Analytical Modelling for Quality of Service and Energy Efficiency of Small Scale Cellular Networks

Hadi Zahmatkesh

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Applied Mathematics and Computer Science

Eastern Mediterranean University
June 2017
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Mustafa Tümer
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Doctor of Philosophy in Applied Mathematics and Computer Science.

Prof. Dr. Nazim Mahmudov
Chair, Department of Mathematics

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Doctor of Philosophy in Applied Mathematics and Computer Science.

Asst. Prof. Dr. Mustafa Rıza
Supervisor

Examining Committee

1. Prof. Dr. Rashad Aliyev
2. Prof. Dr. Mehmet Ufuk Çağlayan
3. Prof. Dr. Celal Çeken
4. Assoc. Prof. Dr. Enver Ever
5. Asst. Prof. Dr. Mustafa Rıza

ABSTRACT

In recent years, with the rapid increase in the number of mobile-connected devices and mobile data traffic, mobile operators have been trying to find solutions to provide better coverage and capacity along with higher Quality of Service (QoS). One promising solution in this regard is deployment of small cells such as femtocells. This thesis presents performability analysis of small cells in terms of various performance metrics like throughput, Mean Queue Length (MQL), Response Time (RT), and energy consumption.

The model developed in this thesis considers mobility of the users, multiple channels (servers) for the small cells as well as failure and repair behavior of the channels (servers) since failure may also occur in the system. Numerical results are presented for the developed model by applying the spectral expansion solution approach for a typical scenario in smart-cities towards more green future Heterogeneous Network (HetNets). In this scenario a hybrid wireless cellular HetNet consisting of a macrocell and several small cells is considered as a case study in smart-cities.

In this work, simulations are also accomplished to confirm the accuracy of the findings obtained from the numerical solution approaches.

Keywords: Smart-cities, Small cells, Queuing theory, LTE, Cellular radio

ÖZ

Son yıllarda mobil bağlantılı cihazarın ve mobil data trafiğinin hızlı artışıyla, mobil hizmet sağlayıcıları daha geniş yanyın alanı ve kapasite artışıyla birlikte hizmet kalitesinin (HK) de artırılması için çözüm üretmeye çalışıyorlar. Bu bağlamda en umut verici çözümler femtocell gibi small cell uygulamaları görünüyor. Small cell uygulamları veri hacmi, ortalama sıra uzunluğu (OSU), yanıt süresi (YS), ve enerji tüketimi gibi performans ölçütleri bağlamında bu tezde incelenmektedir.

Bu tezde geliştirilen model kullanıcıların hareketini, small cell'ler için çok kanallılığı (sunucular), ve sistem'de de hata meydana geldiği için kanalların (sunucuların) hata ve onarım davranışını incelemektedir. Bu modelin spektral çözüm yöntemiyle gelecekteki yeşil heterojen ağlarda (HetAğ) tipik bir akıllı şehir senaryosuna uygulanıp nümerik sonuçları sunulumuştur. Sunulan senaryoda bir macro cell ve birkaç small cell den oluşan hibrid kablosuz hücresel HetAğ'ı akıllı şehirler için bir örnek çalışması yapılmıştır.

Bu çalışmada, simülasyonlar nümerik çözüm yöntemiyle bulunan sonuçların doğrulğunu desteklemektedir.

Anahtar Sözcükler: Akıllı Şehirler, Small Cell, Sıralama Teorisi, LTE, Gözesel Radyo

To My Family

ACKNOWLEDGMENT

First and foremost I would like to thank my supervisor Assist. Prof. Dr. Mustafa Rıza, for his continuous support and valuable suggestions and remarks throughout this study. His constructive and valuable guidance, and unlimited support and supervision helped me in every stage of my PhD studies at Eastern Mediterranean University.

I also would like to express my special appreciation and thanks to Assoc. Prof. Dr. Enver Ever for introducing me to this research area and for his countless feedbacks, enlightening comments, and outstanding supervision. This survey would have not been possible without his support, guidance, help, and precious contributions.

I am most grateful to Assoc. Prof. Dr. Fadi Al-Turjman who was very supportive and provided useful discussions throughout this research.

I also would like to thank all my friends who supported and encouraged me to endeavor to achieve my goal.

Last but not least, I am deeply grateful to my father, my mother, and my brothers and sisters for providing me with the opportunity to be where I am today. Without my family's love and unconditional support, this work would not have been possible. I would like to dedicate this study to my family for their love, patience and for standing next to me through this journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

5G	5th generation of mobile network
AMC	Adaptive Modulation and Coding
AP	Access Point
AWGN	Additive White Gaussian Noise
BAN	Body Area Network
BAS	Building Automation System
BS	Base Station
CAC	Call Admission Control
CSG	Closed Subscriber Group
D2D	Device-to-Device
DAS	Distributed Antenna System
FAP	Femtocell Access Point
FBS	Femtocell Base Station
FCFS	First Come First Served
FMC	Fixed Mobile Convergence
FPGA	Field Programmable Gate Array
GSM	Global System for Mobile Communications
HBS	Home Base Station
HetNet	Heterogeneous Network
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things

ISP	Internet Service Provider
LED	Light-Emitting Diode
Li-Fi	Light Fidelity
LTE	Long Term Evolution
LTE-A	LTE Advanced
M2M	Machine-to-Machine
MGM	Matrix Geometric Method
MQL	Mean Queue Length
MTU	Maximum Transmission Unit
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
RF	Radio Frequency
RT	Response Time
SIR	Signal-to-Interference Ratio
SINR	Signal-to-Interference plus Noise Ratio
SOHO	Small Office and Home Office
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UWB	Ultra-Wide Bandwidth
VLC	Visible Light Communication
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WSP	Wireless Service Provider

Chapter 1

INTRODUCTION

1.1 Introduction

Next generation of wireless networks includes different Radio Access Technologies (RATs) such as Global System for Mobile Communications (GSM), Universal Mobile Telecommunication System (UMTS), High Speed Packet Access (HSPA), Long Term Evolution (LTE), LTE-Advanced (LTE-A), Worldwide Interoperability for Microwave Access (WiMAX), Wireless Local Area Network (WLAN), etc. for users in order to connect them to the Internet. Mobile users prefer to be online anywhere and anytime which enable them to do online shopping, watch a movie online, download music, use the e-mail system and social networking applications such as Twitter, Instagram, Facebook, etc. and participate in video conferencing. Nowadays, with the rapid development in technology, mobile devices such as iPads, smartphones, tablets, etc. are easy to use and people can easily connect to the Internet anytime and anywhere. In other words, mobile users expect services at high quality levels. According to Cisco (Cisco, 2016), global mobile data traffic will encounter 8-fold growth from 2015 to 2020. It is also expected that the number of mobile connected-devices in 2020 will exceed the world's estimated population at that time (Cisco, 2016). Therefore, mobile operators have been searching for new solutions to deal with this explosive growth in mobile data traffic and the number of mobile-connected devices in terms of coverage and capacity. One promising solution in this regard is the deployment of small cells such as femtocells that is thoroughly covered in the next chapters. In this research project, performance and availability (performability) measures of femtocells are evaluated using two performance evaluation techniques (Ever et al., 2017).

1.2 Performance Evaluation Techniques

Nowadays, computer and communication systems are broadly used in various sectors such as research, industry, and business sectors. For instance, these systems are widely used in traffic monitoring systems, ticket reservation systems, patient monitoring systems, scientific researches, etc. With the rapid speed in technology advances and increase in the users' demands, the complexity of these systems also increases. Therefore, it would be more difficult to understand different characteristics of the systems and to rely on the results provided by these systems.

Performability analysis of communication and computer systems helps developers, researchers, and users to discover possible weaknesses of the systems in advance. Performance evaluation is also useful for understanding the influences of different factors on the performance of a communication system (Jain, 1991; Law and Kelton, 2000). According to Banks et al. (2005) and Jain (1991), performance and availability analysis of many systems plays a significant role in the success or failure of the systems.

Benchmarking, simulation and analytical modelling are three different approaches that are used for performance evaluation of communication systems (Jain, 1991; Banks et al., 2005). The technique which is performed by actual measurements is called benchmarking. Benchmarking gives precise results but it is only possible when there already exists something similar to the system under study. The other two performance evaluation techniques, analytical modelling and simulation, are quicker and more cost effective. According to Banks et al. (2005), the technique which is used to imitate, or simulates, the operations of a real-world system over time is called simulation. Results obtained by simulation technique are fairly precise but this technique requires high computation times (Law and Kelton, 2000). Similar to benchmarking, simulation is also an empirical approach which is costly and very expensive especially in terms of time.

Analytical modelling is a technique used to simulate behaviors of a system using mathematical concepts and language. Comparing to simulation, this approach is computationally more efficient (Banks et al., 2005; Law and Kelton, 2000). According to Jain (1991), Analytical modelling approach provides the best information for the different factors' effects and the interactions between them. This technique is broadly applied in computer science for performability evaluation of various communication systems. Analytical modelling is the best approach for fast and relatively accurate results once it is confirmed (Trivedi, 2002; Banks et al., 2005).

1.3 Scope of Investigation

In the present study, analytical modelling techniques are applied to model small cells as fault tolerant wireless communication systems in a scenario where a set of small cells are deployed within the coverage area of a macrocell. For more realistic performance measures, mobility of the users, multiple channels (servers), as well as failure and repair behavior of the channels (servers) are considered for small cells. Numerical results are demonstrated using spectral expansion method and analyzed in terms of various performance metrics like throughput, MQL, response time and energy consumption. Simulation as the second performance evaluation technique in this work is used to validate the accuracy of the analytical modelling approach.

1.4 Thesis Outline

The rest of this study is structured as follows. In Chapter 2, the background work related to the use of queuing networks in performance evaluation of wireless communication systems is reviewed. The importance of small cells, market opportunity, and application of small cells in the next generation of HetNets are outlined in Chapter 3. The proposed system model and the analytical solution approach are displayed in Chapters 4 and 5, respectively. In Chapter 6, a typical case study about mobile users under small cell coverage in smart-cities is presented. The numerical and simulation results for the case study mentioned in Chapter 6 are presented in Chapter 7. Eventually, Chapter 8 concludes this work and discusses some suggestions for future studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

For many years queuing theory has been utilized to model telecommunication systems (Marsan and Meo, 2014; Da Silva et al., 2012; Ambene and Anni, 2014). Based on the system and the goals of the analysis, various performance metrics such as average number of customers in the system, average queue length, average waiting time in the queue, average power consumption of the system, average utilization, throughput, etc. derived from queuing models (Marsan and Meo, 2014; Bolch et al., 2006). All these modelling approaches can be classified as follows: static, dynamic, and hybrid models. The static model is a model without considering mobile users in the system. In contrast to static models, dynamic models are those with mobile users in the system. In addition to static and dynamic models, hybrid models are formed from macrocell and small cells such as femtocells when considering the system. In static models such as the studies presented in Marsan and Meo (2014), Da Silva et al. (2012), Ever (2014), Borodakiy et al. (2014) and Gong et al. (2011), performance measures of wireless cellular networks have been studied without considering mobility in the system. Unlike static models, mobility as one of the most important issues in performance evaluation of wireless communication systems is considered in dynamic models (Kirsal et al., 2015; Kirsal et al., 2014; Baloch et al., 2010; Kirsal et al., 2012; Zeng and Agrawal, 2002). In addition, performance evaluation of hybrid cellular HetNets consisting of macrocell and femtocells has been investigated in Kumar et al. (2013), Kumar et al. (2014), El-atty and Gharsseldien (2015), Kong (2015), Ge et al. (2014) and Chowdhury and Jang (2013) using the concept of queuing theory as detailed in the following subsections.

2.2 Models With the Assumption of Static Users

Energy consumption of a campus WLAN is studied in Marsan and Meo (2014). The authors used a simple approximate queuing model to save energy in dense WLANs by considering sleep modes for Access Points (APs) and activation of APs based on the user demand. They finally proved that a considerable amount of energy used to power on a campus WLAN can be saved. They also showed that queuing models are an easy and effective way to analyze behaviors of the system.

Another similar study is presented by Da Silva et al. (2012) who demonstrated a set of algorithms to activate network resources based on the user demand rather than having always power on APs in dense WLANs. The main goal of the study is to decrease the energy consumption of the WLAN and to provide better service quality to the users. The results presented show that in a dense WLAN, a substantial amount of energy can be preserved by using sleep modes for a section of the APs when the number of users connected to the network is small.

In the study presented by Ever (2014), a new approach is presented to model computer and communication networks using two stage open queuing systems. Multiple servers, blocking, and failures at both stages are considered in the study and performance measures like MQL and blocking probability are then calculated. Numerical results are acquired by using spectral expansion solution approach for two-dimensional Markov processes. Simulation is applied as well in order to validate the accuracy of the analytical model presented.

An admission control problem for a multi-service LTE radio network is addressed by Borodakiy et al. (2014). The authors propose a model for video on demand and video conferencing services which are resource demanding video services. Teletraffic and queuing theories are applied by the authors to obtain a recursive algorithm in order to calculate performance measures of interest such as mean bit rate, and pre-emption probability.

In the research conducted by Gong et al. (2011), a queuing analysis of Adaptive Modulation and Coding (AMC) systems with sleep mode is proposed. An algorithm is then obtained to enhance the energy efficiency of the system. Numerical results obtained by analyzing the consumed energy per packet, the packet loss rate, and the average delay show that using sleep mode to the AMC system remarkably improves the energy efficiency when the traffic range is low.

In all the aforementioned studies, mobility as one of the key factors in performance evaluation of wireless communication systems was ignored which dramatically can affect the performance of the system under study.

2.3 Models With Mobile Users

In (Kirsal et al., 2015), an integrated heterogeneous wireless system consisted of the cellular system and WLAN is modelled applying two-stage open queuing systems for highly mobile users. The analysis of the system is performed using guard channel and buffering to obtain high levels of QoS in heterogeneous environments. Spectral expansion solution approach is employed to give an exact analytical solution of the system. The results presented are beneficial for vertical handover decision management in such an integrated cellular/WLAN system.

A similar approach to model an integrated cellular/WLAN system is presented in (Kirsal et al., 2014). In this study, performance characteristics of the system such as MQL, blocking probability, and throughput are studied by modelling the system as a two-stage open queuing network. Numerical results are presented using spectral expansion solution approach. Computer simulation confirmed that the results acquired by the analytical model are accurate. Another similar approach to model an integrated heterogeneous wireless system such as cellular/WLAN system is presented in (Kirsal et al., 2012).

Wireless communication systems may experience failure as a result of many different factors such as human error, hardware, software, or a mixture of the mentioned factors (Ma et al., 2001; Selim et al., 2016). Wireless communication systems with failure and recovery are modelled in (Kirsal and Gemikonakli, 2009) using a Markov reward model. An S-channel per cell in homogeneous cellular network is considered in the system. The authors also consider mobility in the system as one of the main issues in performance evaluation of wireless communication systems. An analytical model is used to present some performance measures of the system such as MQL and blocking probability.

In the study conducted by Baloch et al. (2010), an analytical model is presented to carry out research on complete and partial channel allocation schemes. Markov models based on shared channels are employed to present the results for performance characteristics of the system such as MQL and blocking probability.

The authors in (Zeng and Agrawal, 2002) suggested and analyzed two handoff schemes with and without preemptive priority procedures for integrated wireless mobile networks. They classified the service calls into the following four different types: originating voice calls, originating data calls, voice handoff request calls, and data handoff request calls. The system is modelled using a three-dimensional Markov chain and performance of the system is analyzed in terms of the following performance measures: average transmission delay of data calls, blocking probability of originating calls, and forced termination probability of voice handoff requests. The findings presented show that if the number of reserved channels for handoff request calls increases, forced termination probability of voice handoff requests can be reduced.

2.4 Hybrid HetNet Modelling

The authors in (Kumar et al., 2013) demonstrated a detailed queuing model of a hybrid cellular system consisting of a macrocell and several femtocells. They modelled the system using an M/M/1 queue and then used Matrix Geometric Method (MGM) to solve the network model. They finally analyzed the system performance in terms of power savings and average system delay. The authors then extended their work in (Kumar et al., 2013) and analyzed the system using a finite capacity queuing system in (Kumar et al., 2014).

In (Kumar et al, 2014), a hybrid cellular network of a macrocell and femtocells is considered. Performance characteristics of the system such as packet blocking probability, average packet delay, and utilization for different buffer sizes are analyzed using a finite capacity queuing model (M/M/1/K). The results presented show that for a system similar to the one under study, traffic intensity and buffer size, highly affect the mentioned QoS parameters.

Together with the concept of the adaptive reserved channel, an adaptive Call Admission Control (CAC) policy is presented in (El-atty and Gharsseldien, 2015) to achieve QoS requirements for handover traffics in a system where femtocell technology is integrated with the macrocellular networks. This integration helps mobile operators to decrease the traffic load of macrocells and consequently reduce blocking probability (El-atty and Gharsseldien, 2015). In this study, a teletraffic model is presented together with the queuing theory concepts and Markov chains for analyzing the performance measures of the integrated femtocell/macrocell networks in terms of the blocking probability of new calls and failure probability of handover traffics.

A two-tier cellular HetNet comprised of macrocell and femtocells is considered in (Kong, 2015; Ge et al., 2014). In (Kong, 2015), a two-dimensional Markov chain model is presented to find out the average packet delay of mobile users as a function of traffic arrival rate in a two-tier cellular HetNet. Numerical results which have been also validated by simulation show that minimum packet delay is obtained by finding suitable femtocell density using the proposed model.

Performance characteristics of 2-tier femtocell networks are also studied in (Ge et al., 2014). In their study, a Markov chain model is used to analyze some important performance measures in the system such as user blocking probability in a macrocell and the blocking probabilities of femtocell and macrocell users in a macrocell. In addition, the authors also propose energy and spectrum efficiency models of the system. Simulation results reveal the effects of key parameters on the 2-tier femtocell networks. These parameters include the number of femtocells deployed in a macrocell, the number of femtocell users, and the number of open or closed channels in a femtocell. The proposed energy efficiency model can also be applied to specify the number of deployed femtocells in a macrocell.

Mobility management is one of the main issues in the integration of femtocell technology with the current macrocell networks (Chowdhury and Jang, 2013). In (Chowdhury and Jang, 2013), a Markov chain model is developed for the queuing analysis of femtocell and macrocell layers of the integrated femtocell/macrocell networks. An algorithm is proposed by the authors to make a neighbor cell list with the most suitable number of cells for handover. The results presented show that mobility management is significant issue in the deployment of dense femto-cellular networks.

