ISTANBUL TECHNICAL UNIVERSITY ★ INFORMATICS INSTITUTE

INTRA-CELL FREQUENCY BAND EXILING IN GREEN CELLULAR NETWORKS

M.Sc. THESIS

Ahmet Burak ÖZYURT

Applied Informatics Department

Information and Communications Engineering Programme

DECEMBER 2019

ISTANBUL TECHNICAL UNIVERSITY ★ INFORMATICS INSTITUTE

INTRA-CELL FREQUENCY BAND EXILING IN GREEN CELLULAR NETWORKS

M.Sc. THESIS

Ahmet Burak ÖZYURT
(708181001)

Applied Informatics Department

Information and Communications Engineering Programme

Thesis Advisor: Prof. Dr. Lütfiye DURAK ATA

DECEMBER 2019

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ BİLİŞİM ENSTİTÜSÜ

ÇEVRECİ HÜCRESEL AĞLARDA HÜCRE İÇİ FREKANS BANT SÜRGÜNÜ

YÜKSEK LİSANS TEZİ

Ahmet Burak ÖZYURT
(708181001)

Bilişim Uygulamaları Anabilim Dalı

Bilgi ve Haberleşme Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Lütfiye DURAK ATA

ARALIK 2019

Ahmet Burak ÖZYURT, an M.Sc. student of ITU Informatics Institute ID 708181001 successfully defended the thesis entitled "INTRA-CELL FREQUENCY BAND EXILING IN GREEN CELLULAR NETWORKS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Lütfiye DURAK ATA** Istanbul Technical University	....
Jury Members :	**Assoc. Prof. Dr. Sinem ÇÖLERİ ERGEN** Koc University	....
	Assist. Prof. Dr. Mehmet Akif YAZICI Istanbul Technical University	....

Date of Submission : **15 November 2019**
Date of Defense : **18 December 2019**

To my grandfather,

FOREWORD

I would like to express my sincere gratitude to my awesome advisor, Prof. Dr. Lütfiye Durak Ata for giving me valuable advice during my graduate education. Her guidance have pushed me beyond my expectations and I wouldn't think of getting higher education without her support. It is a great chance to have the opportunity to work with her.

Besides my thesis advisor, my sincere thanks must also go to Dr. Mehmet Başaran and Mine Ardanuç for their great support. I would like to thank the members of the examining committee for their valuable discussion, comments and suggestions.

To all my family and especially my brother, I am greatly indebted to their encouragement, emotional support, and prayers. Also, there are other pillars, all my wonderful friends, which are my source of life. I am willing to give names but afraid to forget the one of them. They are in the deepest part of my heart and always will be in there.

I am very happy to dedicate thesis to my grandfather who always admire of my initiatives and studies. Also, I always see him as a role model in my life because of his humility, perseverance, and morality. When I talk with him, portrait of the true believer becomes more apparent in my mind. May God give him a healthy long life.

"Remember to look up at the stars and not down at your feet. Try to make sense of what you see and wonder about what makes the universe exist. Be curious. And however difficult life may seem, there is always something you can do and succeed at. It matters that you don't just give up."

Stephen Hawking

December 2019 Ahmet Burak ÖZYURT

TABLE OF CONTENTS

Page

ABBREVIATIONS

ASE	: Area Spectral Efficiency
BS	: Base Station
CAPEX	: Capital Expenditure
CSO	: Cell Switch On-Off
CRN	: Cognitive Radio Network
CZ	: Cell Zooming
CZF	: Cell Zooming Factor
DL	: Downlink
EE	: Energy Efficiency
ICE	: Intra-cell Frequency Band Exiling
ICT	: Information and Communications Technology
LFB	: Lower Frequency Band
LTE	: Long Term Evolution
MNO	: Mobile Network Operator
NR	: New Radio
OFDMA	: Orthogonal Frequency Division Multiplexing
OPEX	: Operational Expenditure
PPP	: Poisson Point Process
SE	: Spectral Efficiency
UE	: User Equipment
UFB	: Upper Frequency Band
UL	: Uplink

SYMBOLS

α	: Path Loss Exponent
d	: Distance
g	: Channel Gain
η_{ASE}	: Area Spectral Efficiency
η_{EE}	: Energy Efficiency
λ	: Intensity of mobile users
μ	: Mean Value
N_0	: Noise
P_{BS}	: Total Power Consumption of BS
P_c	: Cumulative Circuit Power of All Transmitters
P_T	: Transmit Power
S	: Size of Voronoi Cell
σ	: Standard Deviation
x_k	: Traffic Density
W	: Signal Bandwidth

LIST OF TABLES

Page

LIST OF FIGURES

Page

INTRA-CELL FREQUENCY BAND EXILING
IN GREEN CELLULAR NETWORKS

SUMMARY

Green communications has been gaining a lot of attraction in recent years due to the increasing power consumption in rapidly evolving cellular networks. With upcoming technology, namely 5G and beyond, some characteristics of the previous generations, such as data rate and delay, are expected to be enhanced. However, these demands cause not only more energy-related costs but also environmental consequences in the mobile communication industry. Information and communication technology (ICT) sector is responsible from 10% of the total energy consumption and 2% of global CO_2 emissions. Among the main ICT sectors, 37% of the total ICT energy consumption are due to the communication equipments. Also, many communication technology companies, taking actions for decreasing harmful effects of ICT tools, have announced that their 2025 goals are to reduce greenhouse gas emissions up to 40%.

The drive to make cellular networks more "green" begins with base stations (BSs) since, the power is mostly consumed by BSs at around 60%. Thus, smaller improvements in power consumption bring huge energy savings.

After all of that, the most important factor for determining the energy consumption level is traffic density. User traffic load varies in the cells during the day. The biggest reason for this is the mobility of mobile users. For example, while traffic density is high in working areas during the day, traffic density is much less in residential and living areas. In the evening, we can observe the opposite of this traffic intensity model. Setting parameters of each macrocell considering to the most dense time results in serving cells running under their own capacities. The 80% of BSs works in a serious unsaturated state in the 80% of all time. In the future, this traffic fluctuation is expected to become a more serious problem.

In next generation wireless network systems, it is envisaged to increase the energy efficiency by changing the coverage area of BSs by two basic methods: cell switch on-off (CSO) and cell zooming (CZ). However, neither CSO nor CZ are sufficient solutions for energy efficiency in wireless networks. These techniques may not guarantee to meet the demands such as covering whole service area, computational simplicity, and fast processing. Therefore, intra-cell frequency band exiling (ICE) is proposed as a promising energy-efficient technique due to the fact that radio units of lower frequency bands (LFBs) consume less power than radio units of upper frequency bands (UFBs). In ICE scenarios, we reduce the power consumed by a BS through switching the frequency bands. Hence, energy efficiency can be improved by assigning user equipments (UEs) from UFBs to LFBs.

In this work, we introduce an energy-efficient technique, ICE, by adjusting the coverage areas of multiple frequency bands supported by the communication network. Also, it is shown that total ASE and EE can be increased by ICE till $10^7 Kbytes/km^2$

traffic value. The contributions of this work are listed as: i) the condition for assigning users from a UFB to LFB is explained in terms of energy efficiency, ii) ICE probability of a cellular system is derived, iii) the performance of ICE is investigated in terms of ASE and EE, and iv) the trade-off between EE and ASE is provided.

ÇEVRECİ HÜCRESEL AĞLARDA
HÜCRE İÇİ FREKANS BANT SÜRGÜNÜ

ÖZET

Gelişen mobil haberleşme sistemleriyle birlikte artan baz istasyonları güç tüketiminde önemli bir artışa neden olmaktadır. Bu artış enerji verimli sistemleri ön plana çıkarmaktadır. Artan enerji tüketimi hızla gelişen mobil iletişim sistemlerinde kritik bir konudur. Yaklaşan 5G teknolojisi ile milyonlarca baz istasyonu ve milyarlarca akıllı cihaz için enerji verimli sistemlerin tasarlanması gerekmektedir. Günümüzde genellikle iletişim sistemleri, enerji verimliliğinden daha ziyade performans odaklı olarak tasarlanmaktadır. 2030 yılına ilişkin tahminlere göre, 50 milyar akıllı cihaz sisteme bağlanacak ve kişi başına altı akıllı cihaza sahip olunacaktır. 2030'da bilgi ve iletişim teknolojilerinin % 75'inin kablosuz olacağı düşünülürse enerji verimli sistemler gelecekte önemli bir rol oynayacaktır.

Günümüz teknolojisinde kullanılan büyük hücreler çok sayıda kullanıcının haberleşmesine imkan vermektedir. Fakat kendi kendilerini organize etmelerinde birçok zorluk bulunmaktadır. Kullanıcıların farklı bölgelerde yoğunlaşması ve veri kullanan cihazların sayısında görülen hızlı artış var olan büyük hücre altyapısı tarafından desteklenemeyecektir. Gelişen 5G teknolojisiyle büyük hücre yapısı yerine küçük hücreler kullanılmaya başlanacaktır. Gün boyunca mobil kullanıcıların hareketi nedeniyle hücrelerdeki trafik yoğunluğu değişkenlik gösterir. Eğer her makro hücre trafik yoğunluğunun en fazla olduğu zamana göre planlanırsa, sistemde daima kapasitesinin altında çalışan hücreler olacaktır. Hiçbir sabit hücre planlaması değişen trafik yüküne uygun bir çözüm getirmeyecektir. Gelecekte bu trafik dalgalanması daha ciddi bir enerji problemler oluşturacaktır. Baz istasyonları, mobil haberleşme sistemlerinde en çok güç tüketen unsur olup trafikteki dalgalanmalara bağlı enerji verimliliğinin artırılması için iki temel yöntem belirtilmektedir: hücre açma/kapama (cell switch on/off, CSO) ve hücre yakınlaştırma/uzaklaştırma (cell zooming, CZ) yöntemleri.

