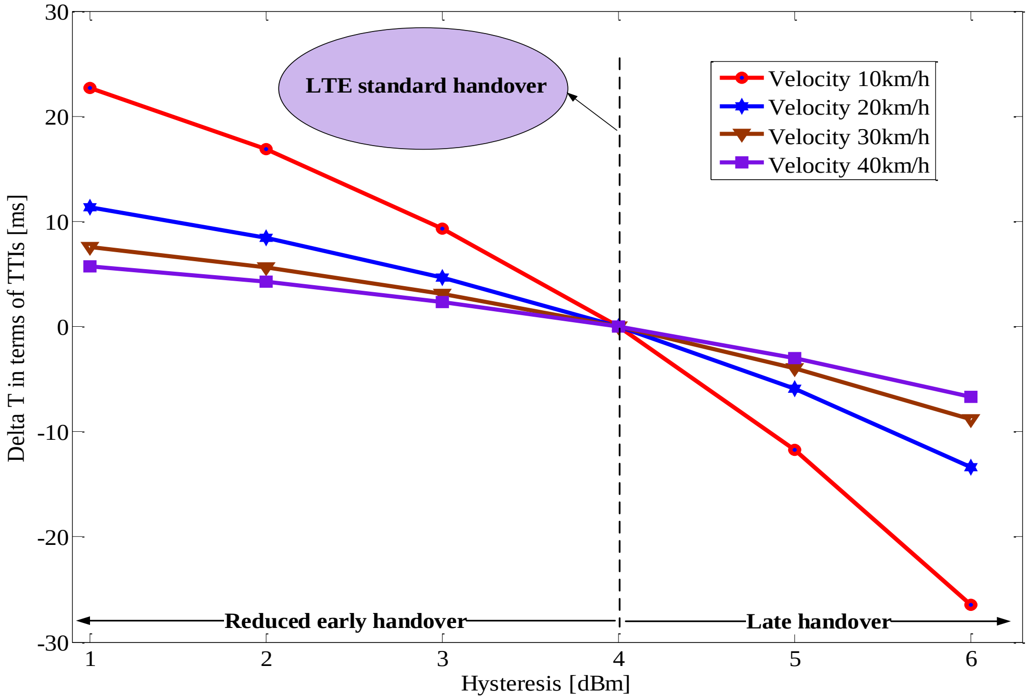


Figure 5.3: Early handover ΔT and Hysteresis

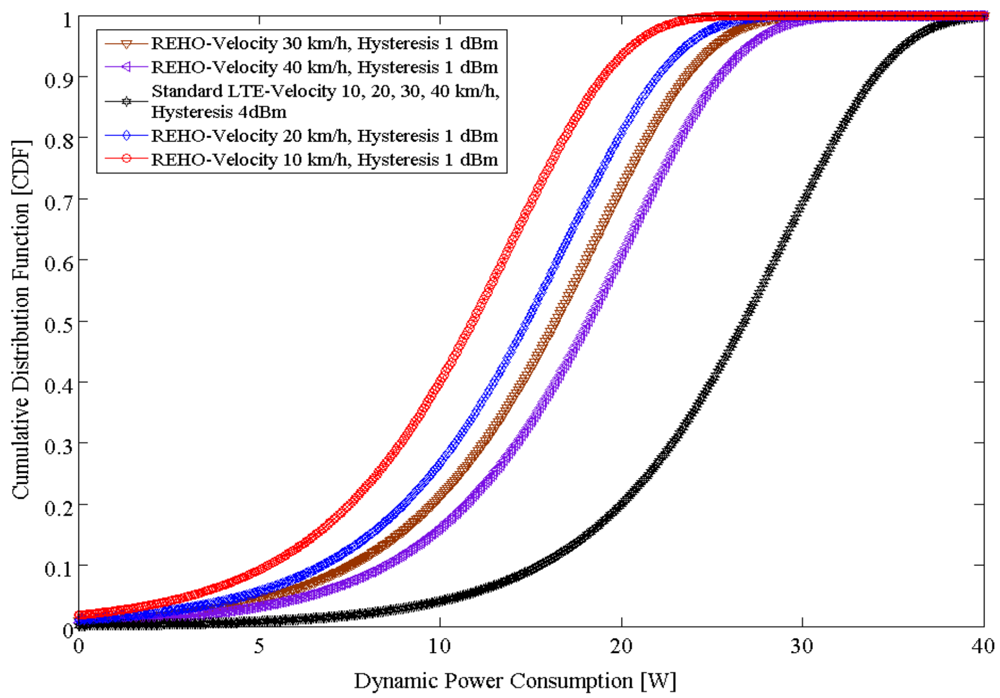


Figure 5.4: REHO vs LTE- Dynamic Power Consumption

5.4.2.2 REHO and Radio Link Failure

Noteworthy, the rest of the results presented in the chapter employ velocity of 40 km/h, hysteresis value of 1 dBm. The power model (RWP) employed in our subsequent analysis is the same as used in previous chapter 4. Importantly, since REHO implements reduced early handover using reduced values of hysteresis, thus the increased ES is achieved at the cost of slightly RLF while compared to standard LTE UEs. For sake of comparison, REHO (hysteresis 1 dBm) results into around 5 percent RLF compared to LTE (hysteresis 4 dBm, RLF of 2 percent). However it is still within acceptable range in densely deployed networks [154]. Figure 5.5 presents relationship for ES, RLF with varying values of hysteresis. Clearly, results from analytical analysis are in strong relationship to results obtained from simulation based analysis. Figure 5.5 also delivers a guideline for vendors to choose suitable value of hysteresis, while achieving appropriate results of ES and RLF.

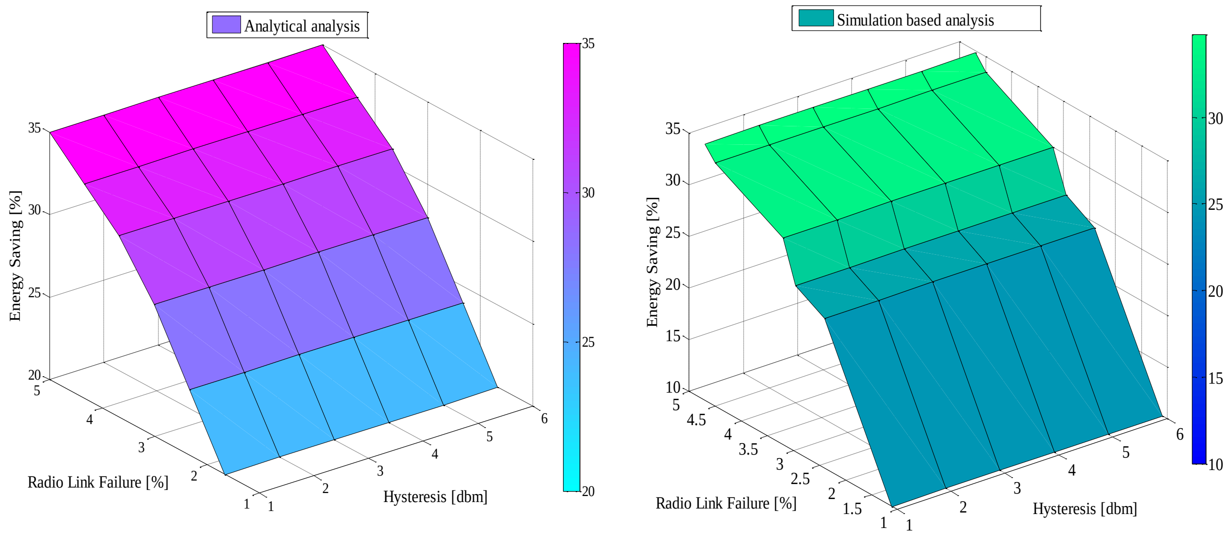


Figure 5.5: REHO Analytical and Simulation based analysis

5.4.3 Comparative Analysis

Following presents detailed comparative analysis

5.4.3.1 Energy Efficiency

Figure 5.6 presents energy efficiency achieved in REHO while compared to other state of art [103] [155] and LTE standard. This analysis is carried out by comparing REHO with BS switching OFF ES scheme [155], Bandwidth expansion based scheme [103] and LTE standard [56]. It can be clearly seen that based on the fact that REHO employs reduced early handover, thus REHO enabled LTE network enjoys highest energy efficiency as compared to the other schemes. The V-BEM energy efficiency is lower than REHO while better then switching OFF scheme. Further BS switching OFF scheme achieves lowest energy efficiency as compared to other two schemes, however still better then LTE standard.