In this thesis, unlike the studies in the literature, an analytical modelling approach is presented which is capable of considering various workloads, ranges, mobility-related issues, as well as the availability of channels (servers) in femtocell infrastructure. To the best of our knowledge, this study is the first two-dimensional modelling attempt with exact solution and high accuracy as well as efficacy. The modelling approach in this thesis can be quite useful in discovering the operational space of different femtocell configurations. Femtocell systems with channel failures (Morrison and Huber, 2010; Lopez-Perez et al., 2012) or with partially open channels (Ge et al., 2014) can be considered for traditional performance measures as well as the expected value of energy consumed together with channel availabilities by using the approach presented in this thesis.

2.5 The Contributions

In research works carried out in (Da Silva et al., 2012; Marsan and Meo, 2014; Bolch et al., 2006; Borodakiy et al., 2014; Gong et al., 2011), performance measures of the wireless communication system under study are investigated with the assumption of static users, and mobility as one of the most significant issues in performance evaluation of wireless networks (Kirsal and Gemikonakli, 2009) is not taken into account. Please note that ignoring the mobile users which may leave the system not because they have received service successfully, but instead due to mobility, can cause misleading QoS measurements. Although, the works presented in studies such as (Kirsal et al., 2015; Kirsal et al., 2014; Baloch et al., 2010; Kirsal et al., 2012; Zeng and Agrawal, 2002) investigated performance measures of the system by considering mobility of the mobile users, none of the aforementioned studies have considered the effects of different velocity of the mobile users on the system performance. This is an important issue in any HetNet setup because mobile users with higher velocity will perform handover to the neighboring cells in a shorter time period compared to the mobile users with lower velocity. Therefore, although there are similar studies considering queuing related issues of similar wireless communication systems, in this thesis, we considered users which can leave the system while accommodated in the queue due to mobility. Furthermore, for a more realistic presentation, different velocities of mobile users are considered and their effects on the performance characteristics of the system such as MQL, throughput, and response time are investigated.

The works presented in (Kumar et al., 2013; Kumar et al., 2014; El-atty and Gharsseldien, 2015; Kong, 2015; Ge et al., 2014; Chowdhury and Jang, 2013) consider HetNets consisting of macrocell and femtocells which is similar to the system under study in the current thesis. In (Kumar et al, 2013) a simple M/M/1 model is employed to represent the transmission of data traffic in femtocell networks. A single channel wireless communication system is used as model. The server considered may be available at a given time or may be on vacation. In order to solve the resulting two-dimensional Markov process, MGM is employed which is the main competitor to spectral expansion solution employed in this study. Apart from reducing the number of channels to one, (Kumar et al., 2013) also overlooks the potential unavailability of the channels. In other words, the fault tolerant nature of wireless communication systems is not considered. Therefore, even for modelling single channel communication systems, the results presented for performance evaluation (average response time is presented), which is an essential part for QoS of femtocells are optimistic. Instead, in our study, the models presented can consider single or multi-channel systems in presence of channel unavailability. Therefore, comparing the QoS together with the energy efficiency of femtocell systems is performed in a much more realistic way.

In (Kumar et al., 2014), an M/M/1/K queue model is applied to represent the transmission of data to a femtocell access point in uplink. Unlike our model, the model employed in (Kumar et al., 2014) limits the system to have only one channel and ignores the potential unavailability of the channel which is quite common in wireless communication systems (Ever et al., 2013). Similarly in (El-atty and Gharsseldien, 2015; Kong, 2015; Ge et al., 2014; Chowdhury and Jang, 2013) potential unavailability of the channels is not considered in performance evaluation of the HetNet of macrocell and femtocells which makes the results unrealistic since wireless communication systems tend to be prone to failures due to many different factors like human error, hardware, software and/or a mixture of the mentioned factors as discussed in (Ma et al., 2001; Selim et al., 2016).

In (Morrison and Huber, 2010; Lopez-Perez et al., 2012) channel failures are discussed as one of the different sources that can lead to handover failures in HetNets. Using our approach, these systems can be utilized to analyze different performance metrics such as throughput, MQL, and Response Time (RT) as well as expected value of energy consumption in presence of channel failures. Therefore, the contributions of our study can be summarized as follows:

- An analytical approach is presented by considering different traffic loads, ranges, mobility, as well as channel availability in small cell infrastructure.

- While considering mobility-related issues, the effect of velocity of mobile users on the performance of the system is investigated by categorizing the state of mobile users into low, medium, and high mobile states.

- To the best of our knowledge, the present study is the first two-dimensional modelling attempt of small cell infrastructure where the effects of mobility and the fault tolerant nature are considered with the exact solution, high accuracy, and efficacy.

- Our approach can be used by other small cell systems with channel failures (Morrison and Huber, 2010; Lopez-Perez et al., 2012) or with partially open channels (Ge et al., 2014) to investigate traditional performance measures of wireless systems such as MQL, throughput, and response time.

Chapter 3

CHARACTERISTICS OF SMALL SCALE CELLULAR NETWORKS

3.1 Introduction

Globally, mobile data traffic has approximately doubled in each of the recent years and there are strong evidences that this trend will continue. Such a growth is a result of the increase in the number of mobile connected devices as well as the average amount of data information incurred by the devices of each mobile user. To deal with the huge demand for mobile data traffic in the coming years, mobile network operators are now facing with the challenge of having to increase the capacity of mobile access networks by 1000 times (Ngo and Le-Ngoc, 2014). One of the promising solution in this regard is deployment of small cells in conjunction with the existing large cells such macrocells (Ngo and Le-Ngoc, 2014).

There are different types of small cells. Each cell has a limited size which is determined by the maximum range at which the receiver and the transmitter can successfully hear each other. Each cell also has a limited capacity which is the maximum combined data rate of all the mobiles in the cell. These limits result in the existence of different types of cell (Cox, 2012). *Microcells* have a size of a few hundred meters and provide a better capacity that is suitable for densely populated urban areas. *Picocells* are used in large indoor environments such as shopping malls and office buildings and have a size of a few tens of meters. Another type of small cell is femtocell which a cell that provides cellular coverage and is served using a Femtocell Base Station (FBS). FBSs are typically installed in indoor environments to supply better mobile coverage and capacity (Chandrasekhar et al., 2008; Boccuzzi and Ruggiero, 2010). Based on Zhang and De la Roche (2010), providing suitable indoor coverage is a major challenge for mobile operators since in cellular networks it is calculated that over 60% of calls and 90% of data traffics are generated in indoor environments. Femtocells are considered to be promising for providing good indoor coverage. A typical and conventional way to provide indoor coverage is to use outdoor macrocells. Such approach has a number of disadvantages as listed below (Zhang and De la Roche, 2010):

- It is quite costly to supply indoor coverage via applying an approach which is considered to be an 'outside-in' approach. For instance, an indoor user in UMTS may need higher level of power drain from the Base Station (BS) in order to successfully control high penetration loss. This will lead to fewer powers to be used by other users and therefore result in decreased cell throughput. This is due to the fact that the power used by indoor users is inefficient in terms of providing capacity, and capacity in UMTS is related to the power. Therefore, using an 'outside in' solution to provide indoor coverage will be more costly compared to using an indoor approach.

- A lot of outdoor BS sites are needed for a high capacity network which makes deployment strategies very challenging in heavily populated areas.

- Because of the interference and higher power drains from BSs to provide services to indoor users from outdoor macrocells, it is less possible to use an 'outside in' approach to build a high capacity network.

- In the dense deployment of the cell sites, the planning and optimization of the network will be a big challenge.

- There would be no guaranty in indoor network performance especially in the side which is not facing the macrocell sites. Higher modulation and coding schemes are required to obtain enhanced data rates. These schemes in LTE, High Speed Downlink Packet Access (HSDPA), and WiMAX need better channel conditions that may only be satisfied close to those sides facing macrocell sites.

Therefore, indoor approaches are better solutions to provide indoor coverage. These solutions such as Distributed Antenna System (DAS) and picocells are deployed by operators in public places such as shopping malls and business centers to offload traffic from outdoor macrocells, improve indoor coverage, and enhance QoS. Using indoor approaches, the orthogonality in UMTS can be enhanced which will cause increased throughput. The aforementioned indoor solutions are more cost effective compared to ‘outside in’ approaches such as outdoor macrocells in providing indoor coverage. However, these solutions are still too costly to be utilized for personal communications and entertaining for home users, as well as in scenarios like Small Office and Home Office (SOHO). Recently, low-cost indoor solutions are provided with the development of femtocells for such scenarios. In addition, many mobile operators have recently started using FBSs in outdoor environments in rural and densely populated areas as well as in public transportation vehicles such as busses, and trains to offload mobile traffic from loaded macrocell networks (Haider et al., 2011; Qutqut et al., 2013). From the operators’ point of view, deployment of femtocells will also decline the requirement of adding expensive macro BS towers

(Chandrasekhar et al., 2008).

3.2 Why Are Small Cells Important?

With deployment of small cells, more users can be packed into a given area on the same radio spectrum which allows for a greater area spectral efficiency. Also, because of the shorter distance between UEs and the serving BSs, these devices can lower their transmit power while still achieving a high SINR. Another benefit of deployment of small cells is that they can reduce the load of macrocells so that macrocells can dedicate radio resources to provide better services to their own users (Ngo and Le-Ngoc, 2014).

For instance, femtocell is very important in many different aspects (Zhang and De la Roche, 2010). Some of them are listed as below:

- Femtocell is able to provide indoor coverage in locations where macrocells cannot.
- Femtocell can offload traffic from loaded macrocells to provide indoor coverage and enhance the capacity of the macrocells.
- Significant power savings can be achieved for User Equipment (UE) by using femtocells.
- Femtocell Access Points (FAPs) need to be turned on when the users are at home in the case of the home femtocell (or at work in the case of enterprise femtocells), therefore, using femtocell is much greener than macrocells.
- A perfect solution for Fixed Mobile Convergence (FMC) can be provided by femtocells.
- Femtocell is a significant part of mobile broadband and ubiquitous communications.

3.3 Small Cell Market Opportunity

Small cells create an exciting and promising market opportunity for Wireless Service Providers (WSPs) who have the benefits from the new services as well as increased macrocell user satisfaction as a result of traffic offloading. The delivery of services through small cells such as femtocells affects on the economics of the services for WSPs in different aspects such as decreasing cost, increasing revenue, reducing energy consumption, and increasing the speed of deployment (Saunders et al., 2009).

Economic growth of IoT-based services is fairly large for businesses as well. For example, healthcare applications and other Internet of Things (IoT) based services such as mobile health (m-health) together with small cells can be used to monitor a set of medical parameters in elder people such as blood pressure, body temperature, and heart rate and also enable medical wellness and treatment services to be efficiently delivered using electronic media. These application and services are expected to have annual growth of \$1.1 – \$2.5 trillion by the global economy by 2025 (Manyika et al., 2013).

Moreover, small cells play a significant role in smart homes to build a system that efficiently monitors a house’s temperature, humidity, light, etc. and also to have a Building Automation System (BAS). According to a report (Navigant Consulting Res, 2013), the BAS’s market is expected to attain \$100.8 billion by 2021 which is a 60% increase compared to 2013.

All these statistics reveals a potential of significant growth of the IoT-based applications and services in the near future. It requires that Internet Service Providers (ISPs) to provide networks which have the capability to support Machine-to-Machine

(M2M) traffics in order to make IoT a reality. In addition, it provides a great opportunity for equipment manufacturers to transform into “smart products”.

3.4 Small Cell Communication Technologies

A significant part of IoT traffic is generated in indoor environments (Yaacoub, 2016) and is designed over cellular technologies (The Voice of 5G for the Americas, 2015). Data from smart devices (e.g. electricity smart meters and water smart meters), from home’s monitoring sensors (e.g. to control temperature, humidity, light, and pollution level inside a building), etc. are a few examples of these traffics. As mentioned earlier, IoT traffic can also be generated from m-health applications which are gathering data of elderly people and transferring them into health centers (Bisio et al., 2015). In this regard, small cells may be utilized to deal with these indoor traffics and decrease the load of macro BSs to meet QoS requirements of indoor users.

There are multiple IoT devices available in indoor environments. These devices include electricity-, water-, and gas- smart meters, home’s monitoring sensors, and Body Area Networks (BANs) created by sensors to control elderly people’s health parameters such as blood pressure, temperature, and heart rate for m-health applications. Examples of communication technologies that these IoT devices use to communicate with the network are Bluetooth, Wi-Fi, ZigBee, Ultra-Wide Bandwidth (UWB), LTE-A, and Light Fidelity (Li-Fi). With the development and existence of the fifth generation of mobile network (5G) and the expected increase in the number of IoT devices, these devices, using cellular technology, can communicate with small cell BSs such as FAPs. Figure 3.1 shows several indoor IoT devices which are in communication with an FAP. For example, in the case of BAN, the sensors use the technologies such as Bluetooth, Wi-Fi, or ZigBee to communicate with the smartphone of the patient and then the smartphone communicates with the FAP. With the LTE-A, it may happen by Device-to-Device (D2D) communications. Other devices in Figure 3.1 such as mobile phones and laptops can directly communicate with the FAP. This allows these IoT devices to make profits from 5G features which guaranty high levels of QoS and provides wireless connectivity in indoor environment without any extra costs. This is because the communication between an FAP and IoT devices can be free of charge (Yaacoub, 2016).

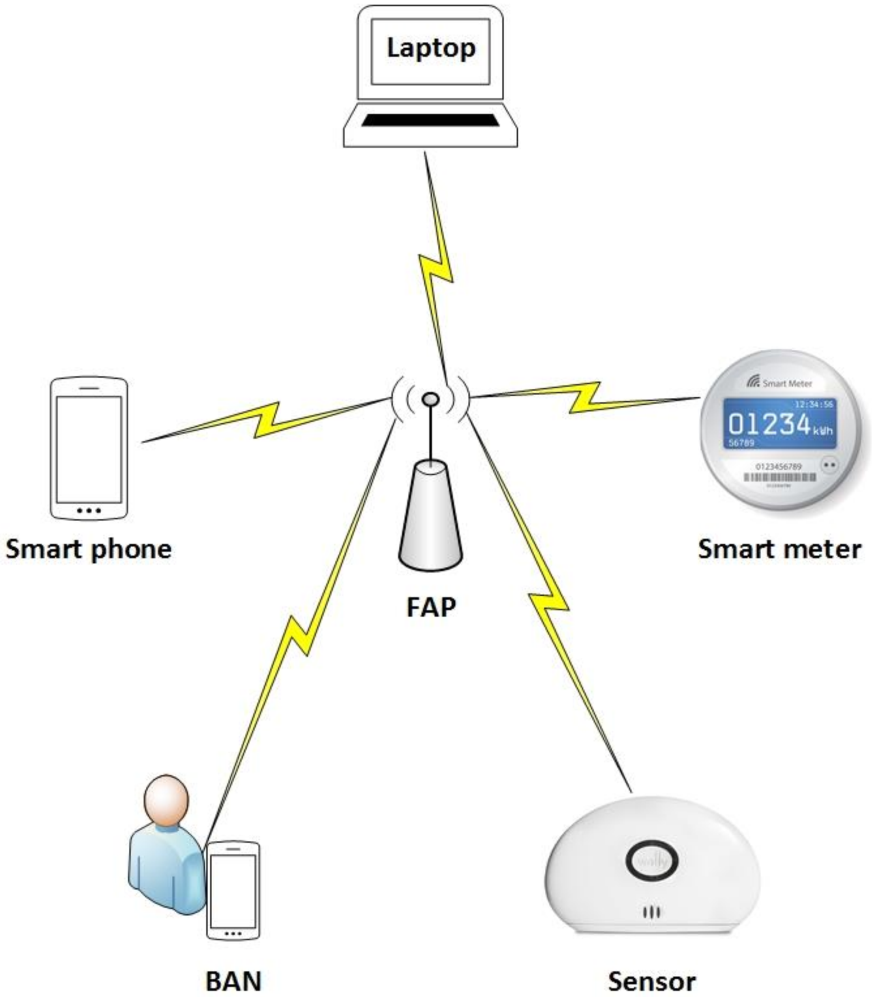


Figure 3.1: Communication of multiple IoT devices with an FAP

Wi-Fi is a communication technology which is utilized to exchange information between devices within a range of up to 100 meters using radio waves (Ferro and

Potorti, 2005). It allows devices to exchange data in an ad-hoc configuration manner without using a router. Bluetooth is another communication technology which uses short wavelength radio to exchange information between devices in short distances in order to reduce power consumption (McDermott-Wells, 2004). Long-Term Evolution (LTE) is a communication technology which is originally used for high speed transfer between mobile devices based on GSM/UMTS (Crosby and Vafa, 2013). Enhanced version of LTE is called LTE-A which supports higher bandwidth up to 100 MHz, and provides enhanced coverage, higher throughput, and lower latencies. The ZigBee is a communication technology designed and created for wireless controls and sensors and is based on IEEE 802.15.4 standard. It allows smart devices to communicate within a range of typically 50 meters and is designed to provide low data rate and low power consumption communication (Kinney, 2003). The UWB is another communication technology that supports communication between devices within a low range coverage area using high bandwidth and low energy (Kshetrimayum, 2009). Li-Fi is a cost-effective and alternative communication technology that was introduced to improve the limitations of Wi-Fi technology. Li-Fi uses Visible Light Communication (VLC) and Light-Emitting Diode (LED) concept for data communications (Singh and Singh, 2014). The concept of small cells such as femtocells can easily be extended to VLC in order to successfully mitigate the high interference of Radio Frequency (RF) spectrum in HetNets (López et al., 2011). Details of the working Li-Fi using femtocells can be found in (Singh and Singh, 2014).

3.5 Small Cell Technologies and Deployments

The technologies used in small cells such as femtocells are the same as cellular networks. The main idea behind small cells is to offload traffic from loaded macrocells and provide higher data rates indoors. A typical heterogeneous small cell network is shown in Figure 3.2. With the purpose of providing services to the end users in a network containing small cell BSs such as FBSs, it is really important to determine the proper location of the FBSs (Mahmud et al., 2013). The deployment of small cells brings a number of changes in the architecture of the current macro-cellular networks and creates new design challenges. The problem of interference in telecommunication systems can be considered as one of the critical challenges (Valcarce and López Pérez, 2010). Therefore, it is vital to have proper strategies and algorithms for the deployment of small cells in the current macro-cellular networks. These strategies can be classified into random, deterministic, and hybrid strategy. In random deployment strategy, small cells are randomly located within the coverage area of the larger cellular network (Valcarce and López Pérez, 2010). For instance, in the case of Home Base Stations (HBSs), they are randomly placed within the coverage area of a macrocell so it will provide higher spectrum efficiency and better coverage in the areas that are not completely covered by the macrocell. However, it is needed to apply interference cancellation/avoidance techniques in order not to have disruption of services in the vicinity of a femtocell (Valcarce and López Pérez, 2010).