CSO'da kapsama alanındaki trafik yoğunluğu hesaplanıp belirlenen eşik değerinin altında çalışan baz istasyonlarının kapatılması amaçlanmaktadır. CSO'yu dinamik, statik ve hibrit olarak üç ana yöntem altında incelemek mümkündür. Dinamik CSO'da sistem, gerçek zamanlı veri kullanarak kapanacak aday hücreyi belirler. Bu nedenle, sistem trafik koşullarındaki değişikliklere kolayca uyum sağlar. Statik CSO'da geçmiş trafik bilgileri kullanılarak aylık veya mevsimsel olarak kapatılacak baz istasyonları belirlenir. Bu yöntem gerçek zamanlı veriye ihtiyaç duymaz. Bu nedenle sistem dinamik yönteme göre daha hızlı çalışır. Hibrit CSO'da statik ve dinamik yöntemler beraber uygulanır. Kapsama alanı sağlamak ve ağ bilgisi toplamak için önceden belirlenmiş bir aktif hücre takımı açık bırakılır. Geriye kalan hücreler ise trafikteki hızlı değişikliklere uyum sağlamak için hazırda kapalı bir şekilde tutulur. Hibrit CSO, işaret ile girişim ve gürültü oranı (SINR) bakımından dinamik CSO'dan, enerji verimliliği bakımından ise statik CSO'dan daha iyi bir performansa sahiptir. Kullanıcılar, baz

istasyonunun kapsama alanı içersinde düzgün bir dağılıma sahip olmadıklarında hibrit yöntemin kullanılması en uygundur. Bu çalışma, toplanan veriler her saat başı analiz edildiği için dinamik CSO olarak sınıflandırılabilir.

Bir diğer yöntem olan CZ'de, kapsama alanı dinamik değiştirilerek baz istasyonunun tükettiği güç azaltılmaya çalışılır. Bununla birlikte, kapsama alanı için baz istasyonunun güç tüketimi tüm sistemin yaklaşık % 10'unu oluşturmaktadır. Ayrıca enerji verimliliği, kullanıcıların farklı bir frekans bandına atanmasıyla artırılabilir. Hücrenin kapsama alanının artırıp azaltılmasında üç farklı yol önerilmiştir. Sürekli CZ tekniğinde, hücre kapsama alanı en uzaktaki kullanıcıya göre ayarlanır. Kesikli CZ tekniğinde, kapsama alanı istenen sayıda alanlara bölünür. Kapsama alanını değiştirmek isteyen istasyon hızlıca bir üst veya alt seviyeye geçerek kapsama alanını değiştirmiş olur. Bulanık CZ tekniğinde, kesikli CZ tekniğiyle belirlenen sınırlar yaklaşık % 10-20 arasında genişletilir. Yapılan benzetimlerde ölçülen SINR değerinin en iyi kesikli CZ'de, sonra bulanık ve sürekli CZ'de elde edilmiştir. Operatörün, kapatılacak veya kapsama alanı azaltılacak hücreye karar vermesinde; hücre yükü, iş hacmi, kullanıcı sayısı ve kullanılan ortalama veri miktarı gibi temel performans göstergeleri kullanılır. Yapılan çalışmalarda hücre yükleri, kullanıcı sayısı ve iyi SINR'a sahip kullanıcı sayısı CSO performans göstergeleri olarak incelenmiş ve en iyi performans, kullanıcı sayısının göz önünde bulundurulduğu durumda elde edilmiş olup bu çalışma da kullanıcı sayısı değişkenliği üzerine temellendirilmiştir. Ayrıca iki farklı frekans bandı (LFB/UFB) kullanılarak hem kapsama boşlukları önlenmiş hem de kullanıcıların UFB'den LFB'ye atanarak enerji verimliliğinin sağlanabileceği gösterilmiştir.

Hızla gelişen mobil haberleşme sistemleriyle artan enerji tüketimi, gelecek yıllarda mevcut sistemlerin enerji verimliliğinin artırılması üzerine odaklanılacağını göstermektedir. Fakat, CSO ve CZ yöntemleri her ne kadar da enerji verimliliği sağlayan yöntemler olsa da bazı eksik yönleri mevcuttur. Bu teknikler servis alanının tam kapsanmasını garanti etmez. Bu nedenle bazı kapsama boşlukları oluşabilir. Ayrıca hesaplama basitliği ve hızlı işlem gerekliliği bu yöntemler için pek yeterli düzeyde değildir.

Bu çalışmada, baz istasyonlarındaki frekans bantlarının kapsama alanlarının dinamik değiştilerek güç tüketiminde verimliliğe ve özellikle LTE sistemlerindeki eNodeB'lerin kapsama alanlarının verimli kullanımına odaklanan hücre içi frekans bant sürgünü yöntemi önerilmiştir. Yöntem sayesinde yüksek frekans bandındaki kullanıcılar daha az güç tüketen düşük frekans bantlarına atanır. Yöntemin uygulanabilirliği teorik ve pratik açıdan incelenmiştir. Bu çalışmayla hücresel sistemin farklı frekans bantlarındaki kapsama alanının belirli koşullar altında değiştirilmesi önerilmektedir. Yüksek frekans bandındaki (upper frequency band, UFB) kullanıcıların düşük frekans bandına (lower frequency band, LFB) atama etkisi analiz edilip farklı frekans bantlarının güç tüketimi özellikleri kıyaslanmıştır. Gerçek veriler yardımıyla önerilen yöntemin benzetimi yapılıp spektral ve enerji verimliliği bakımından değerlendirilmiştir.

Bu çalışmada, ilk olarak CSO ve CZ yöntemlerinin teorik arka planı sunulmaktadır. Ardından belirlenen problem ve bu çalışma sayesinde yaptığımız katkı açıklanmıştır. İkinci bölümde enerji verimli hücresel ağların tasarımıyla ilgili temel bilgiler verilmiştir. Spektral ve enerji verimliliğin sistemin performansını ölçmede iki temel parametre olduğu belirtildi. Üçüncü bölümde mevcut yöntemlere alternatif olarak önerilen hücre içi frekans bant sürgünü yöntemiyle ilgili ayrıntılar verilip, kullanılan gerçek veriler ve güç tüketim modelleri açıklanmıştır. Buna ek olarak, önerilen yöntemin performans ölçümünde kullanılan parametreler açıklanmıştır. Dördüncü bölümde benzetim sonuçları açıklanmış ve önerilen yöntemin belli bir trafik yoğunluğuna kadar verimlilik artışı gösterilmiştir. Son bölümde çalışma özetlenip, gelecekte çalışabilecek ucu açık konular verilmiştir.

1. INTRODUCTION

Green communications has been gaining a lot of attention in recent years due to the increasing power consumption in rapidly evolving cellular networks. With upcoming technology, namely 5G and beyond, some characteristics of the previous generations, such as data rate and delay, are tried to enhance. However, these concerns have not only environmental consequences but also energy-related costs in the mobile communication industry. According to a previous study, information and communication technology (ICT) sector is responsible of 10% of the total energy consumption and 2% of global CO_2 emissions [5]. Among the main ICT sectors, 37% of the total ICT energy consumption are due to communication equipments [6]. Also, many communication technology companies are taking actions for decreasing harmful effects of ICT tools including a worldwide mobile operator, which have announced that their 2025 goals are to reduce greenhouse gas emissons by 40% [7]. In Figure 1.1, it is shown that global energy consumption for network infrastructure and user equipment is increased year by year. During timescale, energy consumption of mobile user devices and mobile networks is expected to mount up more than fixed systems.

The drive to make cellular networks more "green" starts with base stations (BSs) because, around 60% percent of the power is consumed by base stations [8]. In

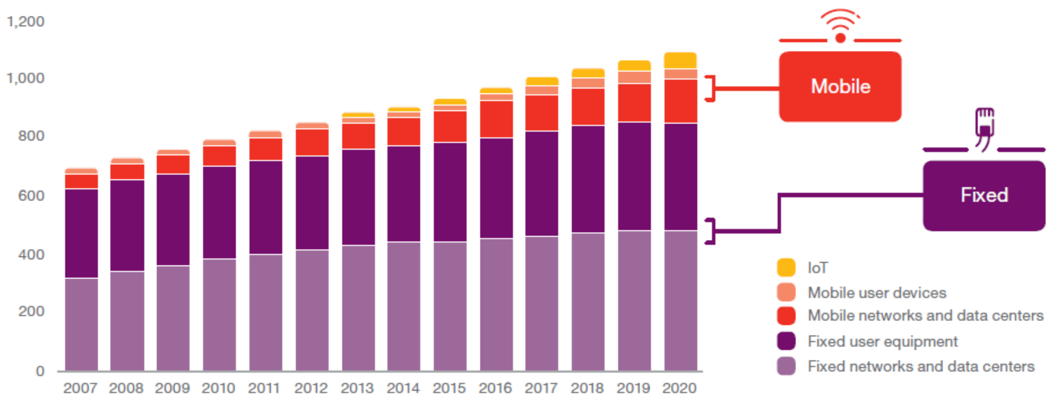

Figure 1.1 : Global power consumption for user equipment and network infrastructure along operational phase (TWh) [1].