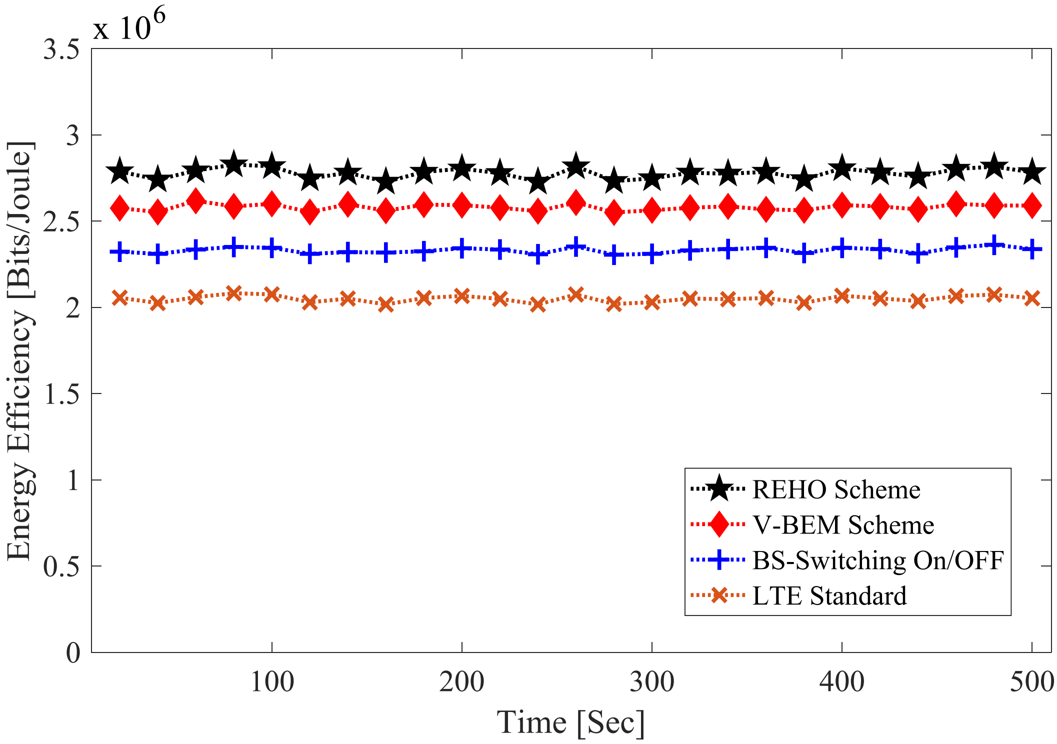


Figure 5.6: Energy efficiency comparative analysis

5.4.3.2 Call Blocking Probability

REHO is compared in terms of performance with other state of art which implements CBP, such as EEBS based scheme [156] and LTE standard whereas QoS threshold is maintained at 2 % [56]. REHO, due to reduced early handover resulted into higher overall system CBP while compared to LTE standard, however it still performed better compared to other state of art, i.e. EE-BS scheme (Figure 5.7). Further, overall system CBP increased across the board with increase in data rate. Importantly, higher data rate requires more resources thus effecting overall system capacity thereby leading towards higher CBP (Figure 5.7). LTE standard always remained below 3GPP threshold of 2% whereas REHO exceeded this threshold at data rate of approximately 10 Mbps compared to EE-BS scheme at data rate of approximately 7 Mbps.

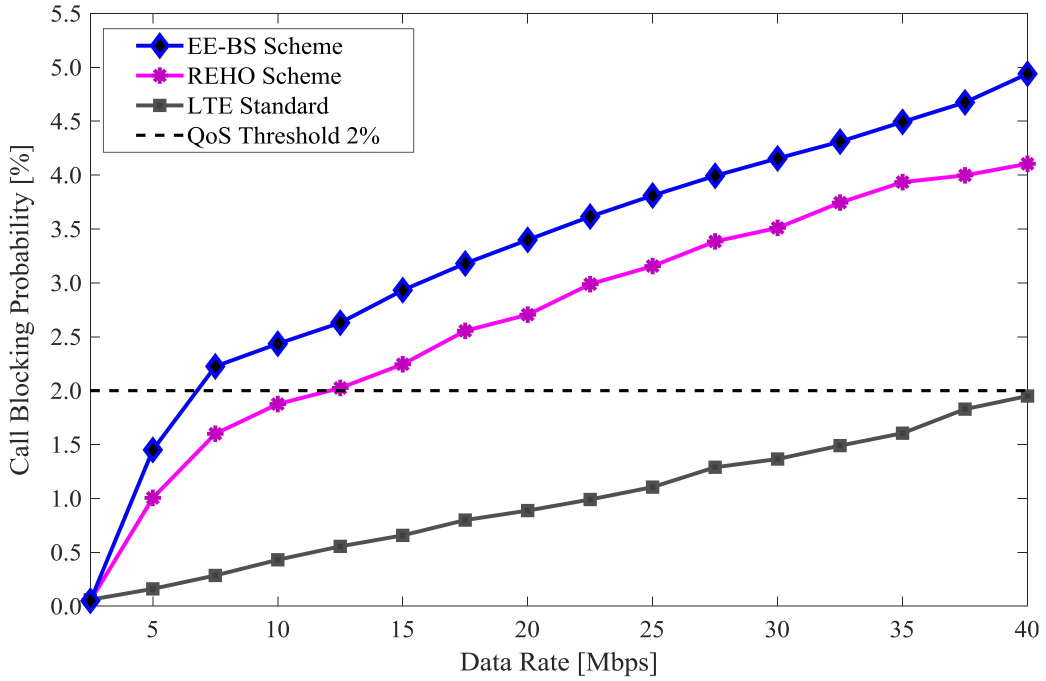


Figure 5.7: Call blocking probability

5.4.4 Overall System Efficiency

Overall system efficiency is investigated through the analysis of channel outage probability as follow.

5.4.4.1 Channel Outage Probability

Since REHO implements early handover, it is vital to investigate the impact of reduced early handover on channel outage probability. Subsequently, outage probability for REHO is investigated at varying data rates for increasing number of UEs, both for outbound handovers at serving cell and inbound handovers at target cell respectively. As shown in Figure 5.8 serving cell outage probability reduces with increasing outbound handovers due to the fact that it turns off its RBs right after reduced early handover thus resulting in reduced channel outage probability due to lesser interference component in the cell. In line with CBP results, outage probability is also higher at higher data rates due to higher level of RBs utilisation, interference and vice versa (Figure 5.8). In the same context, Figure 5.9 presents target cell outage probability in relation to the incoming UEs from serving cell. Importantly, incoming UEs demand additional resources from target cell thereby increases the level of radio signals transmission in cell leading towards higher interference which directly impacts channel outage probability. Further, the outage probability also grows with increasing number of inbound UEs because higher number of incoming UEs demands more and more resources. Notably the level of interference also imparts from intensity of radio frequency in surrounding area thereby affecting the overall outage probability. In line with channel outage probability for outbound UEs at serving cell, outage probability for incoming UEs at target cell is also higher at higher data rates due to higher level of RBs utilisation, interference and vice versa (Figure 5.9).