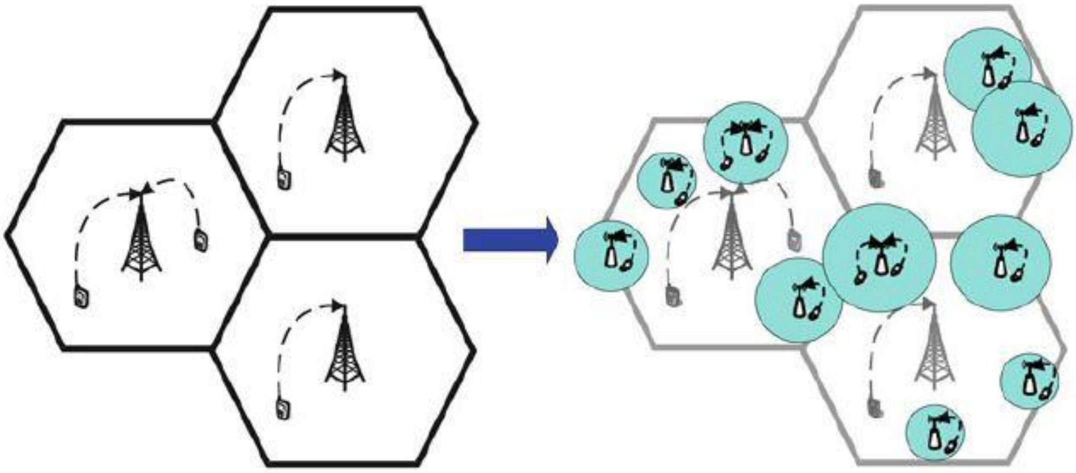


Figure 3.2: From homogeneous networks to heterogeneous small cell networks

Unlike random deployment strategy, in deterministic deployment, position of small cell is not randomly selected and is determined based on different criteria such as path loss (Ji et al., 2002; Jain et al., 2013), Signal-to-Interference Ratio (SIR) statistics (Wang et al., 2012; Ngadiman et al., 2005), controlling the transmission power and radio resource management between the FAP and the outdoor cell-site (Fagen et al., 2008; Ashraf et al., 2010), combination of path loss, SIR statistics, and cell overlapping (Avilés et al., 2015), geometrical segmentation of macrocell, heuristic levels of traffic intensity and user distribution (Emelianova et al., 2012), resource allocation scheme (Ahmed et al., 2014), and interference and its impact on capacity, coverage, and handover (Qutqut et al., 2014; Claussen et al., 2008).

In the hybrid deployment of small cells, both random and deterministic deployment types are employed where randomly available small cells are utilized as hotspots in addition to those which have been deterministically deployed at the beginning based on the cellular network operational conditions such as Siemens e-mobility project.

3.6 Small Cell Access Type

In small cell networks, the number of handovers depends on many different factors and one of them is access type. The choices of access mode highly depend on the cellular user density, with both owner and operator preferences (Khalifah et al., 2014). For example, there are three different access mode in femtocell networks: open, closed, and hybrid. The comparison of theses modes can be seen in Table 3.1.

Open Access: In open access mode, all accessible resources are shared between users and everyone can connect the network. It provides better network performance in terms of throughput and QoS (Claussen, 2007) but the number of handovers is very high since they are deployed in public areas such as shopping malls and airports, and there is no restriction to connect the network.

Table 3.1: Comparison of Femtocell Access Types (Khalifah et al., 2014)

	Open Access	**Closed Access**	**Hybrid Access**
Deployment	Public places	Residential deployment	Enterprise deployment
No. of handovers	High	Small	Medium
Provider Cost	Inexpensive	Expensive	Expensive
Owner preference	No	Yes	Yes
High user densities	No	Yes	Yes
QoS	Low	High	High
Femto-to-macro interference	Increase	Decrease	Decrease

Closed Access: In closed access mode, only Closed Subscriber Group (CSG) users can connect the network but there can be different service levels between users. In this mode, the femtocell owner does not want to share the femtocell because of some security reasons or because of the limited source of the backhaul. Therefore, based on Zhang and De la Roche (2010), any UE which is not in the CSG would be rejected by the femtocell. The number of handovers is very low in closed access mode since they are mainly used in individual home deployment.

Hybrid Access: Hybrid (or semi-open) access mode merges open and closed access modes so that it permits specific outside users to access a femtocell. However, the conditions to connect the femtocell by a user from outside of the CSG are defined by the operator and new entries to the system are requested by the owner (Zahir et al., 2013). These users (non-CSG) can get only limited services depending on the operator management (Wu, 2011). In hybrid (or semi-open) access mode, the number of handovers are less than open access mode but more than closed access mode. Vodafone Group (2008) provide more information regarding hybrid access.

3.7 Small Cell Applications

Small cell technology is one of the main components in the HetNet deployments (Haider et al., 2016). Many applications can be enabled by deployment of small cells to provide better coverage and capacity as well as to reduce traffic loads from the macrocell layer. For example, in heterogeneous cellular networks, deployment of small cells such as microcells and picocells along with the macrocell improves the throughput and spectral efficiency of the network with least cost (Pal et al., 2016; Okino et al., 2011). One of the main usages of the small cells is in indoor environments such as a home or office buildings to improve indoor coverage. For example, indoor femtocells significantly decrease penetration loss and packet loss due to the fact that receivers and transmitters are close to each other. Therefore, energy consumption can be effectively reduced (Feng et al., 2013). Femtocells can also be deployed in indoor public places like shopping malls or airports to enhance users' internet experience. Nowadays, electronic health (e-health) monitoring systems are becoming more popular since they can provide instant information about physical and psychological fitness while being far from a health center (De and Mukherjee, 2014; Mukherjee and De, 2014). For example, according to Mukherjee and De (2014), significant reduction in power consumption can be achieved by deployment of small cells especially femtocells. Small cell technology together with other relevant technologies can be used in order to utilize e-health monitoring systems. For instance, femtocell implementation of an intelligent hybrid sensor network is shown in Figure 3.3 in which body sensors control various parameters of the patient such as temperature and heart rate.

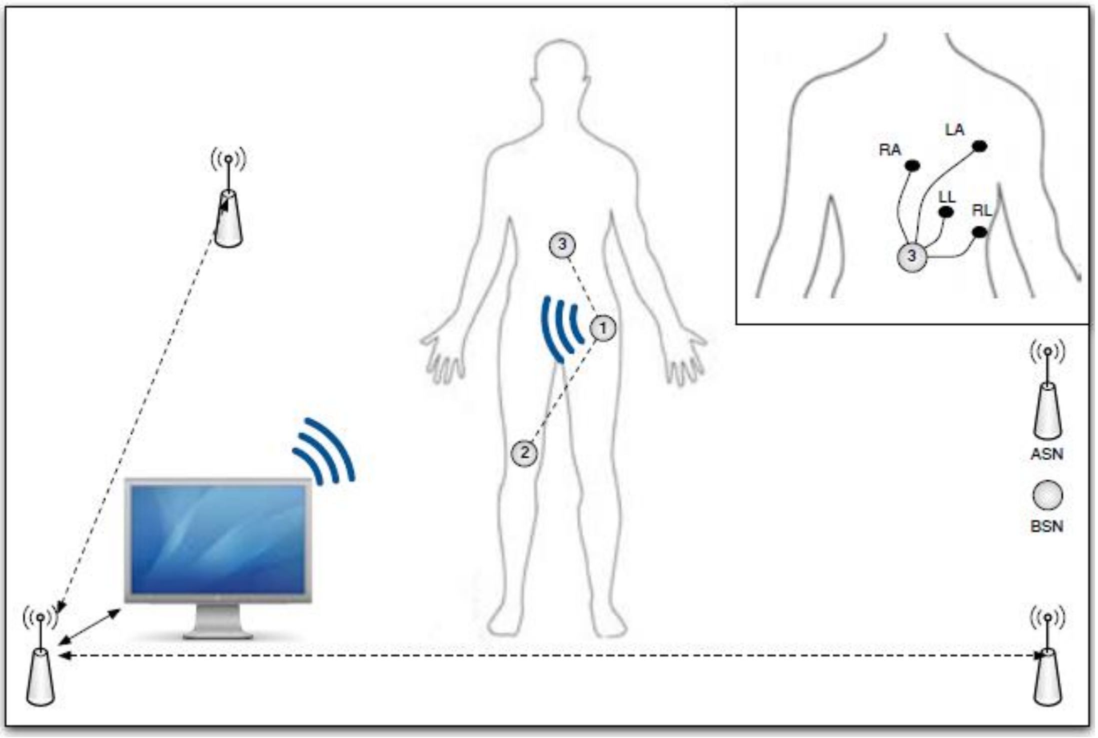


Figure 3.3: Femtocell implementation of intelligent hybrid sensor network

Picocells can also be utilized in e-health monitoring systems. For instance, Figure 3.4 shows a picocell-based telemedicine health service for human UX/UI which is based on sensor network and biomedical technology to overcome the spatial limitations of hospital-oriented medical services in order to improve user satisfactions (Park et al., 2015).

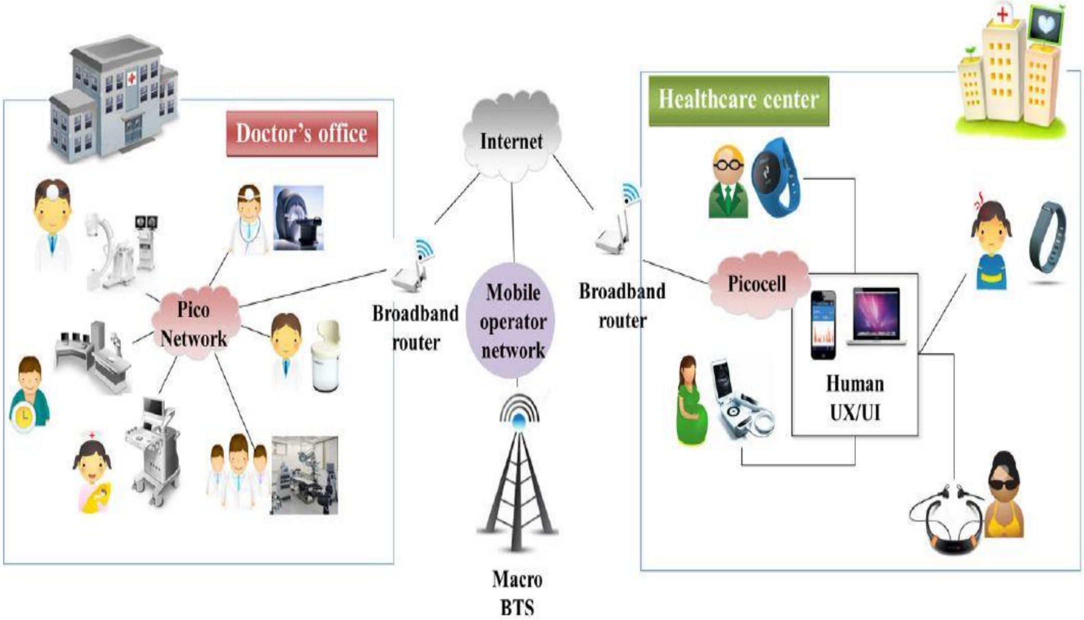


Figure 3.4: Picocell-based telemedicine health service for human UX/UI

Another usage of small cells can be in outdoor environments. For example, small cells such as femtocells can be deployed in public transportation vehicles such as busses (Qutqut et al., 2013) and trains (Zhang et al., 2015) to enhance coverage and provide better internet experience for the users while on the move. An example of utilizing femtocell in public transportation vehicles is shown in Figure 3.5. In smart cities, a broad range of services will be available to users. These services include e-commerce, e-health, e-banking, e-government, intelligent transportation systems, etc. Therefore, mobile users have to support increased coverage and excellent QoS. In this regard, small cells play a significant role in any smart-cities project.

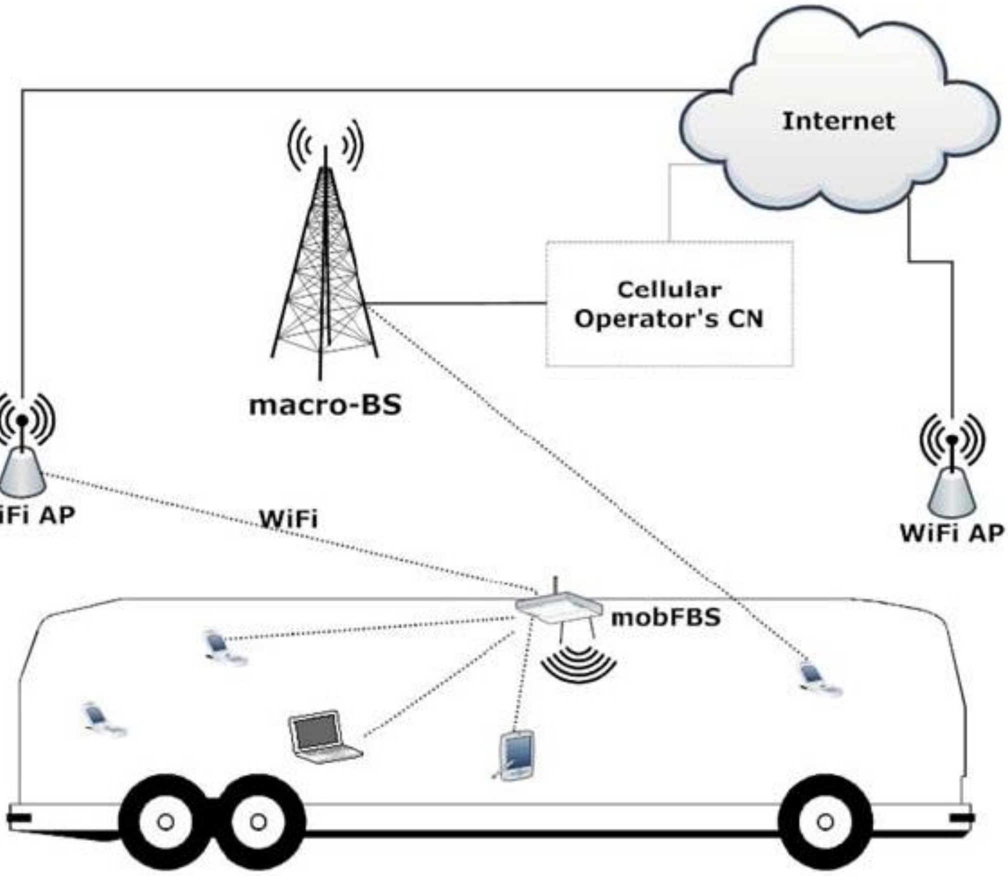


Figure 3.5: Mobile femtocell utilizing Wi-Fi (Qutqut et al., 2013)

Chapter 4

GENERIC SMALL CELL SYSTEM MODEL

4.1 Introduction

In the current chapter, a model is proposed for performance evaluation of a cellular HetNet composed of a macrocell and small cells. Due to explosive growth in the number of connected devices, mobile data traffics, and consumed energy in the current mobile HetNet as well as enormous arrival rates from static or mobile users, deployment and availability of small cells such as femtocells in buildings and roads of smart-cities will enhance coverage and capacity and provide higher QoS to mobile users. In this study, the system is similar to the system considered in (Kong, 2015; Ge et al., 2014; Chowdhury and Jang, 2013). A set of small cells is deployed within the coverage area of a macrocell as demonstrated in Figure 4.1. The incoming requests can be originating from within the small cell, or can be handed over from the macrocell (or other small cells). A queuing system is used to model the proposed system where small cell channels (servers) are subject to failures, and the requests may leave the system because of the mobility of the mobile users. The queuing system under study is represented in Figure 4.2. Please consider that in this study, there are no failures associated with macrocells. In the proposed model, there are N identical channels (servers) available in each small cell. Requests to the small cells are assumed to arrive independently following Poisson distribution similar to the studies in (Alnabelsi and Kamal, 2012; Beigy and Meybodi, 2015; Kirsal et al., 2015; El Bouabidi et al., 2014).