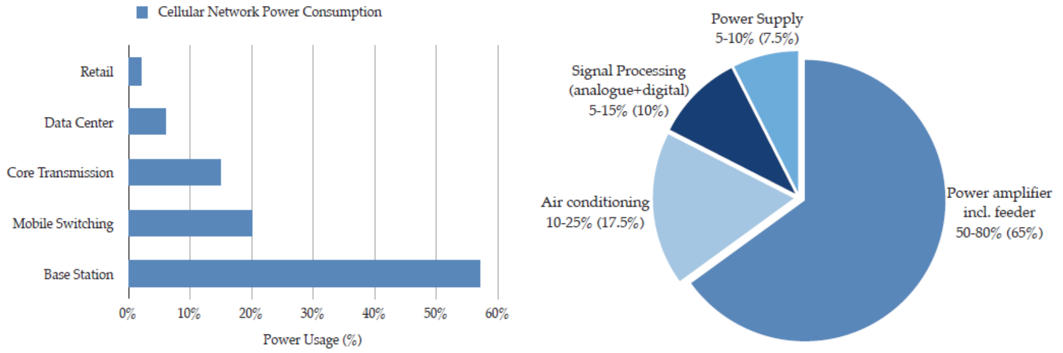

Figure 1.2 : An ordinary cellular network power consumption percentage and corresponding BS.

Figure 1.2, percentage of power consumption in a typical cellular network is shown [8], [9]. Thus, smallest improvement in power consumption will bring huge saving in energy. As an example, Information and Communications Technologies Authority of the Republic of Turkey (BTK) reported in September 2018 that 181.972 base stations (BS) are deployed all over the country and an average base station consumes nearly 2500 Wh [10], [11].

With the increase in the market competition, expenditures became more important for mobile operators. There are two main business expenditures: Capital Expenditures (CAPEX) and Operating Expenses (OPEX). Major physical equipments or services that will be used for more than one year are catogorized in CAPEX. For instance, a company might have CAPEX to increase or improve its fixed assets. OPEX are the costs for a company to run its business operations on a daily basis. In this point, energy expenditures are one of the most important operational costs for mobile network operators (MNOs). In this thesis, we focus to decrease power consumption of BSs in regard to adjust coverage areas of different frequency bands. In the following sections of this chapter, the literature view of ICE is first investigated. Then problem statement and contributions are presented. Finally, thesis organization is given in the end.

1.1 Literature Review

Traffic load in cellular networks varies significantly in time and space because of various factors such as user mobility. For example, while traffic density is high in work areas during the day, traffic density is much less in residential and living areas [12]. In the evening, we can observe the opposite of this traffic intensity model. Setting operating parameters of each macrocell to the most dense time results in serving cells running under their own capacities [13]. No fixed cell planning is a suitable solution to the changing traffic load. In the future, this traffic fluctuation will start to become a more serious problem.

In next generation systems, it is envisaged to increase the energy efficiency of the base stations with two basic methods: Cell switch on-off (CSO) and cell zooming (CZ) [14], [15]. In cell switching method, which is an innovative approach, instantaneous load of each base station is calculated. In this method, the cell is switched off when the intensity of traffic in the coverage area falls below the threshold level. Besides, there is another implementation of balancing variable data traffic. Capacity of the base stations can be dynamically adjusted by the cell zooming method. Today's infrastructure is not enough to provide adequate capacity in intense internet traffic environments. Dynamic planning, which results to increase in the number of large cells and data traffic, is an important new issue in the next generation communications network management for mobile operators.

In [16], another solution for coverage extension technologies is suggested. This alternative solution is the deploy smaller but more cells. With this method, small cells consume less power than macro cells in intense traffic time intervals. In [14], several approaches are offered for implementing CZ such as base station cooperation, relaying, physical adjustment, and base station sleeping. Furthermore, some CZ decision methods are offered: Centralized and distributed algorithms. In [17], setting boundary conditions are explained, and continuous, discrete, and fuzzy CZ are compared with respect to average number of users and inter-arrival times. Besides, users that consume different combinations of voice and data are evaluated. It is also shown in simulations that the best measured signal to interference and noise ratio (SINR) value is observed in non-dynamic cells. In dynamic operations, it is measured as discrete-fuzzy-continuous CZ methods, respectively.

CZ may cause zones that are deprived of coverage and intercellular access. In [14], two different algorithms are proposed for this approach: The centralized decision making algorithm is controlled from a single center, the distributed decision making algorithm, each mobile user selects its own base station according to the traffic load and channel conditions.

As another point to be emphasized, cell switching has become more of an issue due to base stations consume the biggest amount of energy in mobile network systems, and switching off underutilized stations is aimed [18]. It is possible to categorize CSO approach into three as online, offline and hybrid [19], [20]. In online CSO, the system decides the candidate cell to be switched off by using real-time data. Therefore, the system adapts itself easily to the changes in traffic conditions. It is also possible to achieve high energy efficiency levels since there is no constraint in choosing the candidate cell to be switched off. However, real-time processing values and determining the candidate cell to be switched off is time consuming. Implementing this model is more complicated and difficult than offline CSO. On the contrary, some of the cells are predisposed to be switched off using historical traffic information in offline CSO. Once the cells to be switched off are decided, the set of active cells remain switched on until the operator takes any action on purpose. This type of CSO does not need any real time data, that is why it is easier for the system to take action faster. Since the set of active cells do not change by varying traffic, it is easier to track and implement, yet, efficiency and adaptability perform worse than online CSO. It is possible to achieve low interference due to assigning UEs to a certain set of active cells. Offline CSO is more convenient for long-term planning . In hybrid CSO, offline and online CSO are implemented together. First, a set of active cells are decided, then algorithm operates using real time traffic data to select the cells to be switched off. This model performs better SINR than online CSO and better adaptability than offline CSO [19]. In [21], the Energy Efficiency (EE) and Area Spectral Efficiency (ASE) of green random cellular networks, which utilize the Cell Zooming (CZ) techniques, are studied. Also, adaptive cell zooming scheme and cell zooming factor (CZF) is proposed in [22]. They apply the game theory to optimize the CZF based on reduction of area power consumption. In [23], spectrum-energy optimization problem where BSs have the capability to perform cell zooming is examined. A heuristic algorithm is suggested to avoid high computation time and efficiently solve the formulated problem.

The vast majority of the previous contributions focus on the solutions where the user-deployed cells use the same frequency band employed by macrocells. However, it is obvious that many BSs serve at multiple frequency bands up to 5. In LTE-Advanced, Release 8 initiates the band arrangement [24]. In addition, 40 different frequency bands are defined in terms of bandwidth requirement, band separation, and duplex mode. However, some similar frequency band management policies with different scenarios have been studied in the previous works [19-21]. Autonomous component carrier selection method in local area environments for LTE-Advanced is considered as fully distributed and scalable solution to the interference management problem [25]. In case of dynamic multi-cell multi-user environment, optimal radio resource configuration is also studied [26]. Also, in cognitive radio networks (CRNs) spectrum decision technique has gained popularity in the last decade. It is required CRNs because, the capability to decide the available spectrum band among all possible bands according to the QoS requirements of the applications. Once the available bands are decided, the most convenient spectrum band is then selected. Accordingly, the transmission mode and bandwidth for the transmission can be reconfigured [27].

1.2 Problem Statement

User traffic load changes in the cells during the day. The biggest reason for this is the movement of mobile users. For example, while traffic density is high in work areas during the day, traffic density is much less in residential and living areas. In the evening, we can observe the opposite of this traffic intensity model. If each macrocell's parameters are set to the most intense time, there will always be cells which are running under its capacity in the system. No fixed cell planning is a suitable solution to the changing traffic load. The 80% of base stations in the 80% of time works in a serious unsaturated state which load is less than 20% [13]. In the future, this traffic fluctuation will start to become a more serious problem. The method of CZ which is changing dynamically the coverage area of base station are considered as a significant alternative in reducing these problems. However, neither CSO nor CZ are complete solutions for energy efficiency in wireless networks. These techniques cannot meet the demands such as covering whole service area, computation simplicity, and fast processing. Therefore, the ICE is proposed as a promising energy-efficient technique due to the fact that radio units of LFBs consume less power than radio UFBs. In ICE scenarios, we reduce the power consumed by a BS through switching the frequency bands. Hence, energy efficiency can be improved by assigning user equipments (UEs) from UFBs to LFBs.

1.3 Contributions

Considering disadvantages of CSO and CZ tehniques, we propose Intra-Cell Frequency Band Exiling (ICE) which rises as a promising energy efficient technique. It is known that radio units of lower frequency bands (LFBs) consume less power than radio units of upper frequency bands (UFBs) [11]. Therefore, assigning users from an UFB to a LFB with the help of adjusting the coverage area of a BS is a great technique which is not only balancing user traffic but also provide more energy-efficient cellular networks. In ICE scenarios, we try to reduce the power consumed by a BS by changing the coverage area. Thus, energy efficiency can be improved by assigning UEs from UFB to LFB. For that reason, we dynamically adjust the coverage area and analyze ICE probability in BSs through the selection of suitable frequency bands.

In this work, we consider efficient power consumption idea by adjusting coverage area. The applicability of the technique on the system is examined from different theoretical perspectives. Our contributions in this work are listed below.