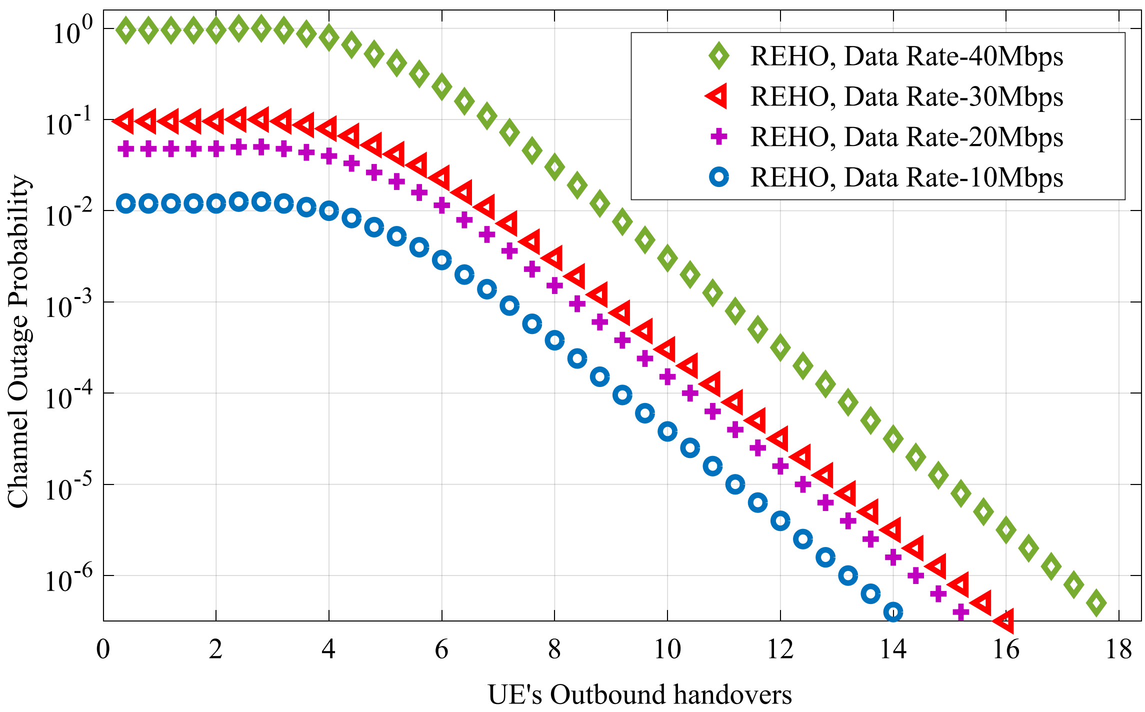


Figure 5.8: Serving cell outage probability

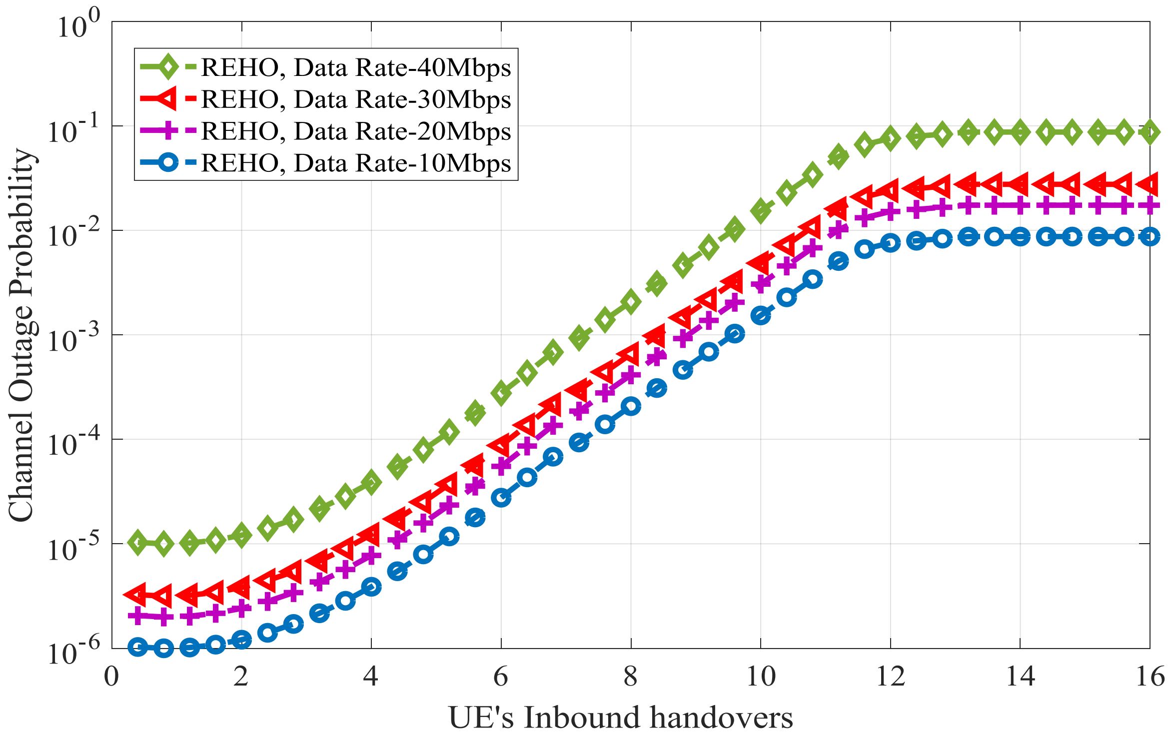


Figure 5.9: Target cell outage probability

5.5 CONCLUSION

In this chapter Axioms of Euclidean geometry are employed to estimate the target cell boundary towards calculation of the time difference ΔT between standard LTE and REHO. Detailed REHO performance analysis has been accomplished which involved comparison of standard LTE with REHO in the presence of varying velocity and Hysteresis values. Early handover ΔT in REHO results into improved energy efficiency at the cost of slightly increased RLF. The key finding of this chapter is the non-sensitivity of UEs towards velocity in standard LTE, whereas REHO leads to considerably improved energy efficiency at low velocity thereby making it an advantageous scheme for urbanised densely deployed LTE networks. Additionally overall system efficiency is investigated in this chapter while results also provided a guideline for vendors to choose suitable value of hysteresis, while achieving appropriate results of energy saving and RLF. REHO implementation is also fairly practical with easy deployment.

Chapter 6

6 Conclusion and Future Work

6.1 Conclusion

In order to provide essential coverage and serve UEs data demands, LTE networks adopts cells deployment methodology where each cell is formed of one or more BSs. These BSs fulfil UEs data requirements at the cost of power consumption. Consequently, enlarged number of UEs directly results in to increased power consumption which directly rises operators OPEX. Prolonged power consumption not only reduces operators profit but also contributes in CO_2 emission. Thus, power consumption has become major issue in mobile communication. In this view; this research work focus in energy efficiency in LTE networks and propose novel ES scheme to reduce dynamic power consumption at BS. The initial version of proposed ES scheme embraces the idea of bandwidth expansion and combine two RBs together to form single super RB which reduces PDCCH overhead thus resulting into reduced power consumption. PDCCH occupy space (RE) in each RB, thus its overhead can be reduced by merging two RBs together and cut down PDCCH signals from second RB. This reduces dynamic power conservation by 28 percent while freed REs can be used for data transmission thereby results into increased system throughput. Research work carried in this thesis not only focus on ES proposals but also incorporate the impact of power consumption on OPEX and global warming thus addressing both economical and environmental aspects. Initially bandwidth expansion based proposed scheme is validated through the analysis of various dynamic power consumption parameters, while its impact on OPEX is investigated at macro level. Afterward, novel reduced early handover (REHO) based ES scheme is introduced and merged with already presented bandwidth expansion to form enhanced ES scheme. REHO scheme lies in the fact that UEs are handed over to target cell earlier and freed RBs of serving cell can be turned off for ES purpose. The early handover is trigged through the modification in A3 event with minimum value of hysteresis. REHO always uses hysteresis value of 1dBm as compare to standard handover value 4dBm. Remarkably a combination of various models including the power, OPEX, profit calculation and CO_2 emission models and real Three tariffs are engaged to carry out this research. The REHO, while combined with bandwidth expansion, offer 35 percent ES. The performance of REHO is validated through system level simulations in Matlab where numerous parameters (i.e. dynamic power consumption, OPEX, profitability, carbon emission) are investigated. Moreover, OPEX is examined at micro level by considering reduced power consumption achieved through REHO. In addition, dynamic power consumption is explored using a variety of mobility models while comparative analysis with LTE standard and other state of the art is also included in this work. Results prove that 35 percent power reduction can significantly increase operators profit when total number of BSs are considered. It can be clearly seen that 35 percent ES results into reduced electricity bills by 0.72 percent. Said profit when combined with trading carbon credits thus together results in approximately 6.4 million profit per year to the operators running 20,000 BSs based network infrastructure.