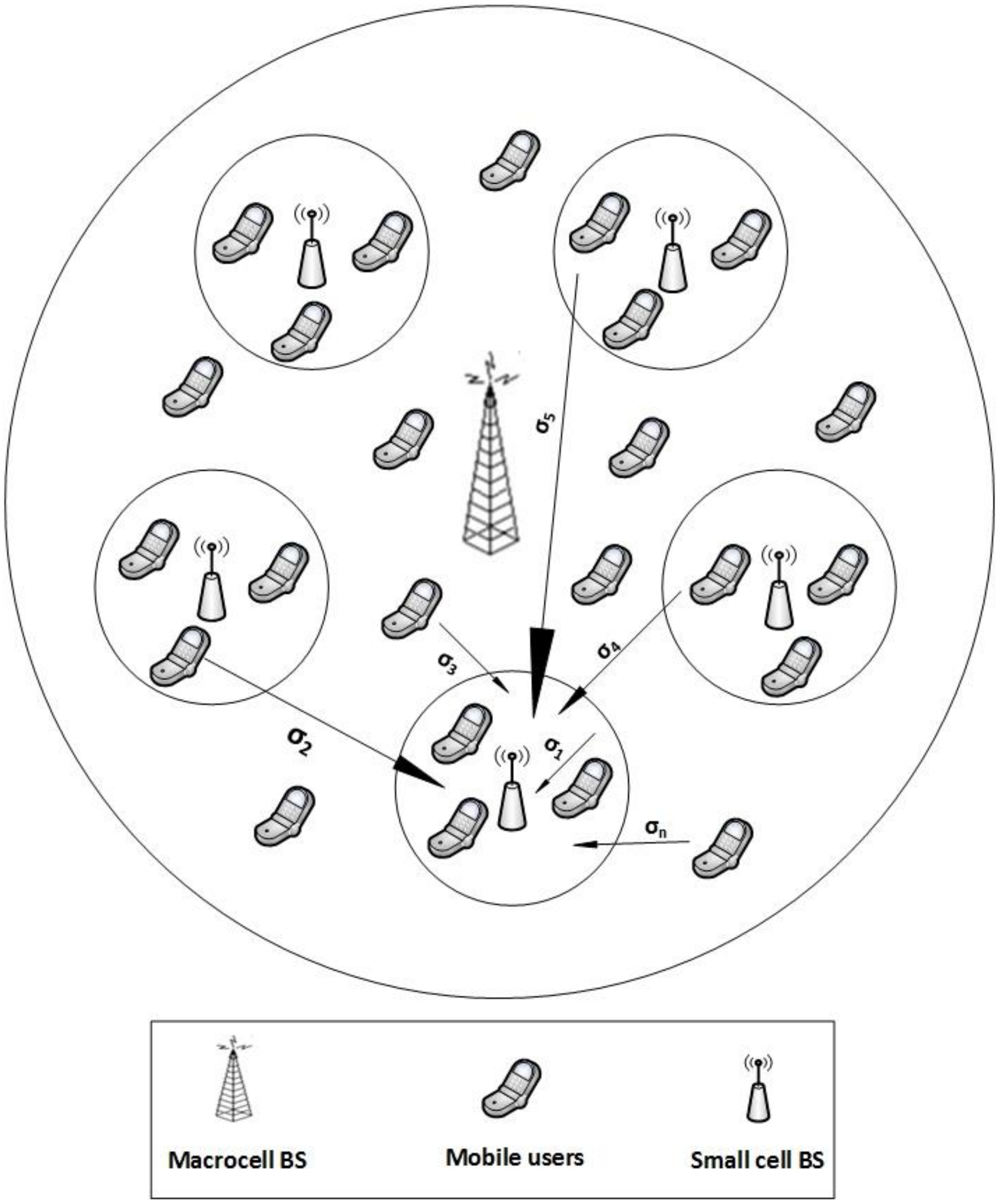
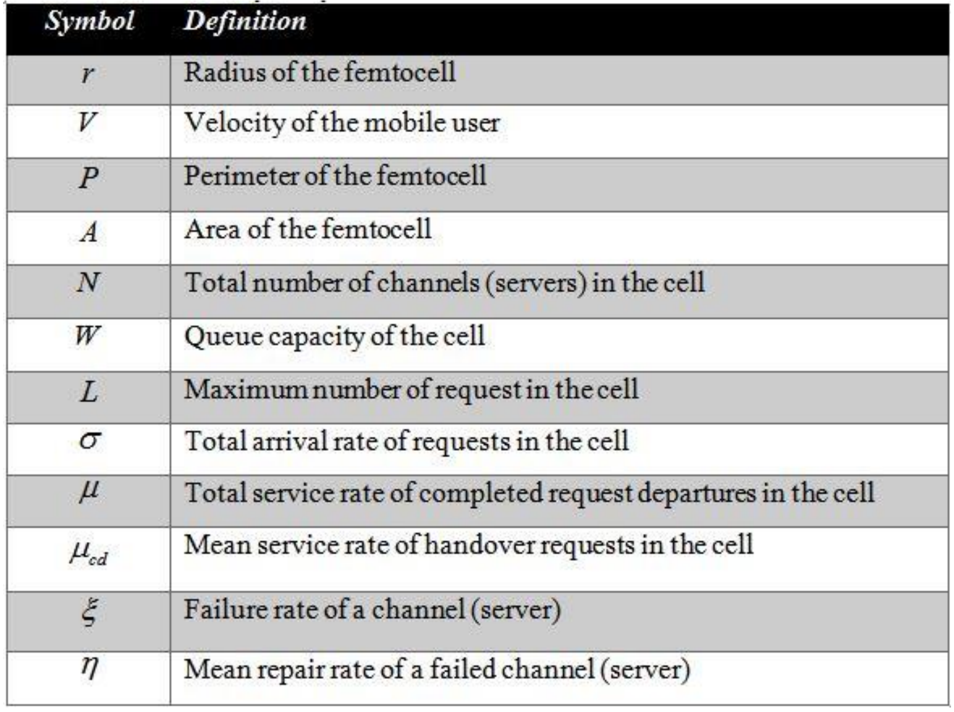


Figure 4.1: A typical network of a macrocell and a set of small cells with different types of arrivals to the small cell

In the model, when all the channels (servers) are busy and serving the requests, the incoming requests begin to queue up within the buffer of size W. However, the maximum number of requests which are allowed in the system is $L = W + N$ where N requests are served using N available channels (servers) and the remaining requests can only handover to a neighboring cell due to the mobility of the mobile users. It is assumed that the queuing strategy is First Come First Served (FCFS). Handover of the mobiles users to the neighboring cells may happen when they are either being served in the system or they are in the queue.

In wireless communication systems, failures can happen because of many different factors such as hardware, software, human errors, or even a mixture of the mentioned factors (Ma et al., 2001; Selim et al., 2016). Unavailability of a channel (server) and failures in wireless communication systems may decrease the performance of the system (Kirsal and Gemikonakli, 2009). In this study, it is assumed that the down time of each channel (server) is exponentially distributed, and the average rate for a channel (server) to become available again is called “repair time”. In the literature for simplifying the shape of the coverage area, some studies such as (El-atty and Gharsseldien, 2015; Kong, 2015; Chowdhury and Jang, 2013) assume hexagon coverage. In this thesis, macrocell coverage area is assumed to be circular with radius R and each macrocell is served by a BS placed at the center. The small cells which are deployed within the coverage area of a macrocell are circular as well with radius r and they are served by small cell BSs. Summary of the parameters used in this model is presented in Table 4.1.

Table 4.1: Summary of symbols



Symbol	Definition
r	Radius of the femtocell
V	Velocity of the mobile user
P	Perimeter of the femtocell
A	Area of the femtocell
N	Total number of channels (servers) in the cell
W	Queue capacity of the cell
L	Maximum number of request in the cell
σ	Total arrival rate of requests in the cell
μ	Total service rate of completed request departures in the cell
μ_{cd}	Mean service rate of handover requests in the cell
ξ	Failure rate of a channel (server)
η	Mean repair rate of a failed channel (server)

4.2 Queuing System

The queuing system used to model the proposed system is presented in this section. As mentioned earlier, mobile users may attempt to use their mobile devices such as smartphones, and iPads for many different reasons (e.g. to use the email system, to take part in video conferencing, to download music or videos, or to use many other applications) while they are in shopping malls or driving over the city roads of smart-cities. These requests of mobile users can be placed into a queue and served using FCFS strategy. In this thesis similar to studies in (Beigy and Meybodi., 2015; El Bouabidi et al., 2014; Kirsal et al., 2015; Trivedi et al., 2002), arrivals of requests to the system are supposed to follow Poisson distribution with the rate of σ, and the servers' service time is exponentially distributed with rate μ. It is a common phenomenon that in a mobile HetNet in smart-cities, mobile users may move to neighboring cells of the network due to mobility when they are being served in the system or they are in the queue. Let us define the service rate due to mobility by μ_{cd}.

The failure rate of the channels (servers) is supposed to be exponentially distributed and is indicated by ξ (Kirsal and Gemikonakli, 2009; Trivedi et al., 2002; Trivedi and Ma, 2002). If failures occur in the system, the failed channel (server) stays down for an exponentially distributed amount of time with mean rate $1/\eta$. The queuing system under study is represented in Figure 4.2.

4.3 Service rate due to Mobility

The time that a UE spends in a given system is called the “dwell time” of a mobile user. For a mobile user in the femtocell, let us define the dwell time by T_{cd} which is exponentially distributed with mean $1/\mu_{cd}$.

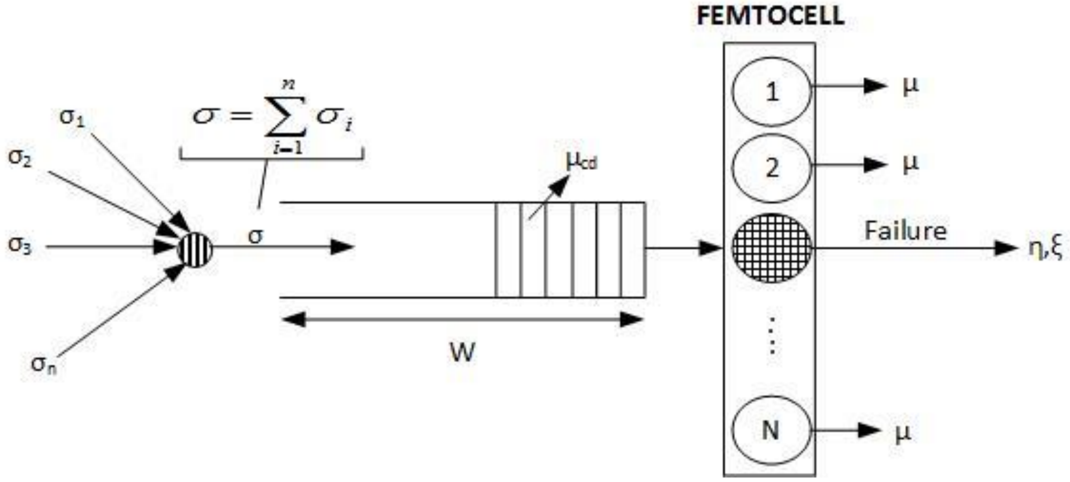


Figure 4.2: The queuing system considered with failures and repairs

Following studies such as (Zeng and Agrawal, 2002; Zeng and Agrawal, 2001; Carvalho et al., 2016) it is possible to calculate μ_{cd} as follows:

$$\mu_{cd} = \frac{E[v]P}{\pi A} \tag{1}$$

Where $E[v]$, P and A are the average velocity of the mobile user, length of the perimeter of the femtocell, and area of the femtocell respectively.

4.4 A Model for Energy Consumption

In the current section, energy consumption of an FBS in HetNets is analyzed using the concept of queuing theory based on practical parameters and LTE-specific values. Based on Shannon's capacity formula, the attainable transmission rate (T_R) of FBSs in bit-per-second under a given transmission power (P_T) and system bandwidth (B) can be computed as follows (Chen et al., 2011):

$$T_R = B\log\left(1+\frac{P_T}{BN_0}\right) \tag{2}$$

Where N_0 stands for Additive White Gaussian Noise (AWGN) power spectral density. Values for the FBS parameters used in equation (2) are given in Table 4.2 adopted from (Zhang and De la Roche, 2010; Bouras et al., 2012; Zhang et al., 2012).

Table 4.2: FBS parameters

Parameter	*Description*	*Value*
B (Hz)	Bandwidth of the femtocell	$5 * 10^{6}$
N_0 (W/Hz)	AWGN noise density	$4 * 10^{-21}$
P_T (W)	Transmission power	0.02

Based on a hardware model presented in (Deruyck et al., 2012a), total power consumption of an FBS (P_{el}) can be formulated as follows:

$$P_{el} = P_{el/mp} + P_{el/FPGA} + P_{el/trans} + P_{el/amp} \tag{3}$$

Where $P_{el/mp}$, $P_{el/FPGA}$, $P_{el/trans}$, and $P_{el/amp}$ are power consumption (in watt) of, the microprocessor, the FPGA (Field-Programmable Gate Array), the transmitter, and the power amplifier respectively. Values for the parameters used in equation (3) can be found in Table 4.3 adopted from (Ashraf et al., 2010; Deruyck et al., 2012a;

Deruyck et al., 2012b).

Table 4.3: FBS power consumption components

Component	***Value***
$P_{el/mp}$ (W)	3.2
$P_{el/FPGA}$ (W)	4.7
$P_{el/trans}$ (W)	1.7
$P_{el/amp}$ (W)	2.4

By dividing equation (2) by total power consumption of the FBS (P_{el}) in equation (3), bit-per-joule energy consumption unit is obtained which is the achievable rate for a unit of energy consumption (Wang and Shen, 2010). According to Riggio and Leith (2012), Maximum Transmission Unit (MTU) of the FBS is assumed to be 1368 bytes. Therefore, by dividing MTU by the bit-per-joule energy consumption unit, E_{pp} which is the energy consumption for each transmitted packet, is calculated for FBSs. $E(x)$ which is the expected energy consumption is then calculated as follows:

$$E(x) = \sum_{j=1}^{L} \sum_{i=1}^{N} P_{i\,j} .i.\mu.E_{pp} \tag{4}$$

Where P_i, i, μ, and E_{pp} are the probability of having i channels (servers) available (sum of all probabilities in columns of Figure 5.1), number of available channels (servers), service rate, and consumed energy for each transmitted packet respectively.

It should be noted that the modelling approach presented combines the fault tolerant nature of wireless communication systems with the energy models demonstrated in (Ashraf et al., 2010; Deruyck et al., 2012a; Deruyck et al., 2012b; Wang and Shen, 2010; Riggio and Leith, 2012). These energy models are combined with state probabilities computed by analyzing the two-dimensional Markov chain representation of the system. Furthermore, the mobility of the mobile users is also embedded into the two-dimensional Markov chain considered. Equation (4) shows that by considering the state probabilities together with the energy consumed in each state, it is possible to derive a mean value for the energy consumed by the system considered. This is the first time that detailed queuing, availability (fault tolerance), and energy efficiency related measures are considered together, which allows us to perform more realistic evaluation by taking QoS in terms of performance, reliability as well as energy efficiency into account.

Chapter 5

THE SPECTRAL EXPANSION METHOD

5.1 Introduction

As a solution approach, spectral expansion is beneficial in performance and dependability modelling of distinct event systems. This approach is used to solve Markov models of a certain type that happen in many different practical system models. The results and applications consist of performability modelling of different sorts of multi-task execution models, multiprocessors, networks of queues with unreliable servers, and many other practical systems (Ever, 2014; Ever, 2016; Chakka and Mitrani, 1995; Chakka and Mitrani, 1992; Elwalid et al., 1991; Chakka and Mitrani, 1994; Ettl and Mitrani, 1994). Although some introductory ideas were known earlier (Neuts, 1984), an efficient algorithm for the solution of spectral expansion method was developed in (Chakka and Mitrani, 1992; Mitrani and Mitra, 1992). The first numerical results on this algorithm were presented in Chakka and Mitrani (1992) and Chakka and Mitrani (1994). This algorithm seems to be better than MGM in terms of ease of use, speed, and accuracy (Chakka and Mitrani, 1995; Mitrani and Chakka, 1995).

There are different methods available to solve the state probabilities of the Markov model. The best known ones of these methods are Seelen’s method, Matrix-geometric solution, Gauss-Seidel iterative method, and the Spectral Expansion method.

In Seelen's method, the Markov chain is first truncated to a finite state, which is an approximation of the original process. It is then used together with a dynamically adjusted relaxation factor in an iterative solution algorithm (Seelen, 1986). One of the state probabilities is computed by the algorithm in each iteration. However, it is stated that the number of iterations required for precise results is not dependent on the buffer size (Seelen, 1986). The dependency of computation time on the number of channels (servers) is not stated as well. The use of an appropriate value for the relaxation factor is vital to have the most accurate results. However, the solution to obtain the value of the relaxation factor is not defined by this method (Seelen, 1986; Chakka, 1995).

Gauss-Seidel iterative method was developed in 1989 and is used to solve many different kinds of simultaneous equations iteratively. In this approach, the infinite state problem is reduced to a linear equation containing vector generating functions and some unknown probabilities. Since each component of the new iterate is dependent on previous computed components, the update cannot be done at the same time. Also, there is no mention about the dependence of the number of iterations to buffer size or the number of channels (servers) (Horton and Leutenegger, 1994; Dayar, 1998). Because of the aforementioned drawbacks, Seelen's method and Gauss-Seidel iterative method are not as popular as the other two methods.

In Matrix Geometric Method (MGM), a non-linear matrix equation is formed from the system parameters and the minimal non-negative solution R is computed by using an iterative method (Neuts, 1981). The main drawback of MGM is that the number of iterations to compute R cannot be predetermined and there is a high computational requirement to obtain R.

Spectral Expansion is a solution approach for the steady state analysis of two dimensional Markov processes in semi-infinite or finite lattice strips. In this method (Chakka, 1995; Chakka and Mitrani, 1994), following the algorithm, the necessary matrices are computed. Then, eigenvectors and eigenvalues are computed to obtain a system of linear equations. It is then possible to solve the system of linear equations with various methods such as LU Decomposition method. In Spectral Expansion method, computation of eigenvectors and eigenvalues has much less computational requirement than computational requirement for obtaining R in matrix geometric method. There are different libraries that provide routines to compute eigenvectors and eigenvalues for the given matrices. One of them is the Numerical Algorithm Group (NAG) library. Spectral Expansion and Matrix Geometric method are the most commonly used approaches for solving state probabilities of the Markov models (Chakka, 1995). The performances of these two methods have been critically analyzed and compared (Mitrani and Chakka, 1995; Haverkort and Ost, 1997; Tran and Do, 1999). In the mentioned studies, it is stated that Spectral Expansion is a better solution method especially when more heavily loaded systems are studied. In this research study, Spectral Expansion has been used for steady state solution of the Markov model.

5.2 The Markov Model and the Solution

Cellular networks play a significant role to support ubiquitous connectivity in smart-cities. It is expected that the next generation of cellular networks will be HetNets which are determined as a combination of macrocells and small cells such as femtocells (Nakamura et al., 2013). In smart-cities, FBSs can be deployed in public/private places such as shopping malls, airports, bus stations, streets, etc. to enhance mobile coverage and capacity, and provide better services to mobile users.

In modelling of such systems, two-dimensional Markov chain processes can be used on a finite lattice strip to describe an abstraction for the interactions considered in the system under study. In the Figure 5.1 the state diagram for the queuing system presented in Figure 4.2 is shown.