- The condition for assigning users from a UFB to LFB is explained in terms of energy efficiency.
- ICE probability of a cellular system is derived.
- The characteristics of different frequency bands are proposed by means of power consumption. Also, we used quadratic form as the power consumption model of BS. In the previous works, power consumption is modeled as a linear formula.
- The performance of ICE is investigated in terms of area spectral efficiency (ASE) and energy efficiecny (EE).
- The trade-off between EE and ASE is provided.

In addition, this work is important since it proposes a new idea on the efficient utilization of energy by ICE that assigns users from UFBs to LFBs thanks to adjusting the coverage area of a BS. Furthermore, we have provided the traffic density assumptions for realistic simulations of cellular networks.

1.4 Thesis Organization

The rest of this thesis is organized as follows. In Chapter 2, energy efficient cellular network design is described. In Chapter 3, cell exiling in green cellular networks is introduced. In Chapter 4, simulation results are presented. Finally, concluding remarks and future works are addressed in Chapter 5.

2. ENERGY-EFFICIENT CELLULAR NETWORK DESIGN

In this chapter, energy-efficient cellular network design, which is a very significant issue for mobile operators to decrease both operational expenditure and environmental pollution, is evaluated . As BSs dominate energy consumption and are responsible of nearly 60% of overall network energy consumption, energy-efficient cellular networks can be designed with help of several current technologies. A few examples are:

- Link level: energy-efficient transmission, low power circuit design, dynamic mode switching, etc.
- Multi-user level: resource management and energy-efficient scheduling.
- Network level: energy-efficient mobility management and energy-efficient topological approaches from deployment to operation [28].

In this chapter, some fundamental trade-offs and deployment scenarios are investigated.

2.1 Fundamental trade-offs in network resource utilization

For determining communication performance, two main metrics which are spectrum efficiency (SE) and energy efficiency (EE) are used by academia and telecommunication market. Generally, there is a trade-off between SE and EE and network architecture is designed based on them. However, it should be emphasized that there is no clear advantage of one metric over the other. Both of them are equally important, and considered when a network is designed. In this section, we investigate the fundamental trade-offs in resource utilization from different views to facilitate network design. Especially, we explain the relationship between SE and EE in different network environments.

In this part, trade-off between EE and SE, which are the maximum total number of bits that the network can deliver per joule and the sum of the maximum average data rates, are evaluated in regard to single and multiple user system. If there is only one UE in the cellular network, the SE of the system is

$$\eta_{SE} = \log_2\left(1 + \frac{pg}{WN_0}\right), \tag{2.1}$$

where g is the channel gain of link, p the tranmission power of link, W is the signal bandwidth, and N_0 is noise power [29].

Considering zero circuit power assumption in which the transmitter's power consumption value is zero, the EE of the system is

$$\eta_{EE} = \frac{W\log_2\left(1 + \frac{pg}{WN_0}\right)}{p}. \tag{2.2}$$

Hence, we can derive a relationship between the SE and the EE by

$$\eta_{EE} = \frac{\eta_{SE}g}{(2^{\eta_{SE}} - 1)N_0}, \tag{2.3}$$

where this relationship is illustrated in Figure 2.1. It is clear that there is an inverse relationship between them.

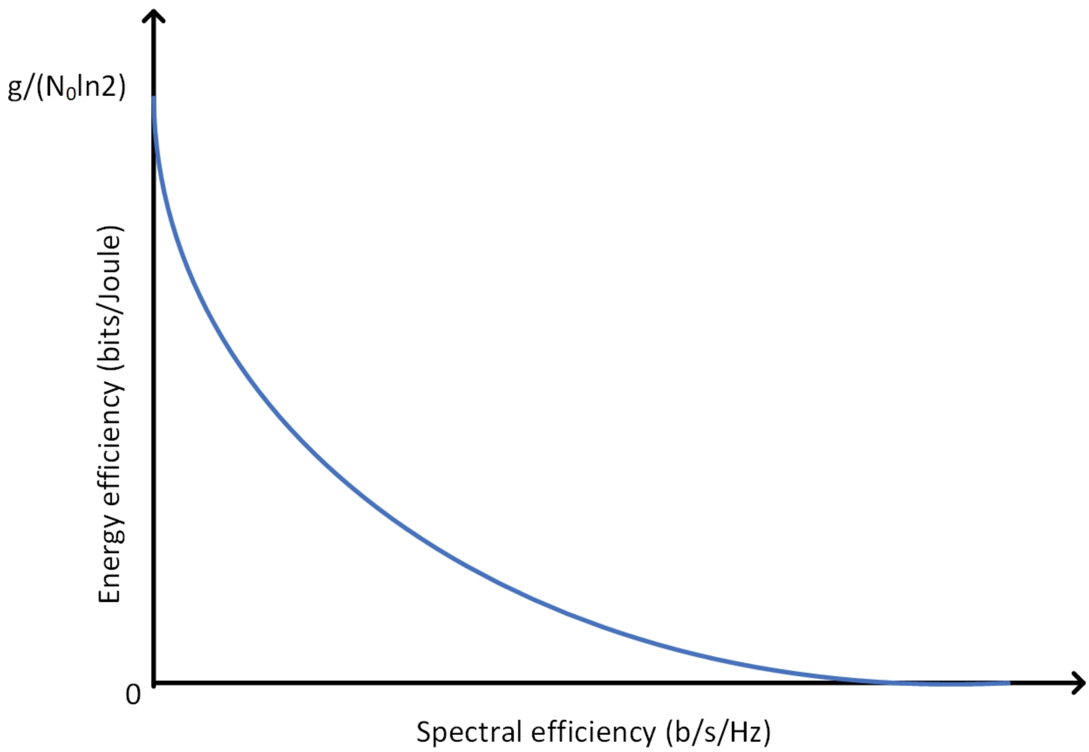

Figure 2.1 : Zero circuit power assumption and the trade-off between EE and SE

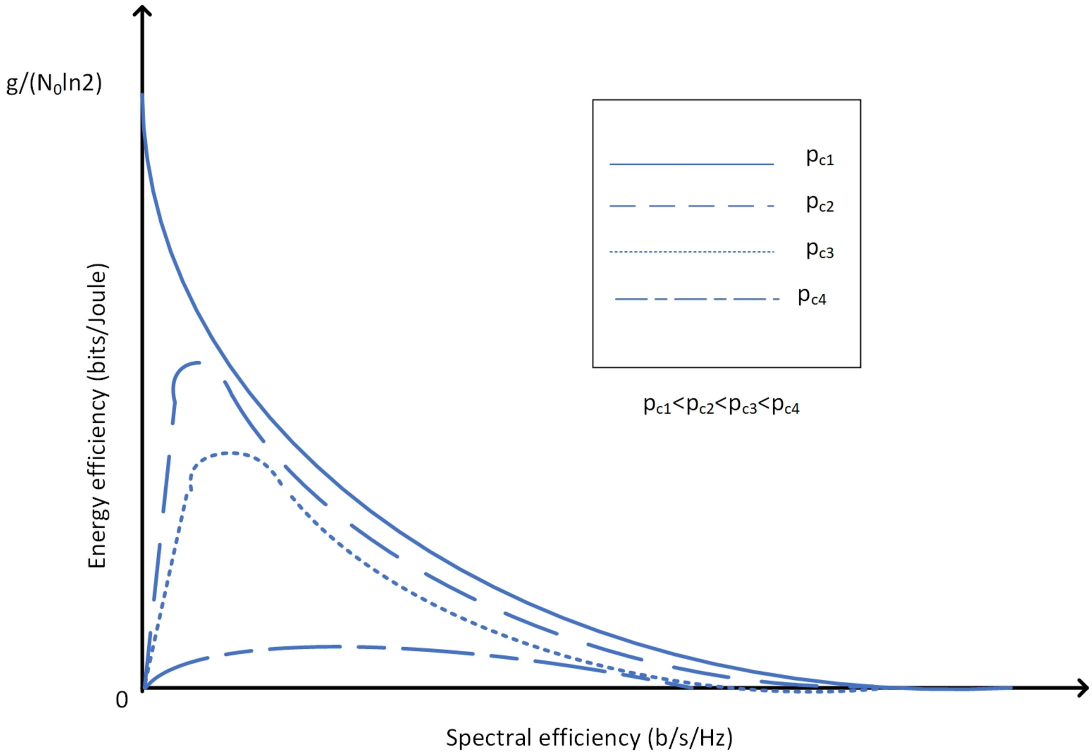

Figure 2.2 : Trade-off between EE and SE in real life.

However, circuit power is not zero in real life and (2.2) can be converted into

$$\eta_{EE} = \frac{W\log_2\left(1+\frac{pg}{WN_0}\right)}{p+p_c}. \tag{2.4}$$

Consequently, we have a new trade-off relationship which is illustrated in Figure 2.2. In this figure, p_{c1}, p_{c2}, p_{c3}, and p_{c4} show different values of circuit power and is expressed as

$$\eta_{EE} = \frac{\eta_{SE}g}{(2^{\eta_{SE}}-1)N_0/g+p_cW}. \tag{2.5}$$

In information theory, the term channel is defined as separate paths through which signals can flow. Also, the channel consists of K orthogonal sub-channels. In a network, each sub-channel has specific bandwidth, which is symbolized by W_i, i=1,..., K. In our assumption, all the K sub-channels are utilized and the allocated power is not zero.