Point to be noted that reduced power consumption not only improve profit but also help operators to stay green and have high profile in green communication. The Delta T (ΔT) which is hallmark of proposed REHO presents actual time difference between early and standard handover is examined in final chapter 5. In parallel many parameters are investigated to inspect the overall system level efficiency. It has come to conclusion that REHO offers significant level of ES with acceptable level of compromise on quality related parameters (i.e. RLF, CBP and outage probability). In the same context, this research work also provides recommendation for operators to choose suitable parameters (i.e. value of hysteresis) while attaining suitable ES and RLF. The REHO scheme is fairly practical and can be easily deployed in existing LTE infrastructure without any major modifications. Importantly all LTE standard BSs must implement A3 event. Since REHO proposes modifications in A3 event, thus the concept of early handover can be easily integrated in existing BSs with minimum chosen value of Hysteresis (i.e. 1 dBm). Once REHO is implemented, accordingly the freed resources of serving BSs can be turned off, thereby resulting into increased ES as described in the above chapters. Finally, on the bases of research work carried out in this thesis, open research issues are discussed in next section which could be very helpful for future research work.

6.2 Open Research Issues

Comparative study of various existing ES schemes has shown that most of them are only effective for lightly loaded networks thus fails to save energy during highly loaded network conditions. The DTX based schemes affected from delay that occur back in active mode [89], therefore further research work is needed to reduce these delays. Importantly reduced delay could have significant effect on overall performance of the system. Next to this distance aware and bandwidth expansion based schemes flop to reduce power consumption during peak traffic hours. Therefore, these schemes could be further explored to provide enhanced ES during highly loaded traffic [94, 95]. Bandwidth expansion schemes could work more effectively in balanced network. Consequently, load balancing could be further exploited with bandwidth expansion [102, 106]. On the other hand, centralized and distributed schemes exchange UEs traffic load information between the BSs thus resulting into increased load information overhead in network and reduces system efficiency [97, 98]. Accordingly new methods should be devised to reduce the load information overhead. Likewise, link adaptation based ES scheme also suffers from overhead produced by energy consumption feedback sent to the BS [100]. Notably feedback overhead reduction could be exploited for improved ES in the LTE networks. Then EE BS deployment provision could be integrated with any other dynamic ES based schemes for enhanced EE systems [105]. MBSFN based ES scheme suffers from control signals which basically reduce the opportunities of turning off the unused RBs [90]. ES through control signals could be further explored for enhanced MBSFN based ES. In other words, few aspects of both the TCoM and MBSFN schemes can be taken into account to develop a hybrid ES scheme which may provide better EE system as compared to the systems using TCoM and MBSFN schemes on individual basis [90, 103].

6.3 Future Work

The further improvements can be done in future work as specified below.

First of the Literature review presented in this thesis can be extended by investigating more advanced ES proposals to provide extra and thorough summary of existing state of the art. Enhanced critical analysis can be added to vast the scope of ES in LT networks. While on the one side, improved critical analysis will help researchers to have broad understanding of existing research in energy management in LTE, on the other side it will provide opportunities to develop more enhanced ES schemes on the bases of disadvantages of existing techniques. Literature view can also be stretched by incorporating BS static power consumption. Where EE hardware can be considered for research and it can be merge with already proposed REHO (dynamic power ES) scheme to provide combined system. Thus, hybrid scheme can be used to provide ES in both static and dynamic components of BS. Next to this proposed ES schemes lies on the concept of bandwidth expansion which cut down only PDCCH overhead. Importantly each RB contains a lot of control signals, in the same context many other control channels can also be examined to find out opportunities for improved reduced overhead thereby resulting into added ES. As discussed in previous chapters, proposed ES scheme combines bandwidth expansion with REHO and initiate early handover through minimum value of hysteresis. REHO while offers significant ES, it also increases RLF up to 5 percent which affect QoS in network. More research work can be carried out for the improvement of RLF, where QoS related schemes can be proposed for less RLF. Notably the idea of Relays deployment between BSs can be significant candidate. RLF could be tackle through appropriate deployment of relay stations in overlapping areas of two cells. Deployed relay station could serve the UEs in overlapping areas at the cost of lower transmission power while both target and serving cell could be turned OFF until UE leaves Relays coverage area. This would not only reduce RLF but also contribute in improved ES. Relays deployment cost adds in network CAPEX which results in to slightly lower profit, yet it could significantly improve RLF which occur due to the weak signal strength having longer distance from BS. Secondly proposed REHO embrace the idea of early handover through minimum value of hysteresis. In the same context, there are three important parameters (offset, TTT and hysteresis) involves in handover procedure. So future work can also consider TTT and offset for better ES and RLF. These parameters play key role in triggering A3 event, so A3 trigger can be move back and forth through the appropriate usage of these parameters values. This work only considers one BS per cell in network model; in future both BSs and UEs per cell can be increased to analyse REHO performance in denser environment. Subsequently proposed work can also be improved through incorporating dynamic cells deployment where cell sizes are different thus providing REHO performance in more realistic scenarios. Finally, additional performance related parameters can be investigated to provide compact validation of REHO. In this view, all above discussed areas can be used as a ground for future work in proposed ES scheme. Depending on research objectives all these areas can be used as significant research topic for better ES and QoS in LTE networks.

REFERENCES

[1] A. Alnoman, G. H. S. Carvalho, A. Anpalagan and I. Woungang, "Energy Efficiency on Fully Cloudified Mobile Networks: Survey, Challenges, and Open Issues," in *IEEE Communications Surveys & Tutorials*, vol. PP, no. 99, pp. 1-1.

[2] M. J. Chang, Z. Abichar and C. Y. Hsu, "WiMAX or LTE: Who will Lead the Broadband Mobile Internet?," in *IT Professional*, vol. 12, no. 3, pp. 26-32, May-June 2010.

[3] F. Rezaei, M. Hempel and H. Sharif, "LTE PHY performance analysis under 3GPP standards parameters," *2011 IEEE 16th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Kyoto, 2011, pp. 102-106.

[4] Y. Cuibo, L. Xiandong, L. Weiyang, Z. Xu and G. Xuerong, "Feasibility Study for the LTE-Advanced System," *2015 4th International Conference on Advanced Information Technology and Sensor Application (AITS)*, Harbin, 2015, pp. 80-83.

[5] S. Oh, H. Kim, B. Ryu and N. Park, "Inbound Mobility Management on LTE-Advanced Femtocell Topology Using X2 Interface," *2011 Proceedings of 20th International Conference on Computer Communications and Networks (ICCCN)*, Maui, HI, 2011, pp. 1-5.

[6] K. P. Makhecha and K. H. Wandra, "4G Wireless Networks: Opportunities and Challenges," *2009 Annual IEEE India Conference*, Gujarat, 2009, pp. 1-4.

[7] A. Pande, V. Ahuja, R. Sivaraj, E. Baik and P. Mohapatra, "Video Delivery Challenges and Opportunities in 4G Networks," in *IEEE MultiMedia*, vol. 20, no. 3, pp. 88-94, July-Sept. 2013.

[8] M. A. Garrett, "Radio astronomy transformed: Aperture arrays — Past, present and future," *2013 Africon*, Pointe-Aux-Piments, 2013, pp. 1-5.

[9] Q. Fan, H. Lu, P. Hong and Z. Zhu, "Throughput–Power Tradeoff Association for User Equipment in WLAN/Cellular Integrated Networks," in *IEEE Transactions on Vehicular Technology*, vol. 66, no. 4, pp. 3462-3474, April 2017.

[10] Y. W. Blankenship, "Achieving high capacity with small cells in LTE-A," *2012 50th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, Monticello, IL, 2012, pp. 1680-1687.

[11] M. Agiwal, A. Roy and N. Saxena, "Next Generation 5G Wireless Networks: A Comprehensive Survey," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1617-1655, thirdquarter 2016.