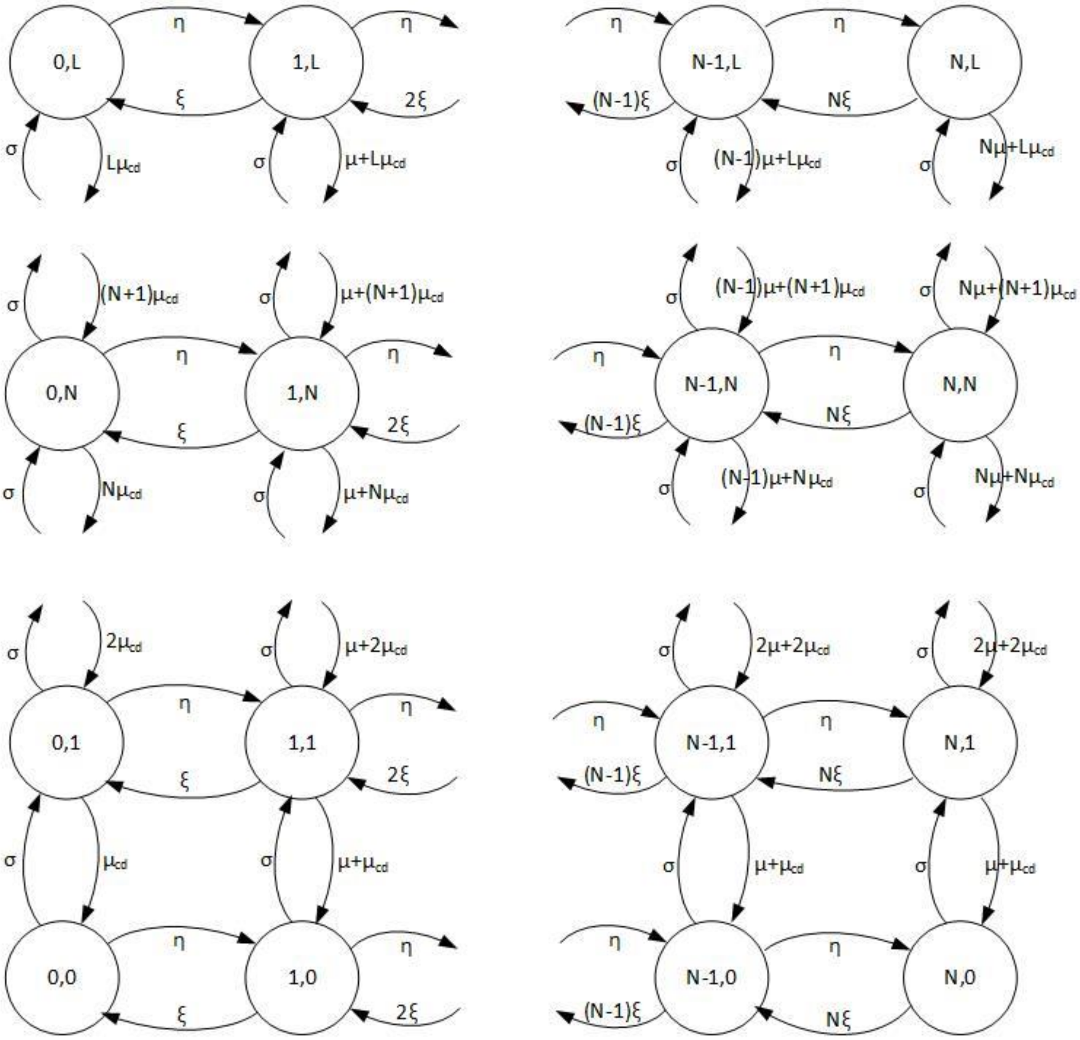


Figure 5.1: The stage diagram of the queuing system

In spectral expansion solution approach, *I(t)* and *J(t)* as a pair of integer-valued state variables can be used to illustrate the state of the system at time *t*, where *I(t)* represents the number of channels (servers) available, and *J(t)* specifies the number of requests existing now in the system at time *t*.

We can suppose that the minimum value of $I(t)$ is 0 and the maximum value is N representing the maximum number of channels (servers) available in the system. The minimum value for the state variable $J(t)$ is also 0 and it may have values up to L which is the overall number of requests at time t containing those requests being served in the system. In this model, the Markov process is indicated by $Z = \{[I(t), J(t)]; t \geq 0\}$ and is used for the performance evaluation of the system under study. It is assumed that Z is irreducible with a state space of $\{0, 1, \ldots, N\} \times \{0, 1, \ldots, L\}$. We also suppose that the number of channels (servers), $I(t)$, is shown in the lateral or horizontal direction, and the total number of requests in the system, $J(t)$, is demonstrated in the vertical direction of finite lattice strip. There are three possible transitions of the model Z which are given by:

a) purely lateral transition from state (i, j) to state (k, j)

b) One-step upward transition from state (i, j) to state $(k, j+1)$

c) One-step downward transition from state (i, j) to state $(k, j-1)$

In the spectral expansion solution approach, matrix A is the matrix of purely lateral transitions of the model Z with zeros on the main diagonal. One-step upward transitions and one-step downward transitions are represented in matrices B and C respectively. The parameters showing transitions rates and their positions in these matrices are used to specify the state transitions. For example, having η at position (0,1) of the matrix A shows that there is a transition possible from the state with zero available channel (server) to state with one available channel (server) with rate η. Similarly having σ on the main diagonal of matrix B reveals the one-step upward transitions with the arrival of new packets. The diagonal of matrix C shows the departures caused by service completion and/or mobility of the mobile users. The specificities of LTE are incorporated through the correct use of the system parameters within the matrices. Consistent with previous studies (Kirsal et al., 2015; Gong et al., 2011; Kirsal et al., 2014; Zeng and Agrawal, 2002; Ma et al., 2001), the generic model which is representing the state transitions can be used with different system specific parameters as provided in Tables 4.2, 4.3, and 6.1. In spectral expansion method, it is assumed that the process has a threshold, M, ($M \geq 1$) which has an integer value (Ever, 2014; Kirsal et al., 2014; Kirsal et al., 2012) such that the transition rate matrices (A, B, and C) do not depend on j for $j \geq M$. However, in our system, the transition rate matrices are always dependent on j, because the requests in the queue can go away from the system because of the mobility of the users regardless of the number of channels (servers) available.

A, B, and C are square matrices, each of size $(N+1) \times (N+1)$. The components of matrix A are dependent only on the failure (ξ) and repair (η) rates of the channels (servers). The matrices A, B, and C are given in the following equations. The matrix C is dependent on the number of requests in the system for $j = 0, 1, \ldots, L$. Consequently, the threshold M is taken as $M = L$.

$$A = A_j = \begin{pmatrix} 0 & \eta & 0 & 0 & 0 & 0 & 0 & 0 \\ \xi & 0 & \eta & 0 & 0 & 0 & 0 & 0 \\ 0 & 2\xi & 0 & \eta & 0 & 0 & 0 & 0 \\ 0 & 0 & 3\xi & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 & \eta & 0 \\ 0 & 0 & 0 & 0 & 0 & (N-1)\xi & 0 & \eta \\ 0 & 0 & 0 & 0 & 0 & 0 & N\xi & 0 \end{pmatrix} \tag{5}$$

$$B = B_j = \begin{pmatrix} \sigma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma \end{pmatrix} \tag{6}$$

$$C_j = \begin{pmatrix} \min(0, j)\mu + j\mu_{cd} & 0 & 0 & 0 & 0 \\ 0 & \min(1, j)\mu + j\mu_{cd} & 0 & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & \min(N, j)\mu + j\mu_{cd} \end{pmatrix} \tag{7}$$

If this is the case that the number of requests is smaller than the number of available channels (servers), each request is served using a channel (server). On the other hand, if the number of requests in the system is greater than the number of available servers (assume that k channels (servers) are available at that time), the first k requests are served using k available channels (servers), and the remaining requests can only perform a handover to a neighboring cell with the service rate μ_{cd}. The spectral expansion method is used for the steady-state solution. More details about the spectral expansion solution approach are available in (Ever, 2014; Ever et al., 2013; Chakka, 1998).

The steady-state probabilities of the states presented in Figure 5.1 can be expressed as follows following the spectral expansion solution:

$$P_{i,j} = \lim_{t \to \infty} P(I(t) = i, J(t) = j)\ ;\ 0 \le i \le N, 0 \le j \le L$$

Theorem. It is now possible to acquire all the state probabilities in the following form.

$$P_{i,j} = \sum_{l=0}^{N} \left(a_l \psi_l(i) \lambda_l^{j-M+1} + b_l \phi_l(i) \beta_l^{L-j} \right),\ M-1 \le j \le L$$

Where *λ* is eigenvalues of *Q(λ)* and *ψ* is left-eigenvector of *Q(λ)*, and *ψ* is a row-vector which is described as follows.

$$\psi = \psi_0, \psi_1, \ldots, \psi_N, \lambda = \lambda_0, \lambda_1, \ldots, \lambda_N \text{ and } \psi Q(\lambda) = 0\,;\ |Q(\lambda)| = 0$$

Similarly, *β* is eigenvalues of $\bar{Q}(\beta)$ and *ϕ* is left-eigenvectors of $\bar{Q}(\beta)$, and *ϕ* is a vector which is described as follows.

$$\phi = \phi_0, \phi_1, \ldots, \phi_N, \beta = \beta_0, \beta_1, \ldots, \beta_N$$

Proof. Let us show certain diagonal matrices of size $(N+1)\times(N+1)$ as follows:

$$D_J^A(i,i) = \sum_{l=0}^{N} A_j(i,l);\ D^A(i,i) = \sum_{l=0}^{N} A(i,l)$$

$$D_J^B(i,i) = \sum_{l=0}^{N} B_j(i,l);\ D^B(i,i) = \sum_{l=0}^{N} B(i,l)$$

$$D_J^C(i,i) = \sum_{l=0}^{N} C_j(i,l);\ D^C(i,i) = \sum_{l=0}^{N} C(i,l)$$

Let us also define $Q_0 = B$, $Q1 = A - D^A - D^B - D^C$, $Q_2 = C$. Then the state probabilities in a row can be expressed as:

$$v_j = \left(P_{0,j}, P_{1,j}, \ldots, P_{N,j}\right);\ j = 0,\ 1,\ \ldots,\ L.$$

The balance equations for $0 \le j \le L$ are as follows.

$$v_0\left[D_0^A + D_0^B\right] = v_0 A_0 + v_1 C_1 \tag{8}$$

$$v_j\left[D_j^A + D_j^B + D_j^C\right] = v_{j-1} B_{j-1} + v_j A_j + v_{j+1} C_{j+1};\ 1 \le j \le M-1 \tag{9}$$

$$v_j\left[D^A + D^B + D^C\right] = v_{j-1}B + v_j A + v_{j+1}C\,;\ M \le j \le L \tag{10}$$

$$v_L\left[D^A + D^C\right] = v_{L-1}B + v_L A \tag{11}$$

The normalization equation is given as:

$$\sum_{j=0}^{L} v_j e = \sum_{j=0}^{L}\sum_{i=0}^{N} P_{i,j} = 1$$

From equation (10)

$$v_0 Q_0 + v_{j+1}Q_1 + v_{j+2}Q_2 = 0\,;\ (M-1) \le j \le (L-2)$$

and the characteristic matrix polynomials can be defined as (Chakka, 1998):

$$Q(\lambda) = Q_0 + Q_1\lambda + Q_2\lambda^2\,;\ \bar{Q}(\beta) = Q_2 + Q_1\beta + Q_0\beta^2$$

where $\psi Q(\lambda) = 0$; $|Q(\lambda)| = 0$; $\phi \bar{Q}(\beta) = 0$; $\left|\bar{Q}(\beta)\right| = 0$, Furthermore,

$v_j = \sum_{l=0}^{N}\left(a_l\psi_l\lambda_l^{j-M+1} + b_l\phi_l\beta_l^{L-j}\right),\ M-1 \le j \le L$ and in the state probability form,

$$P_{i,j} = \sum_{l=0}^{N}\left(a_l\psi_l(i)\lambda_l^{j-M+1} + b_l\phi_l(i)\beta_l^{L-j}\right),\ M-1 \le j \le L$$

where λ_l (l = 0, 1, ..., N) and β_l (l = 0, 1, ..., N) are N+1 eigenvalues each, which are strictly inside the unit circle, and a_l (l = 0, 1, ..., N), b_l (l = 0, 1, ..., N) are arbitrary constants that can be scalar or complex-conjugate. v_j vectors can be acquired using the process in (Chakka, 1998).

The state probabilities ($P_{i,j}$) can be used to compute a number of important performance measures such as MQL and throughput (γ) as well as expected value of energy consumed as explained in Chapter 4 using the following equations.

$$MQL = \sum_{j=0}^{L} j \sum_{i=0}^{N} P_{i,j} \tag{12}$$

$$\gamma = \sum_{j=0}^{L} \sum_{i=0}^{N} i \cdot \mu \cdot P_{i,j} \tag{13}$$

Chapter 6

CASE STUDY

6.1 A Typical Small Cell Case Study in Smart-cities

In smart-cities (Al-Fagih et al., 2013; Singh and Al-Turjman, 2016), small cells such as femtocells will expand to realize the heterogeneous data exchange paradigms including ubiquitous devices, data centers, and personal and environmental monitoring devices connected to mobile users via femtocells both in urban and metropolitan areas. Those distributed femtocells will supply a variety of services to enhance Quality of Experience (QoE) of the mobile users and improve quality of living in smart-cities. In such settings, small cells such as femtocells will be available in large quantities on roads and deployed in public and private buildings such as shopping malls, smart homes, etc. In such a thorough HetNet model, an efficient energy consumption policy is required (Celik and Kamal, 2016a; Celik and Kamal, 2016b) to drive the usage of femtocells in serving hundreds of incoming static or mobile users per hour in a green framework. In addition, the anticipated HetNet model introduces challenges about the system's limitations in terms of the available capacity and targeted QoS, given the diversity of data that is exchanged. For this reason, a green HetNet-driven femtocell scenario in smart-cities is visualized to tackle the aforementioned concerns. Figure 6.1 shows the scenario considered in this study.

Figure 6.1: Small cells serving static/mobile users in a smart-city

In this thesis, a smart-city is considered in which a set of small cells such as femtocells are deployed within the coverage area of a macrocell to provide adequate capacity for the mobile users while maintaining sufficient QoS in terms of throughput, MQL, Response Time (RT), and energy consumption. In this setup, users may be static and/or mobile and may utilize their smart devices and energy-hungry mobile applications such as mobile video while they are shopping in the mall or driving over the city roads. Each FBS has transmission power of 20 mW and a transmission bandwidth of 5 MHZ. Typically users are assumed to be uniformly distributed in the coverage area of their serving cells. The radius of femtocell is considered to be 30 meters (Chandrasekhar et al., 2009). The other parameters utilized in this scenario are mostly extracted from (Zhang et al., 2010; Zhang and De la Roche, 2010; Bouras et al., 2012; Chandrasekhar et al., 2009; Kwon and Cho, 2011) and summarized in Table 6.1.

It should be noted that the models are flexible and level of abstraction allows evaluation of various cellular systems with similar characteristics. The users can modify the system dependent parameters for the analysis of various cellular interactions.

Table 6.1: Summary of the evaluation parameters

Component	***Value***
Femtocell radius	30 m
Mobile user velocity	Low, medium, high
Femtocell transmission power	20 mW
Femtocell transmission bandwidth	5 MHZ
# femtocell channels (servers)	8
Expected service rate per hour (μ)	200 (request/hour)
Expected failure rate per hour (ξ)	0.001
Expected rate for down time of channels (servers) per hour (η)	0.5

6.2 Performance Metrics and Parameters

In order to evaluate the proposed model in this thesis, the following performance metrics are considered:

- ***Throughput (γ)***: γ is set here as a quality measure which is the average percentage of transmitted data packets that succeed in attaining the destination reflecting the effect of node heterogeneity in HetNet setup. γ is measured in “packets per second”.

- ***Mean Queue Length (MQL)***: MQL is measured in “packets” and is described as the average number of the requests pending in the system, either waiting in the queue or being served.

- ***Response Time (RT)***: RT is defined as the time spent by the mobile user from arrival till departure. It plays an important role in performance evaluation of wireless communication systems since it incorporates all the delays involved for a request of a user.

- ***Energy consumption***: It is defined as the amount of energy consumption of a single FBS based on the requests of the mobile users.

The aforementioned performance metrics are evaluated while varying the following parameters:

- ***Arrival rate***: The number of arrivals per unit of time is defined as the arrival rate. In this thesis, different arrival rates are used to analyze the effects of traffic loads on the aforementioned performance metrics in the scenario under study. It should be noted that, for the scenario considered in smart-cities, the incoming requests can be originating from within the small cell, or can be handed over from the macrocell or other small cells. Since the superposition of incoming arrival requests would follow Poisson distribution as well, and since the model is flexible for different incoming traffic loads, it is supposed that the arrival rate incorporates all these incoming streams. The queuing system under study is shown in Figure 4.2. Please note that the arrival rates for the small cells differ according to the application. In this thesis, the order of arrival rates is similar to the measures from previous studies such as (Zhang and De la Roche, 2010). Following this and the number of channels (servers) in a femtocell, the expected service rate can be specified as in Table 6.1.

- ***Mobile user velocity***: Since mobility is one of the most significant issues in the deployment of HetNets (Chowdhury and Jang, 2013), including mobility is always valuable in performance evaluation of such HetNets (Tabany and Guy, 2015). In this thesis, the velocity of mobile users is classified according to studies such as (Zhang et al., 2010):
    1. Low-speed mobile users such as pedestrians and stationary users with the velocity from 0 to 15 km/h.
    2. Medium-speed mobile users like those who ride a bike with the velocity from 16 to 30 km/h.
    3. High-speed mobile users with the velocity above 30 km/h.

6.3 Simulation Setups

Simulation is another performance evaluation technique which is employed in this thesis to validate the findings achieved from the analytical model. The results acquired from the analytical model are presented comparatively with the findings from discrete event simulation which has been written in C++ language. An event-based scheduling approach is considered which is dependent on the events and their effects on the system state. Unlike the commonly used tools for queuing theory, the simulation program employed in this thesis is able to incorporate the effects of mobility, as well as channel availabilities. In other words, the simulation program takes into account an additional stochastic process for specifying the number of channels (servers) at a given time. It also considers the number of requests leaving the system because of the mobility. One of the most commonly used stopping criteria called “relative precision” is employed for the simulation. Therefore, the simulation is stopped at the first checkpoint when the condition $\delta \leq \delta_{max}$, where δ_{max} is the maximum acceptable value of the relative precision of confidence interval at the $100(1-\alpha)\%$ significance level, $0 < \delta_{max} < 1$.

The results achieved from the simulation program are within the confidence interval of 5% with a confidence level of 95%. Therefore, both default values for α and δ_{max} are set to 0.05 in our simulations. It should be noted that the simulation program employed has been proved to be acceptable by applying well known queueing theory models ($M/M/1$, $M/M/c$) and findings obtained from the literature (Ever, 2014; Kirsal et al., 2015; Chakka, 1998; Banks et al., 2005; Law, 2007).

Chapter 7

RESULTS AND DISCUSSIONS

In the current chapter, obtained results are demonstrated for the considered case study in Chapter 6. Different performance measures such as MQL, throughput, and response time are compared for different mobile users' velocity (e.g. low, medium, and high velocity mobile users). The number of allocated channels (servers) to the femtocell under study is N = 8 (Zhang and De la Roche, 2010). It is also assumed that the femtocell can accommodate up to 2000 requests simultaneously including the ones in service. Other system parameters used are mainly taken from (Zhang et al., 2010; Zhang and De la Roche, 2010; Bouras et al., 2012; Chandrasekhar et al., 2009; Kwon and Cho, 2011).

It should be again noted that the models presented in this study is flexible and can be utilized to investigate performance of different cellular systems with similar characteristics. The users can easily change the system parameters and evaluate the performance of different cellular interactions.