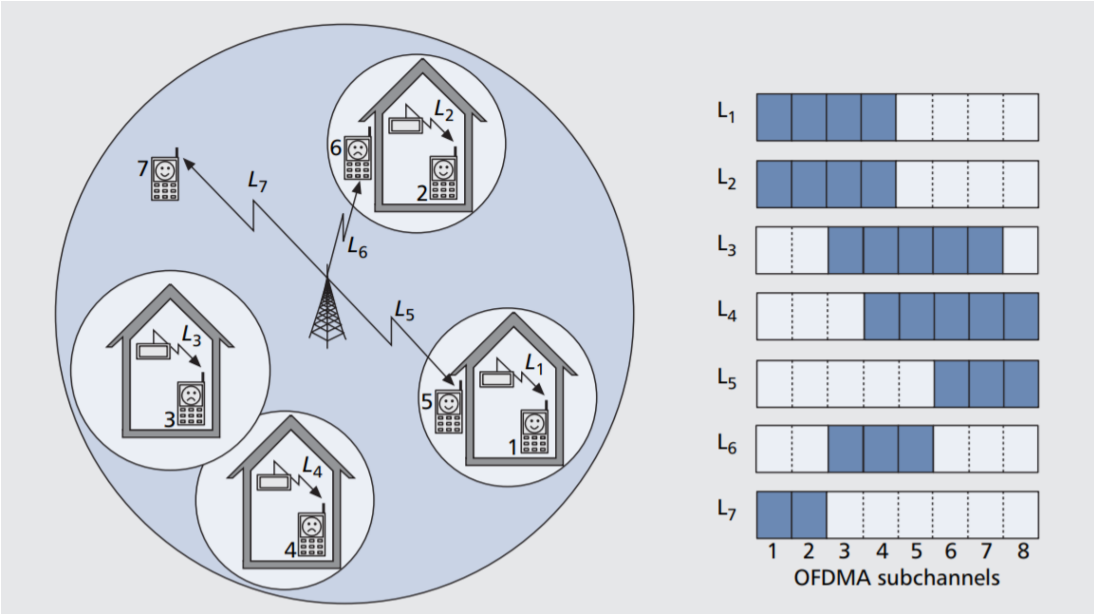

Figure 2.3 : BS uses all the available sub-channels to send information to its users in downlink case [2].

A transmitter can utilize different K active sub-channels, e.g. multiple-input multiple-output (MIMO) or orthogonal frequency division multiplexing (OFDM), or multiple transmitters, e.g. multiple-user MIMO (MU-MIMO), orthogonal frequency division multiple access (OFDMA), coordinated multiple-point transmission (CoMP), where a subset of K sub-channels are assigned to each transmitter. For example, in a cellular network with two cells, one using a 10-subcarrier OFDMA to serve three downlink users and one 2x2 MU-MIMO serving two uplink users. They provide service on other frequency bands and interference does not occur among each other. So there are 10+2=12 sub-channels. In Figure 2.3, a co-channel assignment and downlink allocation of OFDMA subchannels in a macro/femtocells network is illustrated.

In the following, we explain the trade-off between SE and EE as a metric of network SE which is

$$\eta_{SE} = \sum_{i=1}^{K} \log_2\left(1 + \frac{p_i g_i}{W_i N_0}\right), \tag{2.6}$$

where i shows the corresponding sub-channel properties. The overall network transmission power consumption is

$$p_T = \sum_{i=1}^{K} p_i. \tag{2.7}$$

With help of (2.1) and (2.2), network SE and EE can be represented as

$$\eta_{EE} = \frac{W\eta_{SE}}{P_T(\eta_{SE})}, \tag{2.8}$$

which is decreasing and absolutely convex in η_{SE}. When circuit power is taken into account,

$$\eta_{EE} = \frac{W\eta_{SE}}{P_T(\eta_{SE}) + P_c}, \tag{2.9}$$

where P_c is the cumulative circuit power of all transmitters [30].

In this part, we evaluate a multi-user system, which are interference sources for each other. A symmetric single-channel network is considered to facilitate assumptions and obtain insights. In this scenario, all N users experience the same channel power gain which is symbolized as g. All interference channels have the same power gain $\hat{g}$. To characterize the interference level, it is necessary to define a metric which has no relation with transmission power. Define the network coupling factor

$$\alpha = \frac{\hat{g}}{g}, \tag{2.10}$$

which shows at what level different links interfere with each other. α value shows a level of interfering scenario. All users transmit the same power in the equilibrium because of the network symmetry assumption. Define the transmission power of all users to be p. The overall network EE will be

$$u(p) = \sum_{n=1}^{N} \frac{W\log\left(1 + \frac{pg}{\sum_{i,i\neq n} p\hat{g} + \sigma^2}\right)}{p + p_c} = \frac{NW\log\left(1 + \frac{p}{(N-1)\alpha p + \sigma^2/g}\right)}{p + p_c}, \tag{2.11}$$

and the network SE will be

$$r(p) = N\log\left(1 + \frac{p}{(N-1)\alpha p + \sigma^2/g}\right). \tag{2.12}$$

Each user allocates power to selfishly maximize its SE in a non-cooperative power control scenario. The transmission power tends to infinity in the equilibrium when power is limitless. Also, it is clear that $r(p)$ is strictly increasing in p. Therefore, the maximum limit of network SE is reached in the equilibrium and the upper-bound is

$$r_{SE} = \lim_{p\to\infty} r(p) = N\log\left(1 + \frac{1}{(N-1)\alpha}\right) \tag{2.13}$$

with the corresponding EE $u_{SE} = \lim_{p\to\infty} u(p) = 0$, which is totally not energy-efficient, and non-cooperative SE optimal power is not aimed for EE [31].

In Figure 2.4, there is a two-user scenario, where the users transmit at the same power and interfere with each other to illustrate the trade-off. The relation between transmit

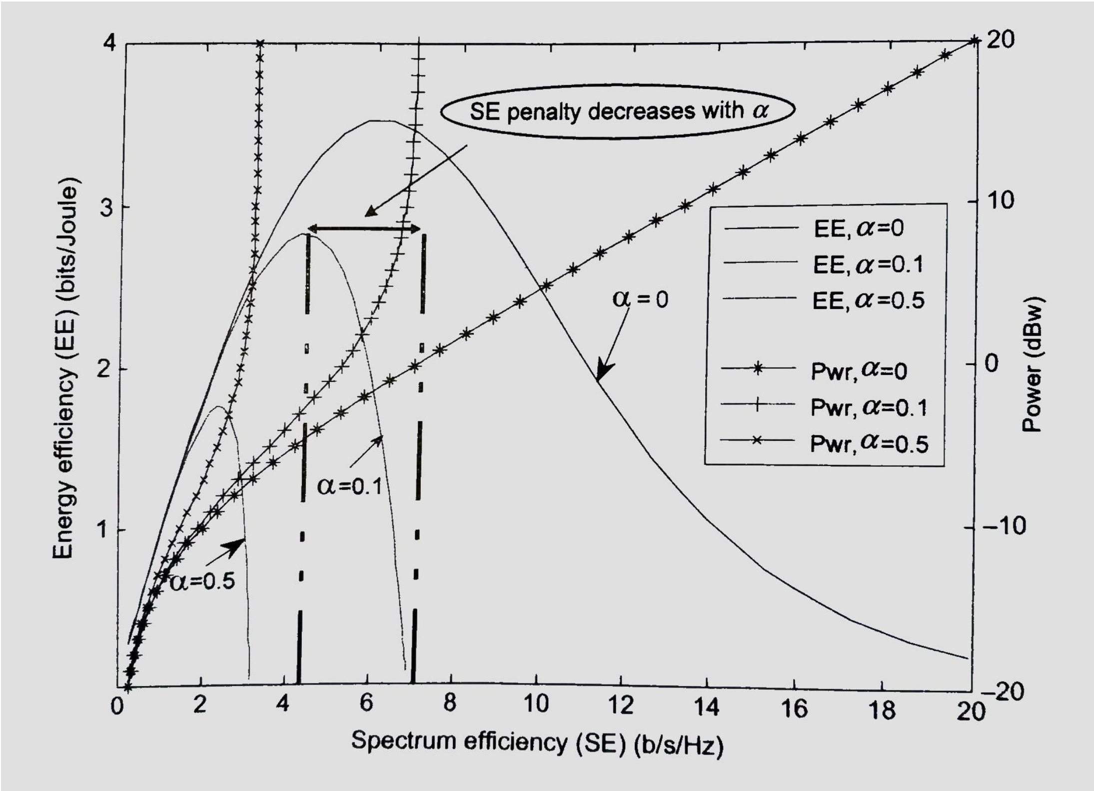

Figure 2.4 : Trade-off EE and SE with different interfering scenarios [3].

and SE is indicated with marked curves when the network has different couplings and EE is showed without markers. In this figure, EE is much more responsive to power selection than SE. For instance, when $\alpha = 0.1$, the transmission power is chosen to be -3 dBw for energy-efficient power optimization. The SE achieved is 4.2 b/s/Hz, while the EE is 2.8 bits/Joule. The EE decreases very rapidly while the SE only improves slightly when the transmission power is increased. To sum up, energy-efficient networks have significant advantages, especially in heavy interference sites, e.g. cell-edge communications.

In this subsection, basic assumptions are made to increase intuitive understanding about the trade-off between the EE and SE. In real life, each user experiences different levels of interference from other users. Furthermore, some users may be exposed to interference due to sharing the same channels, and others experience no interference because of using orthogonal channels. The trade-off between EE and SE will be the statistical mean value of all effects that have been discussed here.