[12] A. Damnjanovic *et al*., "A survey on 3GPP heterogeneous networks," in *IEEE Wireless Communications*, vol. 18, no. 3, pp. 10-21, June 2011.

[13] F. Adachi, "Keynote talk #1: Wireless evolution and challenges for 5G wireless networks," *2015 2nd National Foundation for Science and Technology Development*

Conference on Information and Computer Science (NICS), Ho Chi Minh City, 2015, pp. xxi-xxii.

[14] N. Chandran and M. C. Valenti, "Three generations of cellular wireless systems," in *IEEE Potentials*, vol. 20, no. 1, pp. 32-35, Feb/Mar 2001.

[15] A. Esmailpour, S. Salehi and N. Safavi, "Quality of service differentiation measurements in 4G networks," *2013 Wireless Telecommunications Symposium (WTS)*, Phoenix, AZ, 2013, pp. 1-5.

[16] Y. Tian, A. Nix and M. Beach, "4G femtocell LTE base station with diversity and adaptive antenna techniques," *10th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2014)*, Beijing, 2014, pp. 216-221.

[17] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA): Base Station (BS) radio transmission and reception," TS 36.104, V11.9.0.

[18] M. Nasimi, F. Hashim and C. K. Ng, "Characterizing energy efficiency for heterogeneous cellular networks," *2012 IEEE Student Conference on Research and Development (SCOReD)*, Pulau Pinang, 2012, pp. 198-202.

[19] I. Shayea, M. Ismail and R. Nordin, "Advanced handover techniques in LTE- Advanced system," *2012 International Conference on Computer and Communication Engineering (ICCCE)*, Kuala Lumpur, 2012, pp. 74-79.

[20] U. Dampage and C. B. Wavegedara, "A low-latency and energy efficient forward handover scheme for LTE-femtocell networks," *2013 IEEE 8th International Conference on Industrial and Information Systems*, Peradeniya, 2013, pp. 53-58.

[21] P. Skocir, D. Katusic, I. Novotni, I. Bojic and G. Jezic, "Data rate fluctuations from user perspective in 4G mobile networks," *2014 22nd International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, Split, 2014, pp. 180-185.

[22] S. Abeta, "Toward LTE commercial launch and future plan for LTE enhancements (LTE-Advanced)," *2010 IEEE International Conference on Communication Systems*, Singapor, 2010, pp. 146-150.

[23] M. F. L. Abdullah and A. Z. Yonis, "Performance of LTE Release 8 and Release 10 in wireless communications," *Proceedings Title: 2012 International Conference on Cyber Security, Cyber Warfare and Digital Forensic (CyberSec)*, Kuala Lumpur, 2012, pp. 236-241.

[24] Navita and Amandeep, "Performance analysis of OFDMA, MIMO and SC-FDMA technology in 4G LTE networks," *2016 6th International Conference - Cloud System and Big Data Engineering (Confluence)*, Noida, 2016, pp. 554-558.

[25] U. Varshney and R. Jain, "Issues in emerging 4G wireless networks," in *Computer*, vol. 34, no. 6, pp. 94-96, Jun 2001.

[26] F. A. Mumtaz, "Mobile networks across time," *2015 Annual IEEE India Conference (INDICON)*, New Delhi, 2015, pp. 1-4.

[27] A. El Shafie, T. Q. Duong and N. Al-Dhahir, "QoS-Based Design for Security Enhancement in TDMA-Based Wireless Networks," *2016 IEEE Globecom Workshops (GC Wkshps)*, Washington, DC, 2016, pp. 1-7.

[28] M. L. Roberts, M. A. Temple, R. F. Mills and R. A. Raines, "Evolution of the air interface of cellular communications systems toward 4G realization," in *IEEE Communications Surveys & Tutorials*, vol. 8, no. 1, pp. 2-23, First Quarter 2006.

[29] S. Janaaththanan, C. Kasparis and B. G. Evans, "Comparison of SC-FDMA and HSUPA in the Return-Link of Evolved S-UMTS Architecture," *2007 International Workshop on Satellite and Space Communications*, Salzburg, 2007, pp. 56-60.

[30] M. Yavuz *et al.*, "Interference management and performance analysis of UMTS/HSPA+ femtocells," in *IEEE Communications Magazine*, vol. 47, no. 9, pp. 102-109, September 2009.

[31] K. Ivanov, C. F. Ball and F. Treml, "GPRS/EDGE performance on reserved and shared packet data channels," *2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No.03CH37484)*, 2003, pp. 912-916 Vol.2.

[32] K. Johansson, J. Bergman, D. Gerstenberger, M. Blomgren and A. Wallen, "Multi-Carrier HSPA Evolution," *VTC Spring 2009 - IEEE 69th Vehicular Technology Conference*, Barcelona, 2009, pp. 1-5.

[33] K. Balachandran, Q. Bi, A. Rudrapatna, J. Seymour, R. Soni and A. Weber, "Performance assessment of next-generation wireless mobile systems," in *Bell Labs Technical Journal*, vol. 13, no. 4, pp. 35-58, Winter 2009.

[34] C. de Cosson, "LTE network planning challenges," *2013 Conference on Microwave Techniques (COMITE)*, Pardubice, 2013, pp. 143-147.

[35] C. Ramirez-Perez and V. Ramos, "SDN meets SDR in self-organizing networks: fitting the pieces of network management," in *IEEE Communications Magazine*, vol. 54, no. 1, pp. 48-57, January 2016.

[36] K. Zheng, L. Hou, H. Meng, Q. Zheng, N. Lu and L. Lei, "Soft-defined heterogeneous vehicular network: architecture and challenges," in *IEEE Network*, vol. 30, no. 4, pp. 72-80, July-August 2016.

[37] U. Toseef, C. Goerg, T. Weerawardane and A. Timm-Giel, "Performance comparison of PDCP buffer management schemes in LTE system," *2011 IFIP Wireless Days (WD)*, Niagara Falls, ON, 2011, pp. 1-3.

[38] C. Gessner, R. Kohn, J. Schniedenharn and A. Sitte, "UTRA TDD protocol operation," *11th IEEE International Symposium on Personal Indoor and Mobile Radio*

Communications. PIMRC 2000. Proceedings (Cat. No.00TH8525), London, 2000, pp. 1226-1230 vol.2.

[39] M. A. Seimeni, P. K. Gkonis, D. I. Kaklamani, I. S. Venieris and C. A. Papavasiliou, "Resource management in OFDMA heterogeneous network," *2016 Wireless Telecommunications Symposium (WTS)*, London, 2016, pp. 1-6.

[40] H. Mahdavi-Doost, N. Prasad and S. Rangarajan, "Energy efficient downlink scheduling in LTE-Advanced networks," *2016 8th International Conference on Communication Systems and Networks (COMSNETS)*, Bangalore, 2016, pp. 1-8.

[41] M. Wang *et al.*, "The Evolution of LTE Physical Layer Control Channels," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1336-1354, Secondquarter 2016.

[42] 3GPP, “Physical Layer Aspects for Evolved Universal Terrestrial Radio-Access (UTRA),” TS 25.814, Rel. 7.

[43] A. A. Savochkin, N. M. Daninlina, D. V. Nacharov, R. G. Pavlenko, K. O. Syomochkin and A. N. Yatsenko, "Adaptive OFDM modem — Basis of LTE network physical layer," *2010 20th International Crimean Conference "Microwave & Telecommunication Technology"*, Sevastopol, 2010, pp. 351-352.

[44] 3GPP, “E-UTRA Medium Access Control (MAC) Protocol Specification,” TS 36.321, Rel.8

[45] D. Niyato and E. Hossain, "Call admission control for QoS provisioning in 4G wireless networks: issues and approaches," in *IEEE Network*, vol. 19, no. 5, pp. 5-11, Sept.-Oct. 2005.

[46] C. S. Park and S. Park, "Analysis of RSRP Measurement Accuracy," in *IEEE Communications Letters*, vol. 20, no. 3, pp. 430-433, March 2016.