The effects of the velocity of mobile users on the MQL for different arrival rates is shown in Figure 7.1. It is obvious from the figure that in the case of congestion like in high population density areas such as shopping centers or airports, the MQL will also grow as expected. This is due to the fact that, more users request service from the FBS at the same time. As the mobile users move faster in the cell, the MQL decreases. This is because the service rate due to mobility (μ_{cd}) is directly proportional to the expected velocity of the mobile users (Kirsal et al., 2015; Zeng and Agrawal, 2002). Therefore, as the velocity increases, mobile users will leave the cell faster and the MQL will decrease. For example, the MQL is roughly equal to 160 at the velocity of 1 km/h for σ = 5000. But when the mobile users move faster (e.g. v = 60 km/h), the MQL is approximately 3.4.

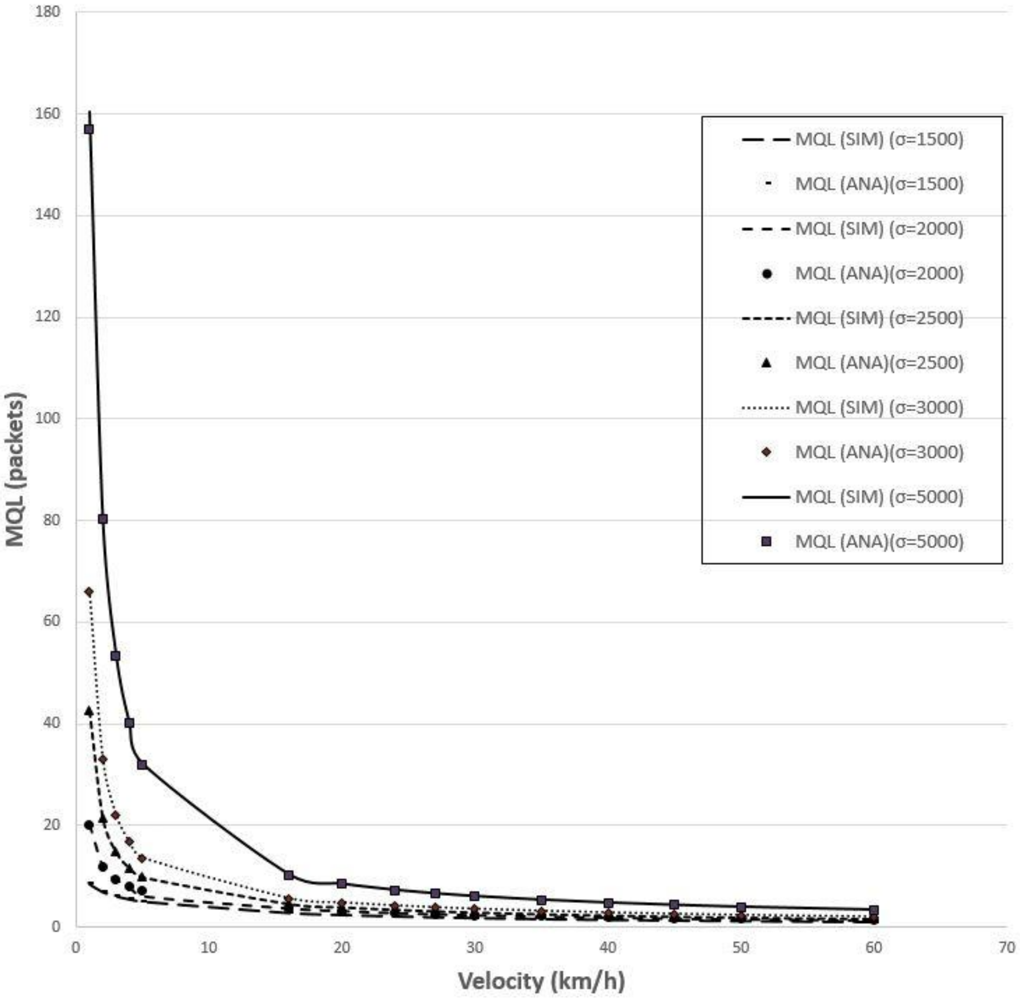


Figure 7.1: The effects of velocity of mobile users on MQL

Figure 7.2 shows the effects of mobile users' velocity on the throughput of the system. The parameters are similar to the parameters used in Figure 7.1. It is clear that as σ increases, more requests are served using the available channels (servers) in the cell and therefore throughput will increase as well. It is also seen that when the velocity of the mobile users rises in the cell, throughput will decrease. This is because of the fact that as mobile users move faster in the cell, they may be moving away from the BS and may leave the cell due to mobility. Therefore, the number of requests served by the channels (servers) will reduce and consequently throughput will decrease as well. It should be noted that in both Figures 7.1 and 7.2, the results of simulation are also demonstrated comparatively with the analytical ones for validation. The maximum discrepancy between the simulation and analytical results are 1.83%, and 0.86% for Figure 7.1 and Figure 7.2 respectively which are both less than the confidence interval of 5%.

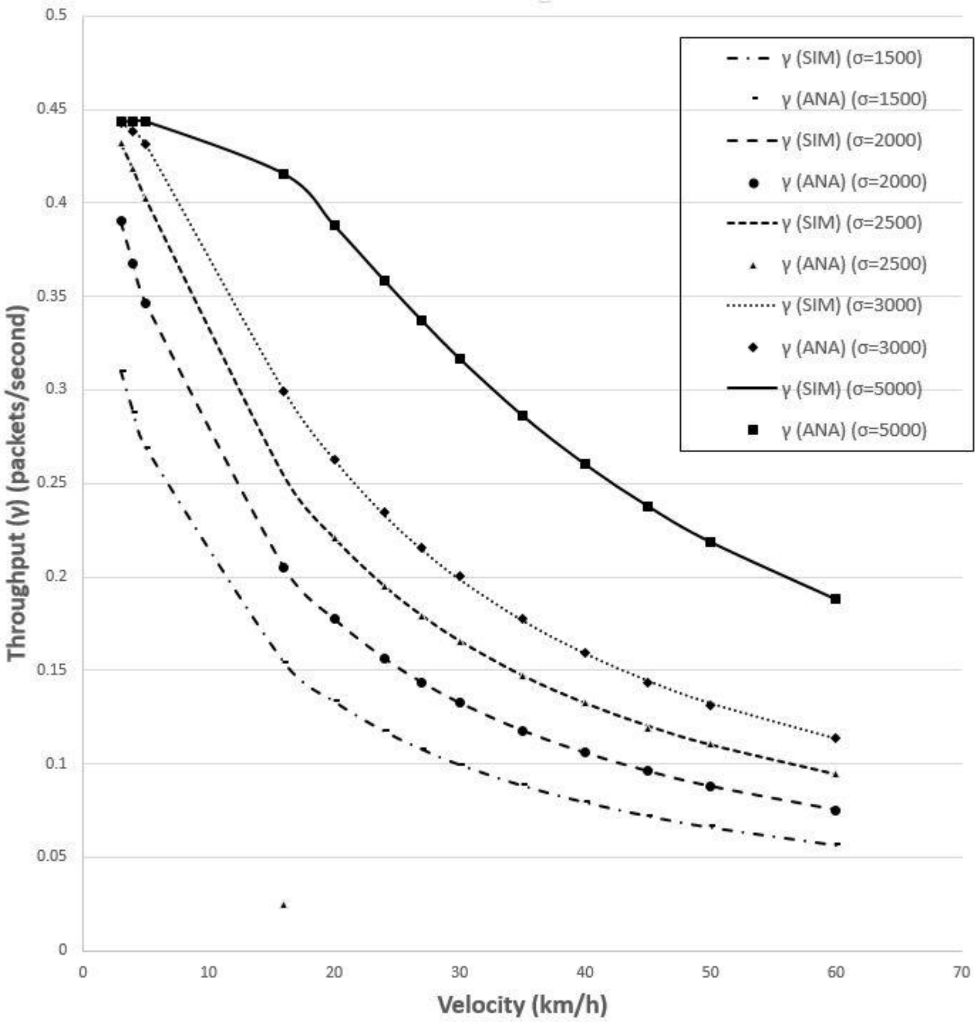


Figure 7.2: The effects of velocity of mobile users on throughput

Table 7.1 shows the results of simulation and analytical models when the stations are not mobile. Parameters used are same as the parameters in Figures 7.1 and 7.2; however, the results are presented separately since the order of MQL and throughput increase significantly.

Table 7.1: The effects of congestion for a scenario without mobility

σ	*MQL-SIM*	*MQL*	*Disc*	*γ-SIM*	*γ*	*Disc*	*Time-SIM*	*Time*
2000	1996.02	1999.34	0.166	1597.12	1573.79	1.46	11675.05	2.016
2500	1998.22	2000.11	0.094	1597.01	1598.90	0.11	12757.94	2.165
3000	1998.86	2000.21	0.067	1597.04	1599.91	0.17	13505.62	2.571
5000	1999.53	2000.54	0.050	1597.02	1599.92	0.18	16519.28	2.825

Disc is discrepancy

Response Time (RT) has an important role in performance measures of the system in queuing models (Chu and Ke, 2006). Figure 7.3 represents the effects of the velocity of mobile users on the response time. The parameters used are same as the ones in Figures 7.1 and 7.2. It is obvious from this figure that for low-velocity mobile users, arrival rate is the most important factor which affects the response time. As the mobile users' velocity increases, velocity becomes the main factor affecting the response time, since the departure of incoming requests becomes significantly higher than the arrival rate. Therefore, for medium and high-velocity mobile users, arrival rate does not affect the response time significantly.

The effects of service rate of the FBS on response time and expected energy consumption of requests per hour is shown in Figure 7.4. At μ = 100, expected consumed energy is approximately 0.53 joules per hour. As service rate increases, response time begins to decrease and at the same time more energy is consumed. For example at μ = 1000, response time is 5.4 seconds which is 60 times lower than when μ = 100. Similarly, at μ = 1000, expected energy consumption is around 5.3 joules which is 10 times higher that when μ = 100.

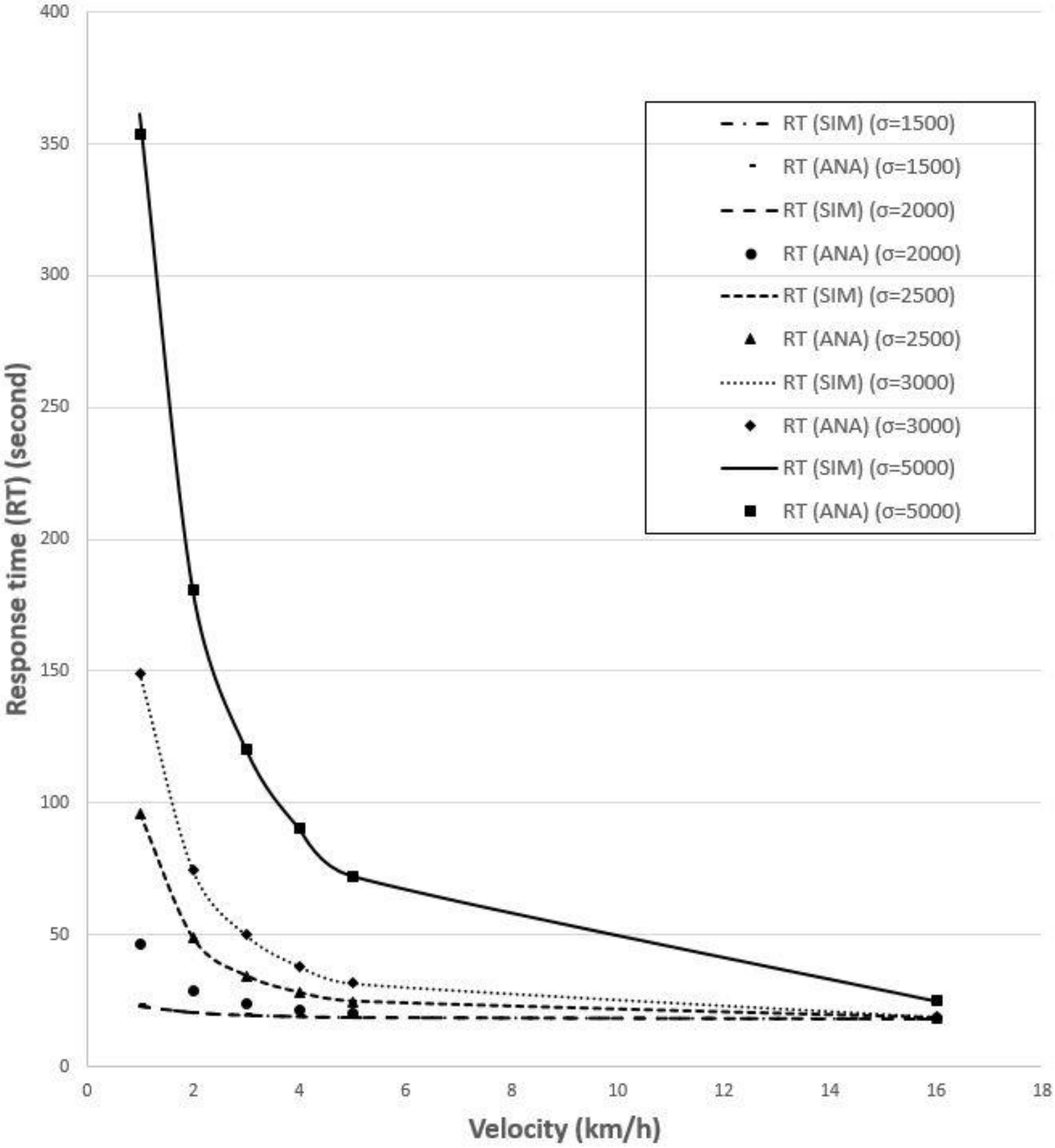


Figure 7.3: The effects of velocity of mobile users on response time

As it is shown in Figure 7.4, the optimum configuration for this scenario is obtained at μ = 300 where the response time is 100.8 seconds and expected consumed energy is approximately 1.59 joules per hour. Figure 7.4 shows that there is a trade-off between energy consumption and the performance of the FBS as expected. It also shows that the proposed approach lends itself as an important tool in order to specify the operative space, considering performance as well as energy consumption accurately and effectively.

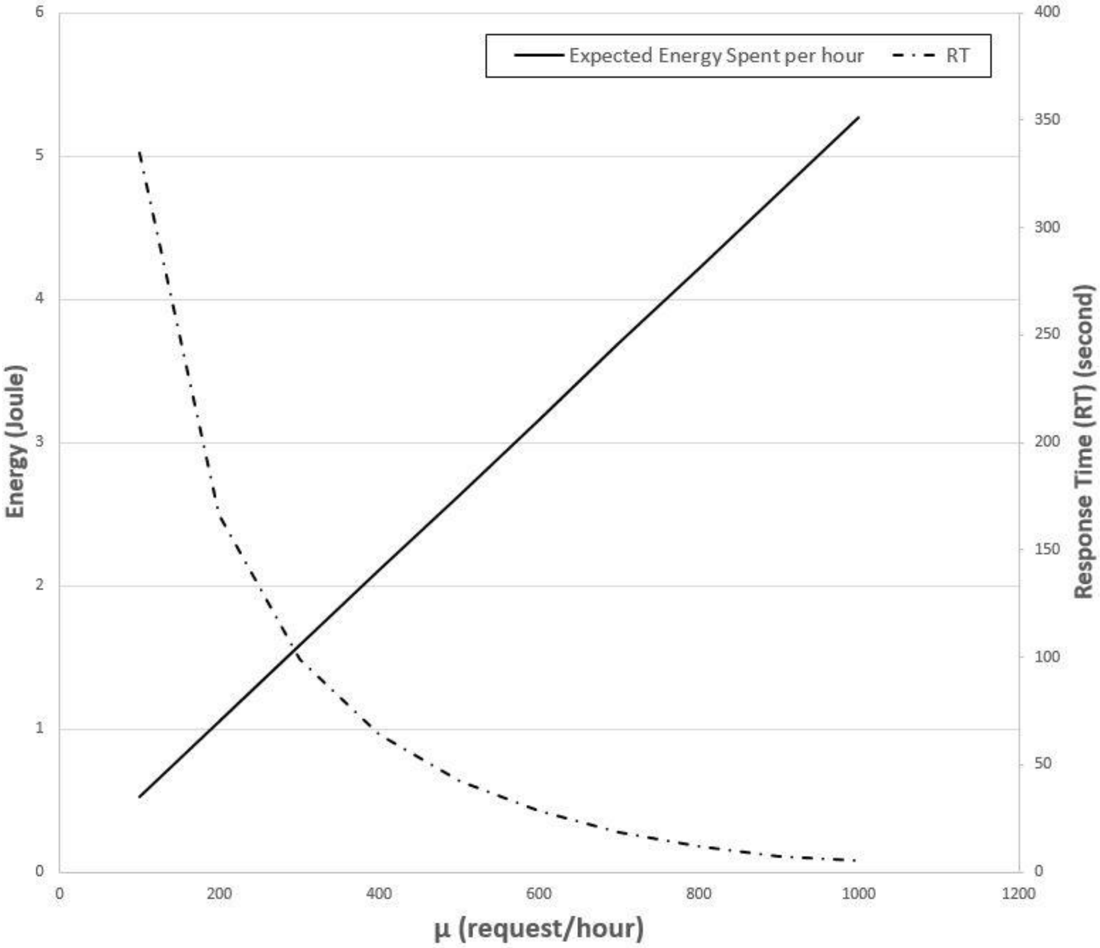


Figure 7.4: Response time and energy spent per hour as a function of service rate

In order to further highlight the effectiveness and the accuracy of the proposed model as well as the effects of channel failures on the performance of the system, Table 7.2 is presented. Table 7.2 displays the effects of channel failures on the MQL and throughput. The results were obtained from the simulation and analytical models by varying σ and channel failure rate (ξ), while keeping μ, μ_{cd}, and η fixed.