2.2 Energy-efficient homogeneous network deployment

Typical Mobile Network Operator (MNO) has two main expenditure when deployment process: CAPEX and OPEX. Generally, building infrastructure, network equipment, site construction is a part of CAPEX. In addition, energy consumption maintenance and site lease constitute OPEX. Both types of costs need to be evaluated in network planning process. EE is the main factor in network deployment and in this section deploying homogeneous cellular network in an energy-efficient way is discussed.

Homogeneous cellular networks consist of one type of BSs. In Figure 2.5, a homogeneous cellular network is illustrated. Any kind of cellular network which does not include additional infrastructure in the form of smaller low-power low-complexity BSs constitute a homogeneous class.

In the downlink of a coverage-limited cellular network, the received power at a distance, d, from the BS is modeled

$$p_r = \frac{p}{d^{\alpha}}, \tag{2.14}$$

where p is the transmission power and α is the path loss exponent. The interference is negligible and the signal-to-noise ration (SNR) is

$$\Gamma = \frac{p}{d^{\alpha} N_0 W}, \tag{2.15}$$

where N_0 is the noise spectral density. Suppose there is always a cell-edge user, with $d = R_{\text{cell}}$, that desires a minimum data rate r_0, which is given by

$$r_0 = W \log_2 \left(1 + \frac{\Gamma}{\theta} \right). \tag{2.16}$$

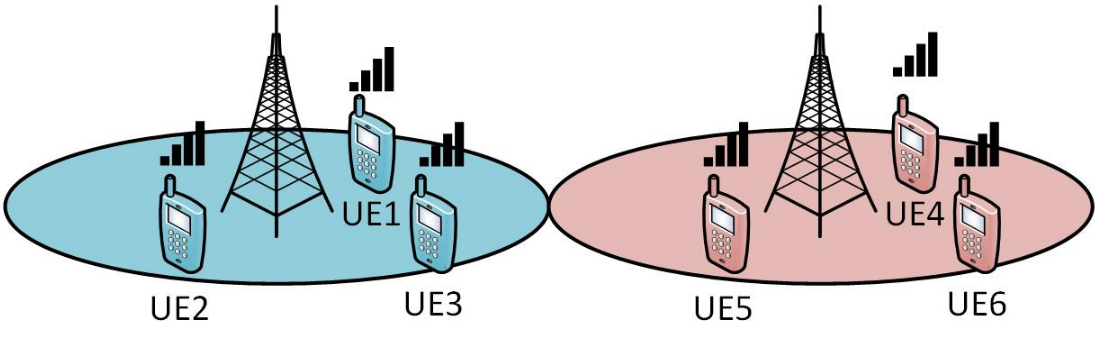

Figure 2.5 : Illustration of a typical homogeneous network.

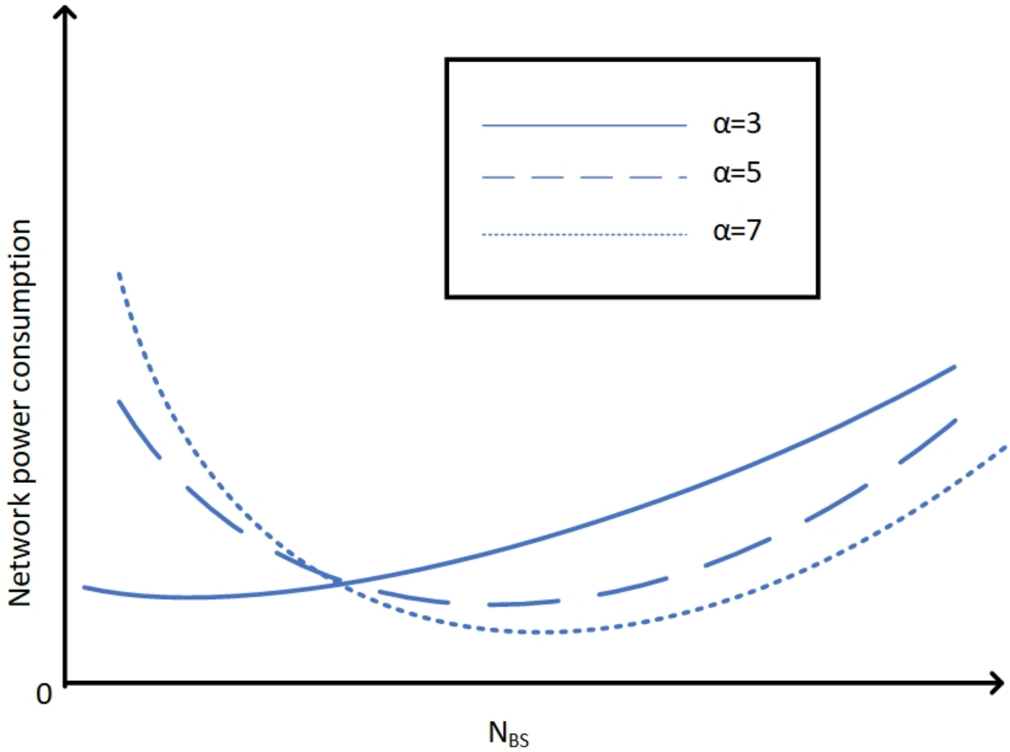

Figure 2.6 : BS density relationship with a cell-edge rate requirement and network power consumption.

With help of (2.14), (2.15), and (2.16) we can see that the total transmission power of a BS with a static service area decreases with the number of BS in the network for any α>2. In real life, α is always higher than 2. Thus, an ultra-dense deployment strategy with many micro BSs is the most energy efficient way. The predicted network EE can be defined as

$$\eta_{EE} = \frac{r_0 N_{BS}^{\alpha/2}}{\left(2^{r_0/W} - 1\right)\theta N_0 W (A/\pi)^{\alpha/2}}, \tag{2.17}$$

which grows exponentially with the number of BSs deployed.

In Figure 2.6, the optimal N_{BS} and the corresponding minimum network power consumption is shown. From above equations, the following conclusions can be derived immediately [3].

The optimal BS density increases with the data rate requirement r_0, coding gap θ, and noise density N_0, and decreases with system bandwidth W, power amplifier efficiency ζ, and circuit power p_c. In practice, it also increases with the path loss exponent.

The minimum power consumption to serve a unit area increases with the data rate requirement r_0, coding gap θ, and noise density N_0, or circuit power p_c, and decreases with system bandwidth W or power amplifier efficiency ζ. In practice, it also increases with the path loss exponent.

2.3 Energy-efficient heterogeneous network deployment

When designing cellular networks, macro BSs are used as the main part of the networks. However, macro BSs have very limited capability for providing broadband services. Conventional solution to increase EE is to decrease the coverage of cells and hence reduce the signal propagation loss to reduce transmission power. One of the most established way to improve network EE is using micro, pico, or femtocells, under umbrella macro BSs. An example of an heterogeneous network is illustrated in Figure 2.7.

Deployment of small cells is a good way to serve users as low power nodes (LPNs). Up to several hundreds of meters, micro or pico cells usually serve. Also, they can be used to serve for smaller areas with ultra-dense traffic, such as malls, subways, hotels, etc. A femtocell provides service for a much smaller area like an individual house and the coverage can be only up to a few meters or ten meters. Small cells have more advantages than macro cells in regard to power efficiency. For instances, several thousands of watts would be needed to support a macro cell. However, a femtocell consumes only 5W in total. Covering on area with too many micro BSs may be expensive because of the growing expenditure on site rental, BS equipment, and maintenance. On the other hand, the BS density in heterogeneous networks can vary in different locations depending on the system bandwidth, channel conditions, and heterogeneous network types. To be more specific, the optimal BS density is given by

$$\frac{N_{BS}}{A} = \frac{1}{\pi}\left(\frac{p_\beta}{p_c}\right)^{2/\alpha}(\alpha/2-1)^{2/\alpha}, \qquad (2.18)$$

where the area A should be the local area where the same type of BSs are deployed, W is the system bandwidth for heterogeneous BS, p_c is the circuit power of the heteregenous BS, and α is the channel path loss exponent for this particular area.

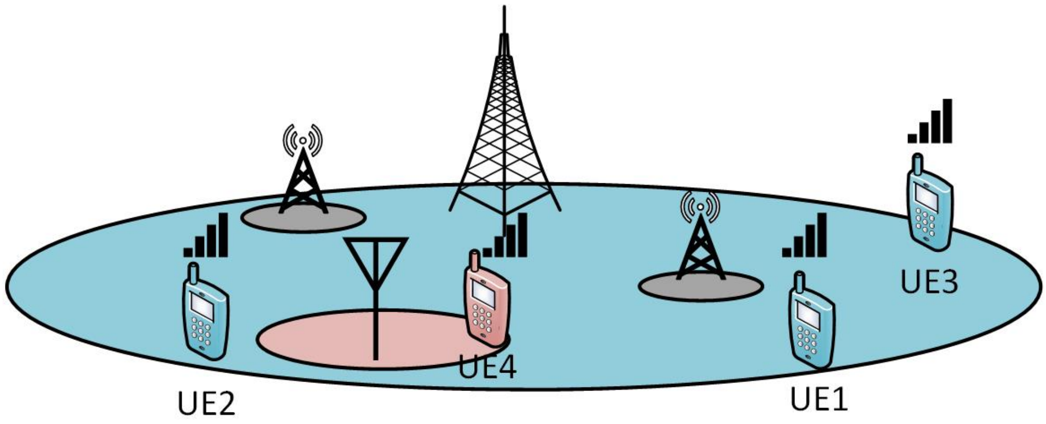

Figure 2.7 : A heterogeneous and dynamic network architecture.