[47] N. Takaharu, "LTE and LTE-advanced: Radio technology aspects for mobile communications," *2011 XXXth URSI General Assembly and Scientific Symposium*, Istanbul, 2011, pp. 1-4.

[48] H. Lee, S. Vahid and K. Moessner, "A Survey of Radio Resource Management for Spectrum Aggregation in LTE-Advanced," in *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 745-760, Second Quarter 2014.

[49] N. Becker, A. Rizk and M. Fidler, "A measurement study on the application-level performance of LTE," *2014 IFIP Networking Conference*, Trondheim, 2014, pp. 1-9.

[50] S. B. Manir, M. M. Rahman and T. Ahmed, "Comparison between FDD and TDD frame structure in SC-FDMA," *2012 International Conference on Informatics, Electronics & Vision (ICIEV)*, Dhaka, 2012, pp. 795-799.

[51] L. Wan, M. Zhou and R. Wen, "Evolving LTE with Flexible Duplex," *2013 IEEE Globecom Workshops (GC Wkshps)*, Atlanta, GA, 2013, pp. 49-54.

[52] R. Ratasuk, A. Ghosh, Weimin Xiao, R. Love, R. Nory and B. Classon, "TDD design for UMTS Long-Term Evolution," *2008 IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*, Cannes, 2008, pp. 1-5.

[53] R. Zheng, X. Zhang, X. Li, Q. Pan, Y. Fang and D. Yang, "Performance Evaluation on the Coexistence Scenario of Two 3GPP LTE Systems," *2009 IEEE 70th Vehicular Technology Conference Fall*, Anchorage, AK, 2009, pp. 1-6.

[54] S. S. Prasad, C. K. Shukla and R. F. Chisab, "Performance analysis of OFDMA in LTE," *Computing Communication & Networking Technologies (ICCCNT), 2012 Third International Conference on*, Coimbatore, 2012, pp. 1-7.

[55] L. A. M. R. de Temino, G. Berardinelli, S. Frattasi, K. Pajukoski and P. Mogensen, "Single-user MIMO for LTE-A Uplink: Performance evaluation of OFDMA vs. SC-FDMA," *2009 IEEE Radio and Wireless Symposium*, San Diego, CA, 2009, pp. 304-307.

[56] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Networks (E UTRAN): Overall description," TS 36.300, V10.4.0.

[57] 3GPP, "Technical Specification Group Radio Access Network; Further advancements for E-UTRA - LTE-Advanced feasibility studies in RAN WG4," TR 36.815., V9.0.0.

[58] 3GPP, "General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access," 3rd Generation Partnership Project (3GPP), TS 23.401, Jun. 2011.

[59] S. B. H. Said *et al.*, "New control plane in 3GPP LTE/EPC architecture for on-demand connectivity service," *2013 IEEE 2nd International Conference on Cloud Networking (CloudNet)*, San Francisco, CA, 2013, pp. 205-209.

[60] F. H. Khan and M. Portmann, "A system-level architecture for software-defined LTE networks," *2016 10th International Conference on Signal Processing and Communication Systems (ICSPCS)*, Gold Coast, QLD, 2016, pp. 1-10.

[61] J. Prados-Garzon, J. J. Ramos-Munoz, P. Ameigeiras, P. Andres-Maldonado and J. M. Lopez-Soler, "Modeling and Dimensioning of a Virtualized MME for 5G Mobile Networks," in *IEEE Transactions on Vehicular Technology*, vol. 66, no. 5, pp. 4383-4395, May 2017.

[62] X. Li *et al.*, "Dimensioning of the LTE S1 interface," *WMNC2010*, Budapest, 2010, pp. 1-6.

[63] A. O. Akinlabi and M. K. Joseph, "Utility based function for optimizing femtocells," *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Milan, 2017, pp. 1-5.

[64] T. D. Assefa, R. Hoque, E. Tragos and X. Dimitropoulos, "SDN-based local mobility management with X2-interface in femtocell networks," *2017 IEEE 22nd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Lund, 2017, pp. 1-6.

[65] N. Hariprasad and M. Biju, "Optimized rate and power control based energy saving transmission for LTE base-station," *2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, Nagercoil, 2016, pp. 1-6.

[66] S. M. Azzam and T. Elshabrawy, "Re-Dimensioning Number of Active eNodeBs for Green LTE Networks Using Genetic Algorithms," *Proceedings of European Wireless 2015; 21th European Wireless Conference*, Budapest, Hungary, 2015, pp. 1-6.

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

[68] K. Hiltunen, "Utilizing eNodeB sleep mode to improve the energy-efficiency of dense LTE networks," *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, London, 2013, pp. 3249-3253.

[69] T. Chen, H. Zhang, Z. Zhao and X. Chen, "Towards green wireless access networks," *2010 5th International ICST Conference on Communications and Networking in China*, Beijing, 2010, pp. 1-6.

[70] S. Srikanth, P. A. Murugesa Pandian and X. Fernando, "Orthogonal frequency division multiple access in WiMAX and LTE: a comparison," in *IEEE Communications Magazine*, vol. 50, no. 9, pp. 153-161, September 2012.

[71] S. Janaaththanan, C. Kasparis and B. G. Evans, "Comparison of SC-FDMA and HSUPA in the Return-Link of Evolved S-UMTS Architecture," *2007 International Workshop on Satellite and Space Communications*, Salzburg, 2007, pp. 56-60.

[72] M. Salem, A. Adinoyi, H. Yanikomeroglu and Y. D. Kim, "Radio Resource Management in OFDMA-Based Cellular Networks Enhanced with Fixed and Nomadic Relays," *2010 IEEE Wireless Communication and Networking Conference*, Sydney, NSW, 2010, pp. 1-6.

[73] M. M. Matalgah, B. Paudel and O. M. Hammouri, "Cross-layer resource allocation approach in OFDMA systems with multi-class QoS services and users queue status," *2013 IEEE Global Communications Conference (GLOBECOM)*, Atlanta, GA, 2013, pp. 1385-1390.

[74] M. Demirtaş and A. Soysal, "Energy efficient microcell deployment for HetNets," *2015 23nd Signal Processing and Communications Applications Conference (SIU)*, Malatya, 2015, pp. 531-534.

[75] W. Tomaselli, D. Sabella, V. Palestini and V. Bernasconi, "Energy efficiency performances of selective switch OFF algorithm in LTE mobile networks," *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, London, 2013, pp. 3254-3258.

[76] G. Cili, H. Yanikomeroglu and F. R. Yu, "Cell switch off technique combined with coordinated multi-point (CoMP) transmission for energy efficiency in beyond-LTE cellular

networks," *2012 IEEE International Conference on Communications (ICC)*, Ottawa, ON, 2012, pp. 5931-5935.

[77] M. Pickavet *et al*., "Worldwide energy needs for ICT: The rise of power-aware networking," *2008 2nd International Symposium on Advanced Networks and Telecommunication Systems*, Mumbai, 2008, pp. 1-3.

[78] Y. L. Chung, "Energy-Saving Transmission for Green Macrocell–Small Cell Systems: A System-Level Perspective," in *IEEE Systems Journal*, vol. 11, no. 2, pp. 706-716, June 2017.

[79] E. Oh, B. Krishnamachari, X. Liu and Z. Niu, "Toward dynamic energy-efficient operation of cellular network infrastructure," in *IEEE Communications Magazine*, vol. 49, no. 6, pp. 56-61, June 2011.

[80] R. Maihaniemi, "ICT Getting Green," *4th International Telecommunication - Energy special conference*, Vienna, Austria, 2009, pp. 1-6.

[81] H. O. Scheck, "ICT & wireless networks and their impact on global warming," *2010 European Wireless Conference (EW)*, Lucca, 2010, pp. 911-915.

[82] Y. Chen, S. Zhang, S. Xu and G. Y. Li, "Fundamental trade-offs on green wireless networks," in *IEEE Communications Magazine*, vol. 49, no. 6, pp. 30-37, June 2011.

[83] R. Wikström, "Innovative energy management to utilize energy efficient solutions in the ICT infrastructure," *2017 IEEE International Telecommunications Energy Conference (INTELEC)*, Broadbeach, Gold Coast, Queensland, Australia, 2017, pp. 570-573.