Table 7.2: The effects of channel failures on MQL and throughput

<table>
<tr><th colspan="7">ξ = 0.001</th></tr>
<tr><th><i>σ</i></th><th><i>MQL</i></th><th><i>MQL-SIM</i></th><th><i>γ</i></th><th><i>γ-SIM</i></th><th><i>Time</i></th><th><i>Time-SIM</i></th></tr>
<tr><td>1650</td><td>8.031</td><td>8.033</td><td>1309.13</td><td>1309.41</td><td>2.515</td><td>9100.18</td></tr>
<tr><td>1900</td><td>10.653</td><td>10.654</td><td>1447.87</td><td>1448.08</td><td>2.25</td><td>6269.49</td></tr>
<tr><td>2200</td><td>15.319</td><td>15.323</td><td>1549.85</td><td>1550.10</td><td>2.203</td><td>7286.84</td></tr>
<tr><td>2400</td><td>19.312</td><td>19.316</td><td>1580.35</td><td>1570.12</td><td>2.141</td><td>7966.4</td></tr>
<tr><td>2650</td><td>24.891</td><td>24.893</td><td>1593.61</td><td>1593.86</td><td>2.016</td><td>8825.34</td></tr>
<tr><th colspan="7">ξ = 0.01</th></tr>
<tr><th><i>σ</i></th><th><i>MQL</i></th><th><i>MQL-SIM</i></th><th><i>γ</i></th><th><i>γ-SIM</i></th><th><i>Time</i></th><th><i>Time-SIM</i></th></tr>
<tr><td>1650</td><td>8.2769</td><td>8.2765</td><td>1298.72</td><td>1299.05</td><td>2.156</td><td>6219.46</td></tr>
<tr><td>1900</td><td>11.087</td><td>11.089</td><td>1429.46</td><td>1429.71</td><td>0.797</td><td>7214.63</td></tr>
<tr><td>2200</td><td>15.964</td><td>15.965</td><td>1522.47</td><td>1522.77</td><td>0.64</td><td>8354.41</td></tr>
<tr><td>2400</td><td>20.038</td><td>20.043</td><td>1549.55</td><td>1549.77</td><td>0.766</td><td>9222.28</td></tr>
<tr><td>2650</td><td>25.656</td><td>25.655</td><td>1561.15</td><td>1561.59</td><td>0.672</td><td>10159.2</td></tr>
<tr><th colspan="7">ξ = 0.05</th></tr>
<tr><th><i>σ</i></th><th><i>MQL</i></th><th><i>MQL-SIM</i></th><th><i>γ</i></th><th><i>γ-SIM</i></th><th><i>Time</i></th><th><i>Time-SIM</i></th></tr>
<tr><td>1650</td><td>11.172</td><td>11.198</td><td>1175.85</td><td>1175.03</td><td>2.687</td><td>6154.57</td></tr>
<tr><td>1900</td><td>15.181</td><td>15.200</td><td>1255.69</td><td>1255.22</td><td>0.641</td><td>7120.35</td></tr>
<tr><td>2200</td><td>21.101</td><td>21.141</td><td>1304.47</td><td>1303.1</td><td>0.672</td><td>8269.22</td></tr>
<tr><td>2400</td><td>25.515</td><td>25.530</td><td>1317.12</td><td>1316.79</td><td>0.718</td><td>9068.28</td></tr>
<tr><td>2650</td><td>31.286</td><td>31.294</td><td>1322.22</td><td>13322.4</td><td>0.657</td><td>10093.5</td></tr>
</table>

It should be noted that in all the results obtained so far using the simulation and analytical models, expected channel failure rate (ξ) of 0.001 per hour was considered. Results in Table 7.2 are presented for cases with different failure rates in order to display the effects of fault tolerant nature of the channels (servers). Similar to Table 7.2, Figures 7.5 and 7.6 also show the effects of higher channel failure rates on the performance measures of the system such as MQL and throughput. The figures obviously show that if the failure rate of the channels (servers) in the system increases, the MQL also increases. That is because the increased number of users stay in the queue as a result of reduced number of available channels (servers). Also, the throughput of the system declines, since the number of available service facilities reduces with the increasing failure rates.

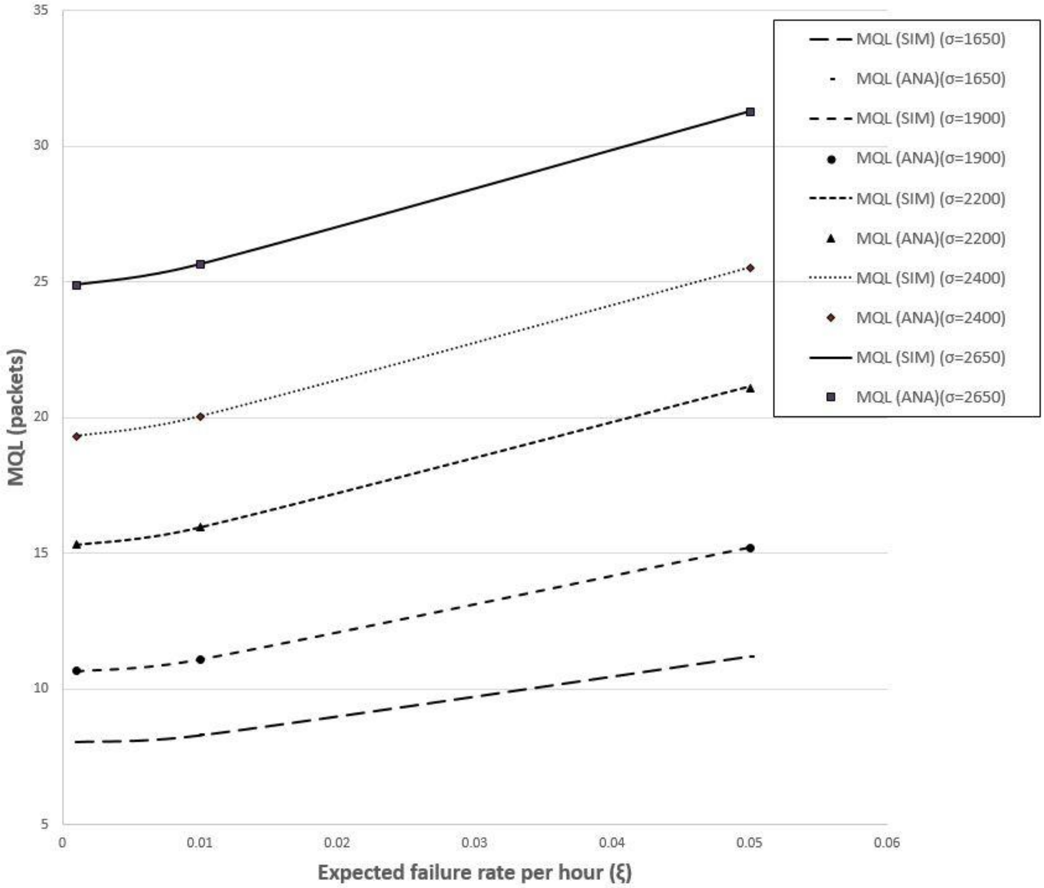


Figure 7.5: The effects of channel failures on MQL

The results in Table 7.2 reveal that the availability of the channels (servers) can significantly affect the performance of a femtocell system, especially for high failure rates. The simulation results confirm that the results achieved by the analytical model are precise. The maximum discrepancies between the analytical models and simulation are 0.19%, and 0.65% for the values of MQL and throughput respectively. Table 7.2 also shows the efficiency of the proposed approach in terms of computation time. For instance, in the case of σ = 1650 and ξ = 0.001, the execution time for the calculation of MQL and throughput was 9100 seconds while it was only

2.515 seconds for the analytical approach to execute the same tasks.

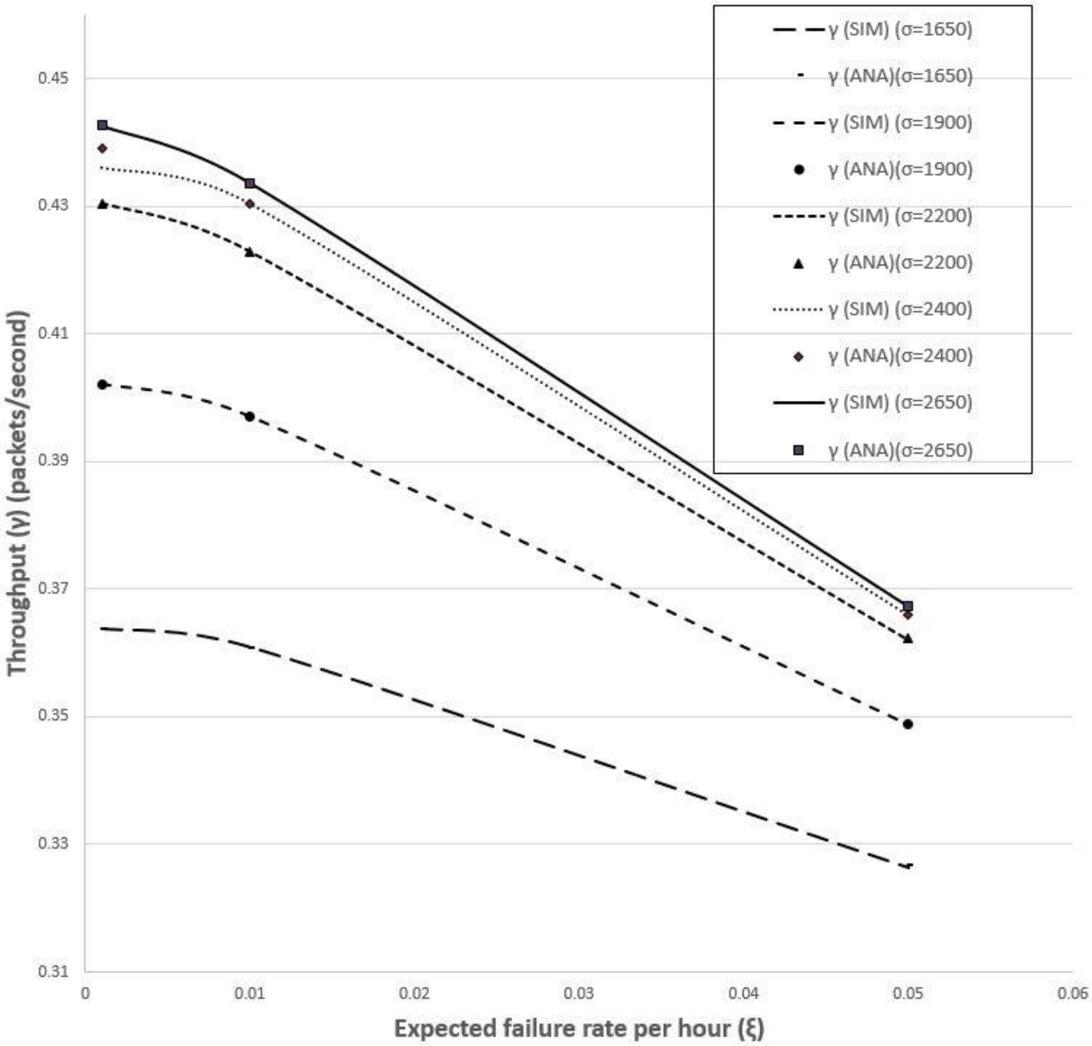


Figure 7.6: The effects of channel failures on throughput

Chapter 8

CONCLUSION AND FUTURE STUDY

8.1 Conclusion

In the current study, a hybrid wireless cellular HetNet consisting of a macrocell and several small cells is considered as a typical case study in smart-cities in presence of failures and recoveries. A new analytical model is presented to model small cells such as femtocells which are quite popularly deployed within the coverage area of macrocells to support increasing traffic loads in smart-city environments. With the introduction of IoT (Al-Turjman and Gunay, 2016), the aid of highly available small cells such as femtocells in such HetNets for the increasing traffic loads will become very important (Al-Dulaimi et al., 2015).

The results obtained from the simulation and analytical models reveal that traffic loads and velocity of the mobile users are vital parameters affecting the performance metrics of the system such as MQL, throughput, and response time as well as the mean energy consumed by the small cell BS. Increasing traffic load in the small cell results in increase in MQL, throughput, and response time since increased number of mobile users request service from the small cell BSs. However, it is obviously shown by the results that for medium- and high-velocity mobile users, traffic load does not affect the response time as significantly as low-velocity mobile users. Unlike the existing studies in the literature, in this thesis, the effects of channel failures on the performance metrics of the system are examined as well and the results presented in

Figures 7.5 and 7.6, and Table 7.2 show the importance of fault tolerance for similar systems under consideration.

It is clear from the results that the analytical approach is accurate with the maximum discrepancy of 1.83% when compared with the simulation results which is less that the confidence interval of the simulation (5%). In addition, the analytical approach can improve the computation time up to more than 34000 times compared to the simulation. Therefore, the analytical technique is an efficient one in terms of computation time. Such an efficient and precise approach can be quite useful in specifying the operative space for femtocells. For instance, as shown earlier in Chapter 7, the threshold between the response time and mean energy consumption is quite important and a well-informed decision is necessary in order to specify the system parameters in the most appropriate way.

8.2 Suggestions for Future Study

A number of research issues and recommendations are outlined below for future investigation.

- A typical HetNet may consist of thousands of macrocell sites and maybe millions of small cells such as femtocells. Therefore, it is really a challenging issue to keep up to date information on the small cells. Scalability is one of the key design features in small cells, and must be encompassed by the deployment and data traffic modeling. The deployment strategy should be scalable enough to make it work with a growing number of UEs, and constantly assures the precise behavior of the application. Furthermore, it should be adjusted to scalability changes in a transparent way, i.e., without the need for the intervention of the user. Therefore, research into solutions applied on small cell BS management would be beneficial in order to have systems that are adapted to various transmission environments and available resources.

- Interference is one of the most significant technical challenges for the dense deployment of small cells. For example, in femtocells, interference can be of two types; cross-tier interference (femto-to-macro) and co-tier interference (femto-to-femto). Interference is an important issue in the deployment of small cells which limits the overall performance of the network and degrades QoS and network capacity. Therefore, more research into interference management algorithms and techniques such as interference cancellation and/or avoidance is of great importance to assure an acceptable level of QoS and improve the performance metrics of the system.

- In this thesis, Analytical modelling approach used to investigate a number of performance metrics of the system such as MQL, throughput, and response time in a single FBS in HetNet environments. This modelling approach should also be utilized to investigate the aforementioned performance metrics for multiple FBSs (small cell BSs) in HetNet setups since interference caused by dense deployment of small cells in HetNet environments may degrade the performance of the whole system quite significantly. Similarly, the simulation tool used in this thesis should also be further extended to consider this issue.

REFERENCES

Ahmed, A. U., Islam, M. T., Ismail, M., & Ghanbarisabagh, M. (2014). Dynamic resource allocation in hybrid access femtocell network. *The Scientific World Journal*.

Al-Fagih, A. E., Al-Turjman, F. M., Alsalih, W. M., & Hassanein, H. S. (2013). A priced public sensing framework for heterogeneous IoT architectures. *IEEE Transactions on Emerging Topics in Computing*, 1(1), 133-147.

Alnabelsi, S. H., & Kamal, A. E. (2012). Performance modeling of secondary users in CRNs with heterogeneous channels. *IEEE Global Communications Conference (GLOBECOM)*, 1326-1331.

Ambene, G., & Anni, G. (2014). Queuing Theory and Telecommunications.

Ashraf, I., Boccardi, F., & Ho, L. (2010). Power savings in small cell deployments via sleep mode techniques. *Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops)*, IEEE 21st International Symposium, 307-311.

Ashraf, I., Claussen, H., & Ho, L. T. (2010). Distributed radio coverage optimization in enterprise femtocell networks. *IEEE International Conference of Communications (ICC)*, 1-6.

Avilés, J. M. R., Toril, M., & Luna-Ramírez, S. (2015). A femtocell location strategy for improving adaptive traffic sharing in heterogeneous LTE networks. *EURASIP Journal on Wireless Communications and Networking,* (1), 1.

Baloch, R. A., Awan, I., & Min, G. (2010). A mathematical model for wireless channel allocation and handoff schemes. *Telecommunication Systems,* 45(4), 275-287.

Banks, J., Carson, J. S., Nelson, B. L., & Nicol, D. M. (2005), Discrete-Event System Simulation, (4th ed.). *Prentice-Hall: Upper Saddle River, NJ.*

Beigy, H., & Meybodi, M. R. (2015). A learning automata-based adaptive uniform fractional guard channel algorithm. *The Journal of Supercomputing,* 71(3), 871-893.

Bisio, I., Lavagetto, F., Marchese, M., & Sciarrone, A. (2015). Smartphone-centric ambient assisted living platform for patients suffering from co-morbidities monitoring. *IEEE Communications Magazine,* 53(1), 34-41.

Boccuzzi, J., & Ruggiero, M. (2010). Femtocells: design & application. *McGraw Hill Professional.*

Bolch, G., Greiner, S., de Meer, H., & Trivedi, K. S. (2006). Queueing networks and Markov chains: modeling and performance evaluation with computer science applications. *John Wiley & Sons.*

Borodakiy, V. Y., Gudkova, I. A., Markova, E. V., & Samouylov, K. E. (2014). Modelling and performance analysis of pre-emption based radio admission control scheme for video conferencing over LTE. *IEEE ITU Kaleidoscope Academic Conference: Living in a converged world-Impossible without standards*, 53-59.

Bouras, C., Kavourgias, G., Kokkinos, V., & Papazois, A. (2012). Interference management in LTE femtocell systems using an adaptive frequency reuse scheme. *IEEE Wireless Telecommunications Symposium (WTS)*, 1-7.

Carvalho, G. H., Woungang, I., Anpalagan, A., & Hossain, E. (2016). QoS-Aware Energy-Efficient Joint Radio Resource Management in Multi-RAT Heterogeneous Networks. *IEEE Transactions on Vehicular Technology*, 65(8), 6343-6365.

Celik, A., & Kamal, A. E. (2016a). Green Cooperative Spectrum Sensing and Scheduling in Heterogeneous Cognitive Radio Networks. *IEEE Transactions on Cognitive Communications and Networking*, 2(3), 238-248.

Celik, A., & Kamal, A. E. (2016b). Multi-objective clustering optimization for multi-channel cooperative spectrum sensing in heterogeneous green CRNs. *IEEE Transactions on cognitive communications and networking*, 2(2), 150-161.

Chakka, R. (1995), Performance and Reliability Modelling of Computing Systems Using Spectral Expansion, PhD Thesis, University of Newcastle Upon Tyne, UK.

Chakka, R. (1998). Spectral expansion solution for some finite capacity queues. *Annals of Operations Research*, 79, 27-44.

Chakka, R., & Mitrani, I. (1992). A numerical solution method for multiprocessor systems with general breakdowns and repairs. *Proceedings of the 6th International Conference Modelling Techniques and Tools*, 289-304.

Chakka, R., & Mitrani, I. (1994). Heterogeneous multiprocessor systems with breakdowns: performance and optimal repair strategies. *Theoretical Computer Science*, 125(1), 91-109.

Chakka, R., & Mitrani, I. (1995). Approximate analysis of open queueing networks with breakdowns and repairs. *Stochastic Networks Workshop, to be held in Edinburgh*.

Chandrasekhar, V., Andrews, J.G. & Gatherer, A., (2008). Femtocell networks: a survey. *IEEE Communications magazine*, 46(9), 59-67.

Chandrasekhar, V., Andrews, J. G., Muharemovic, T., Shen, Z., & Gatherer, A. (2009). Power control in two-tier femtocell networks. *IEEE Transactions on Wireless Communications*, 8(8).