2.4 Energy-efficient cellular network operations

One of the most known technique in energy-efficient cellular network operation is cell zooming. It is also known as cell breathing, cell size adaptation technique, or cell blooming. The application of cell zooming in cellular networks should present some new functions to the existing network architecture. In Figure 2.8, cell zooming is illustrated.

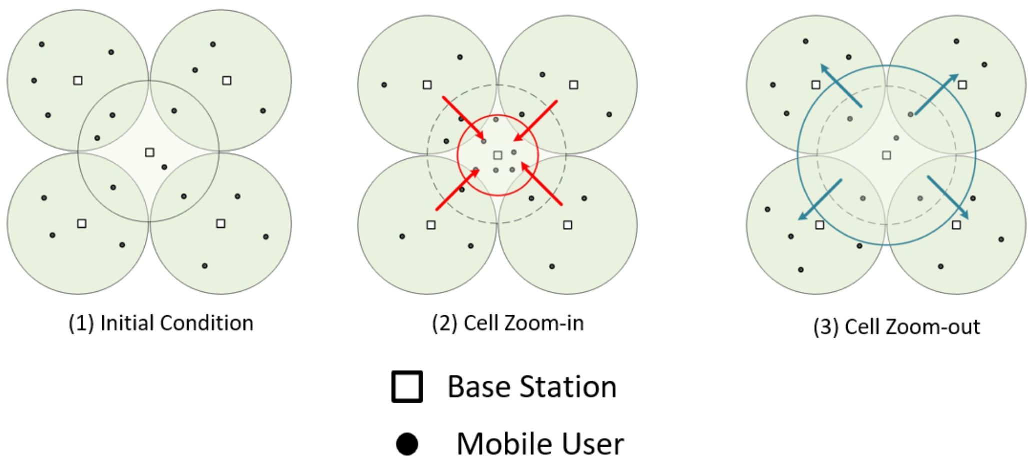

Figure 2.8 : Cell zooming operations in cellular networks: 1) Cell with original size; 2) When load increases, central cell zooms in; 3) When load decreases, cell zooms out.

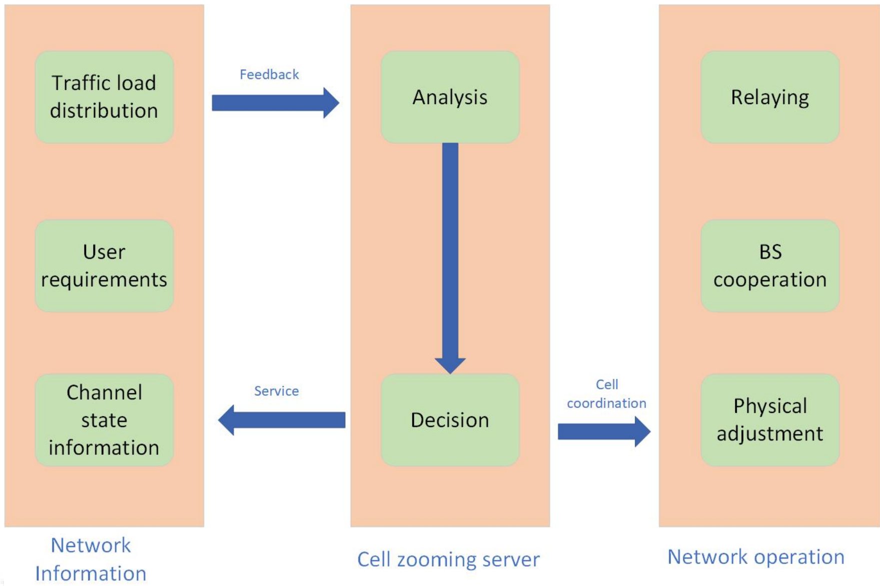

Figure 2.9 : Framework of cell zooming.

The cell zooming frame is shown in Figure 2.9. It is neccassary to control cell zooming procedures, which is performed in the cell zooming server (CS). Cell zooming KPIs such as traffic load, channel conditions, and user requirements information is gathered by the CS. Detection can be performed by specific control mechanisms. Once CS has collected information, it is analyzed and decided whether or not there are opportunities for cell zooming. The neighbor cells communicated via CS, when a cell needs to zoom in or out. Help of the network operations such as physical adjustment, BS cooperation, and relaying these cells will then be zoom in or out.

After all of that it is necessary to decision making methods. Two different algorithms are proposed for this approach as given below.

1. The centralized decision making algorithm is controlled from a single center. After the data is collected, the goal is to keep some base stations awake. It performs better than the distributed decision-making algorithm.

2. In the distributed decision making algorithm, each mobile user selects its own base station according to the traffic load and channel conditions. BS coordination is not required in this algorithm [14].

After decision algorithms are applied for cell zooming, another point is how to cell zooming is performed. Three different techniques are proposed for cell zooming. In the continuous cell zooming techniques, the cell sets the coverage area to the farthest

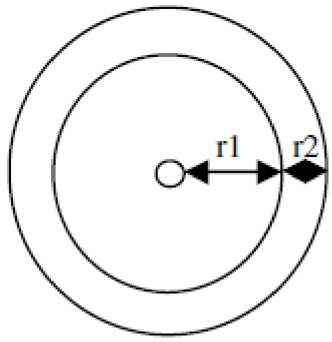

Figure 2.10 : Discrete cell zooming method.

user under sufficient conditions. The continuous cell zooming is the most efficient method, but has some challenges due to the high user mobility and the need for rapid feedback.

In the discrete cell zooming technique which is illustrated in Figure 2.10, the coverage area is divided into Z number of zones. The base station decides which zone is better for performing. This method requires less feedback than continuous cell zooming. The base station does not need coverage range until the user switches from one region to another. As the number of districts, Z increases, energy efficiency increases and at the same time feedback complexity increases.

A number of different ways can be used to distinguish the cell Z from the different zones. For example, Z zones can be determined according to the amount of equal increase in the transmission power of the base station. It is therefore obvious that the area of each region will not be equal. As another method, the radius is divided into the desired number of parts and zones are determined.

The last technique which is fuzzy cell zooming is about 10-20% extension of boundaries used in the discrete cell zooming method. Each zone's coverage area is served by expanding between 10-20%. In the fuzzy model, the farthest user extends the range of coverage to 10-20% in the immediate response of the current discrete level, preventing the system from passing to an upper discrete level. In this way, a better energy efficient system is achieved than discrete cell zooming technique. Fuzzy cell zooming method is illustrated in Figure 2.11.

It is also show in the simulations done in MATLAB that the best measured signal to interference and noise ratio (SINR) value is observed in non-dynamic cells.

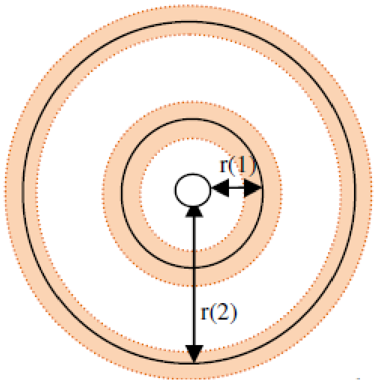

Figure 2.11 : Fuzzy cell zooming method.

In dynamic operations, it is measured as discrete-fuzzy-continuous cell zooming methods, respectively [17].

There are several key performance indicators (KPIs) that the operator can investigate in order to decide the candidate cell to be switched off e.g the cell load, throughput, user number and average amount of data used. In [15], all cells are assumed switched off and the cells to be switched on are selected based on the maximum loads, their maximum number of unconnected UEs and their maximum number of UEs with a good channel quality. Results show that maximum number of cells remained switched off by sorting them by their maximum number of unconnected UEs resulting in 54%energy saving, then by their maximum load resulting in 51%, finally, by their maximum number of UEs with a good channel quality resulting in 50%. The best performance is achieved considering the maximum number of UEs, which our study is also based on.

There are many other techniques that should be redesigned to improve cellular network EE. All device components in the network should be as energy-efficient as possible. For example, in the BS, RF-transmitters and antennas are located at different locations and are connected using long coaxial cables, which adds several dBs loss in power transmission in dB. Therefore, low attenuation RF cables should be used and the RF amplifier should be placed as close to antenna as possible. Air conditioners are needed to cool down the heat, consuming even more energy. The modulation and coding schemes in LTE and NR standards are characterized by signal envelopes that vary significantly with larger than 10 dB.

While numerous efforts have been focused on energy-efficient communication technologies, new energy sources should also be developed to push forward the development of energy-efficient mobile networks. These renewable energy resources can be used as power sources of BSs, especially in remote rural areas. In these areas, the availability of electrical grids is poor and the electricity for BS operations is supplied by diesel powered generators, which are not only expensive to maintain, but also generate a significant amount of CO_2 emissions. In these cases, we can use renewable energy resources like solar, wind, and sustainable biofuels energy systems, which are much more viable at reducing overall network expenditure. For example, a one square meter solar panel can produce 10% of the energy needed for the operation of an LTE macro cell BS [32]. Many MNOs worlwide have started developing solar-driven BSs.