[84] R. Peng and X. Wang, "ICT Solutions Calculation Model for CO2 Emission Reduction and Prediction on Its Emission Reduction Potential," *2009 International Conference on Management and Service Science*, Wuhan, 2009, pp. 1-5.

[85] T. M. Knoll, "A combined CAPEX and OPEX cost model for LTE networks," *2014 16th International Telecommunications Network Strategy and Planning Symposium (Networks)*, Funchal, 2014, pp. 1-6.

[86] J. Moysen and L. Giupponi, "Self Coordination among SON Functions in LTE Heterogeneous Networks," *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*, Glasgow, 2015, pp. 1-6.

[87] T. M. Knoll, "Life-cycle cost modelling for NFV/SDN based mobile networks," *2015 Conference of Telecommunication, Media and Internet Techno-Economics (CTTE)*, Munich, 2015, pp. 1-8.

[88] N. Zhang and H. Hämmäinen, "Cost efficiency of SDN in LTE-based mobile networks: Case Finland," *2015 International Conference and Workshops on Networked Systems (NetSys)*, Cottbus, 2015, pp. 1-5.

[89] P. Frenger, P. Moberg, J. Malmodin, Y. Jading and I. Godor, "Reducing Energy Consumption in LTE with Cell DTX," *2011 IEEE 73rd Vehicular Technology Conference (VTC Spring)*, Yokohama, 2011, pp. 1-5.

[90] D. Migliorini, G. Stea, M. Caretti and D. Sabella, "Power-Aware Allocation of MBSFN Subframes Using Discontinuous Cell Transmission in LTE Systems," *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, Las Vegas, NV, 2013, pp. 1-5.

[91] C. T. Tung, Y. L. Chung and Z. Tsai, "An efficient power-saving downlink transmission scheme in OFDM-based multiple component carrier systems," *2012 14th International Conference on Advanced Communication Technology (ICACT)*, PyeongChang, 2012, pp. 116-120.

[92] Fei Zheng, Wenjing Li, Luoming Meng, Peng Yu and Lei Peng, "Distributed energy saving mechanism based on CoMP in LTE-A system," in *China Communications*, vol. 13, no. 7, pp. 39-47, July 2016.

[93] S. Jin, X. Ma and W. Yue, "Energy-saving strategy for green cognitive radio networks with an LTE-advanced structure," in *Journal of Communications and Networks*, vol. 18, no. 4, pp. 610-618, Aug. 2016.

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

[95] A. Bousia, E. Kartsakli, L. Alonso and C. Verikoukis, "Dynamic energy efficient distance-aware Base Station switch on/off scheme for LTE-advanced," *2012 IEEE Global Communications Conference (GLOBECOM)*, Anaheim, CA, 2012, pp. 1532-1537.

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

[97] K. Samdanis, D. Kutscher and M. Brunner, "Self-organized energy efficient cellular networks," *21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Instanbul, 2010, pp. 1665-1670.

[98] R. Kwan, "Distributed Energy-Saving Mechanism for Self-Organizing Femto LTE Networks," *2012 IEEE Vehicular Technology Conference (VTC Fall)*, Quebec City, QC, 2012, pp. 1-5.

[99] V. Monteiro, T. Ramrekha, D. Yang, J. Rodriguez, S. Mumtaz and C. Politis, "An Energy Efficient Proposal in Shared Relay-Based LTE Network," *ISWCS 2013; The Tenth International Symposium on Wireless Communication Systems*, Ilmenau, Germany, 2013, pp. 1-5.

[100] G. Li, S. Jin, F. Zheng, X. Gao and X. Wang, "Energy Efficient Link Adaptation for Downlink Transmission of LTE/LTE-A Systems," *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, Las Vegas, NV, 2013, pp. 1-5.

[101] D. Ling, Z. Lu, W. Zheng, X. Wen and Y. Ju, "Energy efficient cross-layer resource allocation scheme based on potential games in LTE-A," *The 15th International Symposium on Wireless Personal Multimedia Communications*, Taipei, 2012, pp. 623-627.

[102] Y. Li, W. Liu, B. Cao and M. Li, "Green resource allocation in LTE system for unbalanced low load networks," *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)*, Sydney, NSW, 2012, pp. 1009-1014.

[103] S. Videv, H. Haas, J. S. Thompson and P. M. Grant, "Energy efficient resource allocation in wireless systems with control channel overhead," *2012 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, Paris, 2012, pp. 64-68.

[104] V. J. Kotagi, R. Thakur, S. Mishra and C. S. R. Murthy, "Breathe to Save Energy: Assigning Downlink Transmit Power and Resource Blocks to LTE Enabled IoT Networks," in *IEEE Communications Letters*, vol. 20, no. 8, pp. 1607-1610, Aug. 2016.

[105] C. C. Coskun and E. Ayanoglu, "Energy-Efficient Base Station Deployment in Heterogeneous Networks," in *IEEE Wireless Communications Letters*, vol. 3, no. 6, pp. 593-596, Dec. 2014.

[106] S. Videv and H. Haas, "Energy-Efficient Scheduling and Bandwidth-Energy Efficiency Trade-Off with Low Load," *2011 IEEE International Conference on Communications (ICC)*, Kyoto, 2011, pp. 1-5.

[107] F. Vaz, P. Sebastião, L. Gonçalves and A. Correia, "Femtocell deployment in LTE-A networks: A sustainability, economical and capacity analysis," *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, London, 2013, pp. 3423-3427.

[108] N. Zhang and H. Hämmäinen, "Cost efficiency of SDN in LTE-based mobile networks: Case Finland," *2015 International Conference and Workshops on Networked Systems (NetSys)*, Cottbus, 2015, pp. 1-5.

[109] B. Naudts, M. Kind, F. J. Westphal, S. Verbrugge, D. Colle and M. Pickavet, "Techno-economic Analysis of Software Defined Networking as Architecture for the Virtualization of a Mobile Network," *2012 European Workshop on Software Defined Networking*, Darmstadt, 2012, pp. 67-72.

[110] L. Chiaraviglio, W. Liu, J. A. Gutierrez and N. Blefari-Melazzi, "Optimal pricing strategy for 5G in rural areas with unmanned aerial vehicles and large cells," *2017 27th International Telecommunication Networks and Applications Conference (ITNAC)*, Melbourne, Australia, 2017, pp. 1-7.

[111] T. Smura, A. Kiiski, “Virtual operators in the mobile industry: a technoeconomic analysis,” *NETNOMICS: Econ. Research and Electron. Networking*, vol. 8, no. 1-2, pp. 25–48, 2007.

[112] S. Pattanavichai, N. Jongsawat and W. Premchaiswadi, "Real options analysis for valuing strategic investments and decisions of the Mobile Virtual Network Operator's

investment in E-UMTS," *2011 Ninth International Conference on ICT and Knowledge Engineering*, Bangkok, 2012, pp. 138-144.

[113] T. M. Knoll, "A combined CAPEX and OPEX cost model for LTE networks," *2014 16th International Telecommunications Network Strategy and Planning Symposium (Networks)*, Funchal, 2014, pp. 1-6.

[114] W. Guo, S. Wang, and T. O'Farrell, "Environmental and economically sustainable cellular networks", *Journal of Green Engineering, River Publishers*, Vol. 2, No. 3, April/May 2012, pp. 273-283

[115] D. Katsianis *et al.*, "The financial perspective of the mobile networks in Europe," in *IEEE Personal Communications*, vol. 8, no. 6, pp. 58-64, Dec 2001.

[116] 3GPP, "Digital cellular telecommunications system (Phase 2+); Universal Mobile Telecommunications System (UMTS); Handover procedures" TS 23.009, v.12.0.0.

[117]https://www.nt.tuwien.ac.at/research/mobile-communications/vccs/vienna-lte-a simulators/lte-a-downlink-system-level-simulator/

[118] 3GPP, "3rd Generation Partnership Project; Technical Specification Group Radio Access Networks; Radio Frequency (RF) system scenarios", TR 25.942 V9.0.0

[119] A. Gunther, B. Oliver, G. Vito and G. Istvan,. "Energy efficiency analysis of the reference systems, areas of improvements and target breakdown"*: EARTH, Energy Aware Radio Network Technologies* , v.2., December 31, 2010.