Chen, Y., Zhang, S., Xu, S., & Li, G. Y. (2011). Fundamental trade-offs on green wireless networks. *IEEE Communications Magazine*, 49(6), 30-37.

Chowdhury, M. Z., & Jang, Y. M. (2013). Handover management in high-dense femtocellular networks. *EURASIP Journal on Wireless Communications and Networking*, (1), 1-21.

Chu, Y. K., & Ke, J. C. (2006). Confidence intervals of mean response time for an M/G/1 queueing system: Bootstrap simulation. *Applied Mathematics and Computation*, 180(1), 255-263.

Cisco VNI Global Mobile Data Traffic Forecast, 2015-2020, Available online: http://www.cisco.com/.

Claussen, H., Ho, L. T., & Samuel, L. G. (2008). Self-optimization of coverage for femtocell deployments. *IEEE Wireless Telecommunications Symposium (WTS)*, 278-285.

Claussen, H. (2007). Performance of macro-and co-channel femtocells in a hierarchical cell structure. *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, 1-5.

Cox, C. (2012). An introduction to LTE: LTE, LTE-advanced, SAE and 4G mobile communications. *John Wiley & Sons*.

Crosby, G. V., & Vafa, F. (2013). Wireless sensor networks and LTE-A network convergence. *IEEE 38th Local Computer Networks (LCN)*, 731-734.

Da Silva, A. P. C., Meo, M., & Marsan, M. A. (2012). Energy-performance trade-off in dense WLANs: A queuing study. *Computer Networks*, 56(10), 2522-2537.

Dayar, T. (1998). State Space Orderings for Gauss--Seidel in Markov Chains Revisited. *SIAM Journal on Scientific Computing*, 19(1), 148-154.

De, D., & Mukherjee, A. (2014). Femtocell based economic health monitoring scheme using mobile cloud computing. *IEEE Advance Computing Conference (IACC),* 385-390.

Deruyck, M., De Vulder, D., Joseph, W., & Martens, L. (2012a). Modelling the power consumption in femtocell networks. *IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 30-35.

Deruyck, M., Vereecken, W., Joseph, W., Lannoo, B., Pickavet, M., & Martens, L. (2012b). Reducing the power consumption in wireless access networks: Overview and recommendations. *Progress in Electromagnetics Research*, 132, 255-274.

El-atty, S. M. A., & Gharsseldien, Z. M. (2015). Measuring QoS Metrics in Femto/Macro Cellular Networks with CAC Policy. *International Journal of Wireless Information Networks*, 22(3), 240-251.

El Bouabidi, I., Zarai, F., Obaidat, M. S., & Kamoun, L. (2014). Design and analysis of secure host-based mobility protocol for wireless heterogeneous networks. *The Journal of Supercomputing,* 70(3), 1036-1050.

Elwalid, A. I., Mitra, D., & Stern, T. E. (1991). Statistical multiplexing of Markov modulated sources: theory and computational algorithms. *Teletraffic and*

Datatraffic in a Period of Change, North Holland, 135.

Emelianova, E., Park, S., & Bahk, S. (2012). Deployment algorithm for femtocells in multi-tiered wireless cellular network. *IEEE International Conference on ICT Convergence (ICTC),* 131-136.

Ettl, M., & Mitrani, I. (1994). Applying spectral expansion in evaluating the performance of multiprocessor systems. *Performance Evaluation of Parallel and Distributed Systems,* 1, 45-58.

Ever, E. (2014). Fault-Tolerant Two-Stage Open Queuing Systems with Server Failures at Both Stages. *IEEE Communications Letters,* 18(9), 1523-1526.

Ever, E. (2016). Performability analysis of cloud computing centers with large numbers of servers. *The Journal of Supercomputing,* 1-27.

Ever, E., Al-Turjman, F. M., Zahmatkesh, H., & Riza, M. (2017). Modelling green HetNets in dynamic ultra large-scale applications: A case-study for femtocells in smart-cities. *Computer Networks*.

Ever, E., Gemikonakli, O., Kocyigit, A., & Gemikonakli, E. (2013). A hybrid approach to minimize state space explosion problem for the solution of two stage tandem queues. *Journal of Network and Computer Applications,* 36(2), 908-926.

Fagen, D., Vicharelli, P. A., & Weitzen, J. (2008). Automated wireless coverage optimization with controlled overlap. *IEEE Transactions on Vehicular Technology*, 57(4), 2395-2403.

Feng, D., Jiang, C., Lim, G., Cimini, L. J., Feng, G., & Li, G. Y. (2013). A survey of energy-efficient wireless communications. *IEEE Communications Surveys and Tutorials*, 15(1), 167-178.

Ferro, E., & Potorti, F. (2005). Bluetooth and Wi-Fi wireless protocols: a survey and a comparison. *IEEE Wireless Communications,* 12(1), 12-26.

Ge, X., Han, T., Zhang, Y., Mao, G., Wang, C. X., Zhang, J., & Pan, S. (2014). Spectrum and energy efficiency evaluation of two-tier femtocell networks with partially open channels. *IEEE Transactions on Vehicular Technology,* 63(3), 1306-1319.

Gong, J., Zhou, S., & Niu, Z. (2011). Queuing on energy-efficient wireless transmissions with adaptive modulation and coding. *IEEE International Conference on Communications (ICC),* 1-5.

Haider, F., Wang, C. X., Ai, B., Haas, H., & Hepsaydir, E. (2016). Spectral/Energy Efficiency Tradeoff of Cellular Systems with Mobile Femtocell Deployment. *IEEE Transactions on Vehicular Technology,* 65(5), 3389-3400.

Haider, F., Wang, C. X., Haas, H., Yuan, D., Wang, H., Gao, X., & Hepsaydir, E. (2011). Spectral efficiency analysis of mobile femtocell based cellular systems. In Communication Technology (ICCT). *IEEE 13th International*

Conference, 347-351.

Haverkort, B. R., & Ost, A. (1997). Steady-state analysis of infinite stochastic Petri nets: Comparing the spectral expansion and the matrix-geometric method. In *Proceedings of the Seventh IEEE International Workshop on Petri Nets and Performance Models,* 36-45.

Horton, G., & Leutenegger, S. T. (1994). A multi-level solution algorithm for steady-state Markov chains. ACM, 22(1), 191-200.

Jain, A., Tawar, K., & Rathore, A. (2013). Optimal placement of femtocell base station for indoor environment. *IEEE International Conference in Advanced Computing and Communication Systems (ICACCS),* 1-5.

Jain, R. (1991). The Art of Computer Systems Performance Analysis. *John Wiley & Sons, Inc.*

Ji, Z., Sarkar, T. K., & Li, B. H. (2002). Methods for optimizing the location of base stations for indoor wireless communications. *IEEE Transactions on Antennas and Propagation,* 50(10), 1481-1483.

Khalifah, A., Akkari, N., & Aldabbagh, G. (2014). Dense areas femtocell deployment: Access types and challenges. *IEEE 3rd International Conference in e-Technologies and Networks for Development (ICeND),* 64-69.

Kinney, P. (2003). Zigbee technology: Wireless control that simply works.

Communications design conference, Vol. 2, 1-7.

Kirsal, Y., Ever, E., Kocyigit, A., Gemikonakli, O., & Mapp, G. (2014). A Generic Analytical Modelling Approach for Performance Evaluation of the Handover Schemes in Heterogeneous Environments. *Wireless personal communications,* 79(2), 1247-1276.

Kirsal, Y., Ever, E., Kocyigit, A., Gemikonakli, O., & Mapp, G. (2015). Modelling and analysis of vertical handover in highly mobile environments. *The Journal of Supercomputing,* 71(12), 4352-4380.

Kirsal, Y., & Gemikonakli, O. (2009). Performability modelling of handoff in wireless cellular networks with channel failures and recovery. *IEEE 11th International Conference in Computer Modelling and Simulation (UKSIM),* 544-547.

Kirsal, Y., Gemikonakli, O., Ever, E., & Mapp, G. (2012). Performance analysis of handovers to provide a framework for vertical handover policy management in heterogeneous environments. *The 45th Annual Simulation Symposium in Society for Computer Simulation International*.

Kong, P. Y. (2015). A Markov chain model for packet queueing delay analysis of a mobile user in HetNets. *IEEE Wireless Communications and Networking Conference (WCNC)*, 1990-1995.

Kshetrimayum, R. S. (2009). An introduction to UWB communication systems. *IEEE*

Potentials, 28(2), 9-13.

Kumar, W. A. N. O. D., Kumar, P. A. R. D. E. E. P., & Halepoto, I. A. (2013). Performance Analysis of an Energy Efficient Femtocell Network Using Queuing Theory. *Mehran University Research Journal of Engineering & Technology,* 32(3), 535-542.

Kumar, W. A. N. O. D., Aamir, S. A. M. R. E. E. N., & Qadeer, S. A. R. A. (2014). Performance Analysis of a Finite Capacity Femtocell Network. *Mehran University Research Journal of Engineering & Technology*, 33(1), 129-136.

Kwon, Y. J., & Cho, D. H. (2011). Load based cell selection algorithm for faulted handover in indoor femtocell network. *IEEE 73rd Vehicular Technology Conference (VTC),* 1-5.

Law, A. M. (2007). Statistical analysis of simulation output data: the practical state of the art. *IEEE Simulation Conference,* 77–83.

Law, A. & Kelton W. D. (2000). Simulation Modelling and Analysis (3rd ed.), *McGraw-Hill: NY, USA.*

Lopez-Perez, D., Guvenc, I., & Chu, X. (2012). Mobility management challenges in 3GPP heterogeneous networks. *IEEE Communications Magazine,* 50(12), 70-78.

López, J. D. S., Arturo, A. M., Mendieta, F. J., & Hipólito, I. N. (2011). Trends of the

Optical Wireless Communications, Advanced Trends in Wireless Communications, Dr. Mutamed Khatib (Ed.). *InTech, DOI: 10.5772/15493.* Available from: http://www.intechopen.com/books/advanced-trends-in-wireless-communications/trends-of-the-optical-wireless-communications

Ma, Y., Han, J. J., & Trivedi, K. S. (2001). Composite performance and availability analysis of wireless communication networks. *IEEE Transactions on Vehicular Technology*, 50(5), 1216-1223.

Maciuca, A., Stamatescu, G., Popescu, D., & Struţu, M. (2013). Integrating wireless body and ambient sensors into a hybrid femtocell network for home monitoring. *IEEE 2nd International Conference in Systems and Computer Science (ICSCS)*, 32-37.

Mahmud, S. A., Khan, G. M., Zafar, H., Ahmad, K., & Behttani, N. (2013). A survey on femtocells: Benefits deployment models and proposed solutions. *Journal of applied research and technology*, 11(5), 733-754.

Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., & Marrs, A. (2013). Disruptive technologies: Advances that will transform life, business, and the global economy. *San Francisco, CA: McKinsey Global Institute*, Vol. 180.

Marsan, M. A., & Meo, M. (2014). Queueing systems to study the energy consumption of a campus WLAN. *Computer networks*, 66, 82-93.

McDermott-Wells, P. (2004). What is bluetooth?. *IEEE potentials,* 23(5), 33-35.

Mitrani, I., & Chakka, R. (1995). Spectral expansion solution for a class of Markov models: Application and comparison with the matrix-geometric method. *Performance Evaluation*, 23(3), 241-260.

Mitrani, I., & Mitra, D. (1992). A spectral expansion method for random walks on semi-infinite strips. *Iterative methods in linear algebra,* 141-149.

Morrison, P. S., & Huber, K. D. (2010). U.S. Patent No. 7,855,977. *Washington, DC: U.S. Patent and Trademark Office*.

Mukherjee, A., & De, D. (2014). Femtocell based green health monitoring strategy. *IEEE General Assembly and Scientific Symposium (URSI GASS),* 1-4.

Nakamura, T., Nagata, S., Benjebbour, A., Kishiyama, Y., Hai, T., Xiaodong, S., & Nan, L. (2013). Trends in small cell enhancements in LTE advanced. *IEEE Communications Magazine,* 51(2), 98-105.

Navigant Consulting Res., Commercial building automation systems, Boulder, CO, USA, 2013.

Neuts, M. F. (1981). Matrix Geometric Solutions, Johns Hopkins University Press.

Neuts, M. F. (1984). Matrix-Geometric Solutions to Stochastic Models. *DGOR, Springer Berlin Heidelberg*, 425-425.

Ngadiman, Y., Chew, Y. H., & Yeo, B. S. (2005). A new approach for finding optimal base stations configuration for CDMA systems jointly with uplink and downlink constraints. *IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications,* Vol. 4, 2751-2755.

Ngo, D. T., & Le-Ngoc, T. (2014). Architectures of small-cell networks and interference management. *Springer*.

Okino, K., Nakayama, T., Yamazaki, C., Sato, H., & Kusano, Y. (2011). Pico cell range expansion with interference mitigation toward LTE-Advanced heterogeneous networks. In *IEEE International Conference on Communications Workshops (ICC),* 1-5.

Qutqut, M. H., Abou-zeid, H., Hassanein, H. S., Rashwan, A. M., & Al-Turjman, F. M. (2014). Dynamic small cell placement strategies for LTE heterogeneous networks. *IEEE Symposium on Computers and Communications (ISCC),* 1-6.

Qutqut, M. H., Al-Turjman, F. M., & Hassanein, H. S. (2013). MFW: Mobile femtocells utilizing WiFi: A data offloading framework for cellular networks using mobile femtocells. *IEEE International Conference on Communications (ICC),* 6427-6431.

Pal, S., Babu, K. V., Arthi, M., & Arulmozhivarman, P. (2016). A cost-effective eNB deployment strategy for beyond 4G heterogeneous cellular networks. In *IEEE International Conference on Communication and Signal Processing (ICCSP),* 0138-0142.

Park, R. C., Jung, H., Chung, K., & Yoon, K. H. (2015). Picocell based telemedicine health service for human UX/UI. *Multimedia Tools and Applications*, 74(7), 2519-2534.

Riggio, R., & Leith, D. J. (2012). A measurement-based model of energy consumption in femtocells. *Wireless Days*.

Saunders, S. R., Carlaw, S., Giustina, A., Bhat, R. R., Rao, V. S., & Siegberg, R. (2009). Femtocells: opportunities and challenges for business and technology. *John Wiley & Sons.*

Seelen, L. P. (1986). An Algorithm for Ph/Ph/c Queues, *European Journal of Operations Research*, 23(1), 118-127.

Selim, M., Kamal, A., Elsayed, K., Abd-El-Atty, H., & Alnuem, M. (2016). Self-Healing in 5G HetNets. In *Opportunities in 5G Networks: A Research and Development Perspective*, 149-177.

Singh, G. T., & Al-Turjman, F. M. (2016). A data delivery framework for cognitive information-centric sensor networks in smart outdoor monitoring. *Computer Communications,* 74, 38-51.

Singh, S., & Singh, Y. P. (2014). The Emerging Technology – Li-Fi Using Femtocells. *International Journal of Scientific Research and Reviews,* 3(4), 115-120, Available online at www.ijsrr.org.

Tabany, M. R., & Guy, C. G. (2015). A mobility prediction scheme of LTE/LTE-A femtocells under different velocity scenarios. *20th International Workshop in Computer Aided Modelling and Design of Communication Links and Networks (CAMAD),* 318-323.

The Voice of 5G for the Americas (2015), Cellular Technologies Enabling the Internet of Things - 4G Americas, White paper.

Tran, H. T., & Do, T. V. (1999). Comparison of computational methods for QBD processes. In *Proceedings of the 4th International Conference on Applied Informatics*, 299-311.

Trivedi, K. S. (2002). Probability and Statistics with Reliability, Queuing, and Computer Science Applications. *Wiley, NY, USA.*

Trivedi, K., & Ma, X. (2002). Performability analysis of wireless cellular networks. *In Proceedings of Symposium on Performance Evaluation of Computer and Telecommunication System (SPECTS).* San Diego, USA.

Trivedi, K. S., Dharmaraja, S., & Ma, X. (2002). Analytic modeling of handoffs in wireless cellular networks. *Information Sciences,* 148(1), 155-166.

Valcarce, A., & López Pérez, D. (2010). Interference in the presence of femtocells. Femtocells: *Technologies and Deployment,* 145-178.

Vodafone Group, 'Open and semi-open access support for UTRA Home NB,' 3GPP-

TSG RAN, Prague, Czech Republic, Tech. Rep. R2-085280, Oct. 2008.

Wang, S., Guo, W., & O'Farrell, T. (2012). Optimising Femtocell Placement in an Interference Limited Network: Theory and Simulation. *IEEE Vehicular Technology Conference (VTC),* 1-6.

Wang, W., & Shen, G. (2010). Energy efficiency of heterogeneous cellular network. *IEEE 72nd Vehicular Technology Conference Fall (VTC*), 1-5.

Wu, S. J. (2011). A new handover strategy between femtocell and macrocell for LTE-based network. *IEEE 4th International Conference on Ubi-Media Computing (U-Media),* 203-208.

Yaacoub, E. (2016). Green 5G Femtocells for Supporting Indoor Generated IoT Traffic. In Internet of Things (IoT) in 5G Mobile Technologies. *Springer International Publishing,* 129-152.

Zahir, T., Arshad, K., Nakata, A., & Moessner, K. (2013). Interference management in femtocells. *IEEE Communications Surveys & Tutorials,* 15(1), 293-311.

Zeng, Q. A., & Agrawal, D. P. (2001). Modeling of handoffs and performance analysis of wireless data networks. *IEEE International Conference in Parallel Processing Workshops,* 491-496.

Zeng, Q. A., & Agrawal, D. P. (2002). Modeling and efficient handling of handoffs in integrated wireless mobile networks. *IEEE Transactions on Vehicular*

Technology, 51(6), 1469-1478.

Zhang, H., Wen, X., Wang, B., Zheng, W., & Sun, Y. (2010). A novel handover mechanism between femtocell and macrocell for LTE based networks. *IEEE 2nd International Conference on Communication Software and Networks (ICCSN),* 228-231.

Zhang, H., Wu, H. C., & Guo, L. (2015). Multimedia services scheduling optimization using femtocell on high-speed trains. *IEEE Wireless Communications and Networking Conference (WCNC),* 464-469.

Zhang, H., Zheng, W., Chu, X., Wen, X., Tao, M., Nallanathan, A., & López-Pérez, D. (2012). Joint sub-channel and power allocation in interference-limited OFDMA femtocells with heterogeneous QoS guarantee. *IEEE Global Communications Conference (GLOBECOM),* 4572-4577.

Zhang, J., & De la Roche, G. (2010). Femtocells: technologies and deployment. *New York: Wiley,* 1-13.