[120] W. Guo and T. O'Farrell, "Capacity-Energy-Cost Tradeoff in Small Cell Networks," *2012 IEEE 75th Vehicular Technology Conference (VTC Spring),* Yokohama, 2012, pp. 1-5.

[121] Johansson, R. Schwartz and Magnus, "Carrier WiFi Offload, Building a Business Case for Carrier WiFi ". *s.l. : Wireless 20|20, 2011,* March. available at www.wireless2020.com.

[122] K. Johansson, A. Furuskar, P. Karlsson and J. Zander, "Relation between base station characteristics and cost structure in cellular systems," *2004 IEEE 15th International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE Cat. No.04TH8754)*, 2004, pp. 2627-2631 Vol.4.

[123] C. S. Ranaweera, P. P. Iannone, K. N. Oikonomou, K. C. Reichmann and R. K. Sinha, "Design of cost-optimal passive optical networks for small cell backhaul using installed fibers [invited]," in *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 10, pp. A230-A239, Oct. 2013.

[124] https://www.ofcom.org.uk/consultations-and-statements/category-1/cbfframework

[125] https://www.edfenergy.com/large-business.

[126] G. Sammuel. Mobile Network Providers - *UK. london: MINTEL Oxygen*, 2011, March. http://academic.mintel.com/display/606100/#atom0.

[127] M. M. Khalili, L. Gao, J. Huang and B. H. Khalaj, "Incentive design and market evolution of mobile user-provided networks," *2015 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, Hong Kong, 2015, pp. 498-503.

[128]http://www.three.co.uk/Store/SIM/Plans_for_phones?intid=3main_homepage_SIM_banner

[129] L. Hanzo II, S. M. Mostafavi and R. Tafazolli, "Connectivity-Related Properties of Mobile Nodes Obeying the Random Walk and Random Waypoint Mobility Models," *VTC Spring 2008 - IEEE Vehicular Technology Conference*, Singapore, 2008, pp. 133-137.

[130] C. Bettstetter, G. Resta and P. Santi, "The node distribution of the random waypoint mobility model for wireless ad hoc networks," in *IEEE Transactions on Mobile Computing*, vol. 2, no. 3, pp. 257-269, July-Sept. 2003.

[131] T. Casey, D. Denieffe and G. M. Muntean, "Influence of mobile user velocity on data transfer in a multi-network wireless environment," *2007 9th IFIP International Conference on Mobile Wireless Communications Networks*, Cork, 2007, pp. 126-130.

[132] C. H. Kim, S. Jee, G. D. Jo, K. Lee and B. Kim, "A 2.14-GHz GaN MMIC Doherty Power Amplifier for Small-Cell Base Stations," in *IEEE Microwave and Wireless Components Letters*, vol. 24, no. 4, pp. 263-265, April 2014.

[133] www.parliament.uk/briefing-papers/sn05927.pdf

[134] D. A. Ciupăgeanu, G. Lăzăroiu and M. Tîrşu, "Carbon dioxide emissions reduction by renewable energy employment in Romania," *2017 International Conference on Electromechanical and Power Systems (SIELMEN)*, Iasi, 2017, pp. 281-285.

[135]https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

[136] N. Saxena, B. J. R. Sahu and Y. S. Han, "Traffic-Aware Energy Optimization in Green LTE Cellular Systems," in *IEEE Communications Letters*, vol. 18, no. 1, pp. 38-41, January 2014.

[137] 3GPP, "3rd Generation Partnership Project, Technical Specification Group Radio Access Network Evolved Universal Terrestrial Radio Access (E-UTRA), User Equipment (UE) procedures in idle mode", TS 36.304, Version 12.5.0, 2015-07.

[138] Y. Lang, S. Zhao and Y. Li, "Analysis and comparison of emission reduction effect of real-time electricity price considering carbon trading permits," *2017 International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Denpasar Bali, Indonesia, 2017, pp. 99-104.

[139] B. S. Palmintier and M. D. Webster, "Impact of Operational Flexibility on Electricity Generation Planning With Renewable and Carbon Targets," in *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 672-684, April 2016.

[140] S. Jin, X. Ma and W. Yue, "Energy-saving strategy for green cognitive radio networks with an LTE-advanced structure," in *Journal of Communications and Networks*, vol. 18, no. 4, pp. 610-618, Aug. 2016.

[141] J. Zhang, M. Wang, M. Hua, T. Xia, W. Yang and X. You, "LTE on License-Exempt Spectrum," in *IEEE Communications Surveys & Tutorials*, vol. PP, no. 99, pp. 1-1.

[142] R. Zoican, "Services offered by a packet-switched cellular IVHS with a single radio channel," *2000 10th Mediterranean Electrotechnical Conference. Information Technology and Electrotechnology for the Mediterranean Countries. Proceedings. MeleCon 2000 (Cat. No.00CH37099)*, Lemesos, 2000, pp. 370-373 vol.1.

[143] L. You, L. Lei and D. Yuan, "Optimizing power and user association for energy saving in load-coupled cooperative LTE," *2016 IEEE International Conference on Communications (ICC)*, Kuala Lumpur, 2016, pp. 1-6.

[144] G. Kalogridis and O. Georgiou, "CreD2D: A credit-driven self-evolving D2D towards LTE HetNet energy saving," *2016 IEEE International Conference on Communications Workshops (ICC)*, Kuala Lumpur, 2016, pp. 742-748.

[145] G. Auer *et al.*, "How much energy is needed to run a wireless network?," in *IEEE Wireless Communications*, vol. 18, no. 5, pp. 40-49, October 2011.

[146] Kai Liu, Jinwei He, Jiarui Ding, Yuanchao Zhu and Z. Liu, "Base station power model and application for energy efficient LTE," *2013 15th IEEE International Conference on Communication Technology*, Guilin, 2013, pp. 86-92.

[147] M. Jaber, Z. Dawy, N. Akl and E. Yaacoub, "Tutorial on LTE/LTE-A Cellular Network Dimensioning Using Iterative Statistical Analysis," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1355-1383, Secondquarter 2016.

[148] Maor. E, “A Theme and Variations,” *in The Pythagorean Theorem: A 4,000- Year History*. Princeton University Press, New Jersey, 1st edition, pp.123 – 130, 2007.

[149] J. Stańdo, G. Gwóźdź-Łukawska and J. Guncaga, "From the Pythagorean Theorem to the definition of the derivative function," *2012 International Conference on E-Learning and E-Technologies in Education (ICEEE)*, Lodz, 2012, pp. 54-58.

[150] John, R. Fanchi, "Geometry, Trigonometry, and Hyperbolic Functions," in *Math Refresher for Scientists and Engineers* , 1, Wiley-IEEE Press, 2006, pp.330-339.

[151] Y. Hu and G. Leus, "Self-Estimation of Path-Loss Exponent in Wireless Networks and Applications," in *IEEE Transactions on Vehicular Technology*, vol. 64, no. 11, pp. 5091-5102, Nov. 2015.

[152] I. Gohberg, T. Kailath and I. Koltracht, "A note on diagonal innovation matrices," in *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 35, no. 7, pp. 1068-1069, Jul 1987.

[153] https://www.gov.uk/speed-limits

[154] S. Barbera, K. Pedersen, P. H. Michaelsen and C. Rosa, "Mobility Analysis for Inter-Site Carrier Aggregation in LTE Heterogeneous Networks," *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, Las Vegas, NV, 2013, pp. 1-5.

[155] T. En, W. Ye, D. Fei, P. Zhiwen and Y. Xiaohu, "A practical eNB off/on based energy saving scheme for real LTE networks," *2015 17th International Conference on Advanced Communication Technology (ICACT)*, Seoul, 2015, pp. 12-17.

[156] F. Han, Z. Safar and K. J. R. Liu, "Energy-Efficient Base-Station Cooperative Operation with Guaranteed QoS," in *IEEE Transactions on Communications*, vol. 61, no. 8, pp. 3505-3517, August 2013.