3. CELL EXILING IN GREEN CELLULAR NETWORKS

Substantial increase in the number of BSs enforces society to focus on energy-efficient communication systems. For this purpose, we propose intra-cell frequency band exiling (ICE) technique as a promising energy efficient solution for green cellular networks. In the proposed technique, users are assigned from upper frequency bands (UFB) to lower frequency bands (LFB) by suitably adjusting the coverage area of frequency bands. For this purpose, both the downlink (DL) and uplink (UL) cellular networks consisting of macro BSs and UEs are considered. At first, macro BSs are deployed using a Poisson point process (PPP) model on the Poisson-Voronoi tessellation (PVT) and UEs are distributed according to PPP model. Secondly, ICE technique is described for green cellular networks. Finally, performance metrics are clarified.

3.1 Stochastic Network Model Based on Cellular Networks and Power Consumption Model

Some related works have been focusing on conventional wireless deployments that are square or hexagonal, but in real life base stations are not independent and identically distributed. Therefore, stochastic geometry approach is adopted in deployment in recent years. Stochastic geometry, which leads to a mathematically tractable system, has become favoured as a effectual tool for modelling wireless networks [33]. In this study, Voronoi tessellation, which is one of the significant calculation tools of stochastic geometry, is considered as model for random cellular networks. The tessellation that is a decomposition of the space into the Voronoi cells of a general point process, provides the opportunity to work in areas such as spatial data processing and surface modeling by separating the studied space into sub-regions [34]. As for that Poisson Voronoi tessellation is the structure formed by the positioning of base stations (BS) according to Poisson distribution in Voronoi diagram and if the size of a voronoi cell is indicated by S, the approximate function is as follows [35]:

$$f(S) = \lambda^k \frac{K^k}{\Gamma(K)} S^{(k-1)} \exp(\lambda^k K S) \tag{3.1}$$

where λ is the intensity of mobile users in the Voronoi cell and $\Gamma(K) = \int_0^\infty x^{k-1} \exp(-x) dx$ (gamma function) with factor K=3.575 [36].

On the other hand, locations of objects in real networks often correspond to point processes that is significant issue of stochastic geometry. More particularly, in stochastic geometry analysis, spatial positions of base stations and mobile users(MUs), are modeled as point processes. Poisson point process(PPP) is the commonly preferred process due to its property of independence and tractability. With this approach, performance metrics such as coverage probability and achievable rate can be derived analytically from cellular networks by averaging over their potential topological realizations. Thus, the network system design becomes convenient for some optimization studies such as investigation of energy efficiency [37].

The point process is called a random group of many points that can be counted with a multiple probability, while the PPP is the number of points in a set with a Poisson distribution having parameter λ means density [38]. To explain the PPP more mathematically, point process $\Phi = \{x_{(i)} : i = 1, 2, ...\} \subset R^d$ is a PPP if and only if the number of the points in any compact set $B \subset R^d$ is a Poisson random variable, and the numbers of the points in disjoint sets are independent that has a Poisson distribution:

$$P\{\text{k points in set B}\} = P\{\Phi(B) = k\} = \frac{\Lambda^k}{k!} \exp(-\Lambda) \tag{3.2}$$

where $\Lambda = \int_B \lambda(x) dx$ is the intensity measure of the Poisson random variable for some density $\lambda(x)$. If $\lambda(x)$ is constant ($\lambda(x) = \lambda$), the PPP is said to be uniform or homogeneous PPP (HPPP) [37]. In other words, intensity measure is the expected number of points in a set B [39].

$$\Lambda(B) \stackrel{\text{def}}{=} E[N(B)], \forall B \in R^d \tag{3.3}$$

For every compact set B, $N(B)$ has a Poisson distribution with mean $\lambda|B|$and $|.|$ is the Lebesgue measure of set B. So, the equation (2) becomes as follows:

$$P\{\Phi(B) = k\} = \frac{(\lambda|B|)^k}{k!} \exp(-\lambda|B|) \tag{3.4}$$

In this work, the set B is considered as a two-dimensional Euclidean space and the base stations are distributed on the Voronoi tessellation according to the PPP indicated with Φ with the density λ. Similarly, as shown in Figure 3.1, mobile users are placed on the basis of PPP, Φ_u, with the density of λ_u [21].

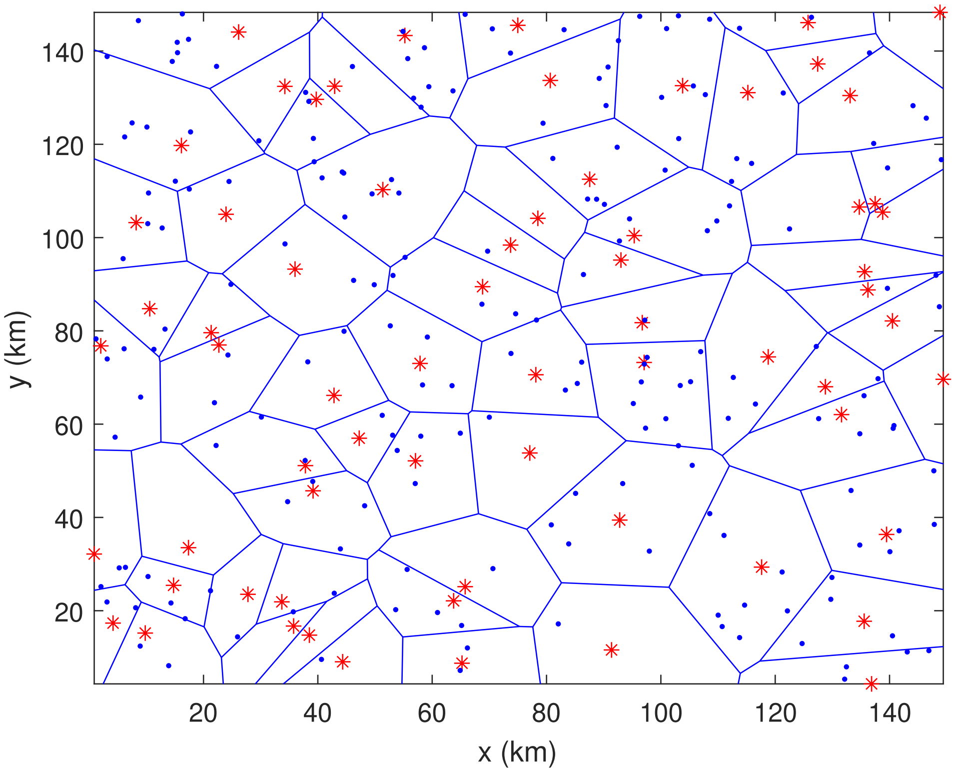

Figure 3.1 : PVT random cellular network with base stations(red dots) and mobile users (blue dots).

Rényi's Theorem: Let Φ be a point process and $\Lambda : R^d \rightarrow R$ be a non-negative function such that $\Lambda(B) = \int_B \lambda(x)dx$ for all bounded B. If $P(\Phi \cap B = \emptyset) = \exp(-\Lambda(B))$ for any Borel B then Φ is poisson with intensity function Λ [39].

According to the theorem above, if the distance r, i.e. distance of MU and the nearest BS, still follows the original PPP with density λ, probability density function of r is obtained as shown below.

Probability that mobile users are outside the coverage area of base station, $P[r > R]$:

$$P(\lambda, k = 0) = \frac{(\lambda \pi R^2)^k}{k!} \exp(-\lambda \pi R^2) = \exp(-\lambda \pi R^2) \tag{3.5}$$

Cumulative distribution function of $P[r \leq R]$:

$$F_r(R) = 1 - \exp(-\lambda \pi R^2) \tag{3.6}$$

So, its probability density function is

$$f_r(r) = \frac{F_r(r)}{dr} = 2\lambda\pi r \exp\left(-\lambda\pi r^2\right) \tag{3.7}$$

Through this approach, the network system design becomes more realistic and appropriate for optimization studies including the investigation of EE and ASE. An illustration of the random cellular network is shown in Figure 3.1 where BSs and UEs are indicated by red stars and blue dots, respectively.

The consumed power by a radio unit of the k-th frequency band, P_k, can be expressed as [11],

$$P_k = \alpha_k (P_k^{(o)} x_k)^2 + \beta_k (P_k^{(o)} x_k) + \delta_k, \tag{3.8}$$

where $P_k^{(o)}$ is the output power of the radio unit at a specific frequency band and α, β, δ are the weighting coefficients. Also, x_k is the traffic density rate of the k-th frequency band that can be expressed as a percentage of configured carrier power for different operating points.

3.2 Intra-cell Frequency Band Exiling Technique

The power consumption of cellular networks directly depends on the user intensity. Hence, aggregating user traffic in less number of frequency bands can decrease energy consumption. Most of the previous studies focus on single-frequency band models for energy efficiency. However, majority of BSs deploy multiple frequency bands such as double, triple or higher bands in real world [24]. Thus, we denote $k \in \{1, ..., K\}$ as total frequency bands of a typical BS. Through assigning a user from a UFB to an LFB, energy efficiency increases in cellular networks because of operating less number of frequency bands. ICE emerges as a promising technique and is illustrated in Figure 3.2. Three types of users are defined here, where UE1 always takes service from a LFB, UE2 is connected to a UFB before and after applying the ICE technique, UE3 is assigned to the LFB from the UFB by applying the ICE technique. BS decides its coverage area according to the performance parameters, which are mainly related with traffic density. In Figure 3.2a, UE3 can take service from the UFB. However, in Figure 3.2b, UE3 is assigned from the UFB to the LFB for decreasing power consumption owing to changing UFB coverage area. Accordingly, aggregation of the traffic intensity at LFBs reduces the traffic density at the UFBs.

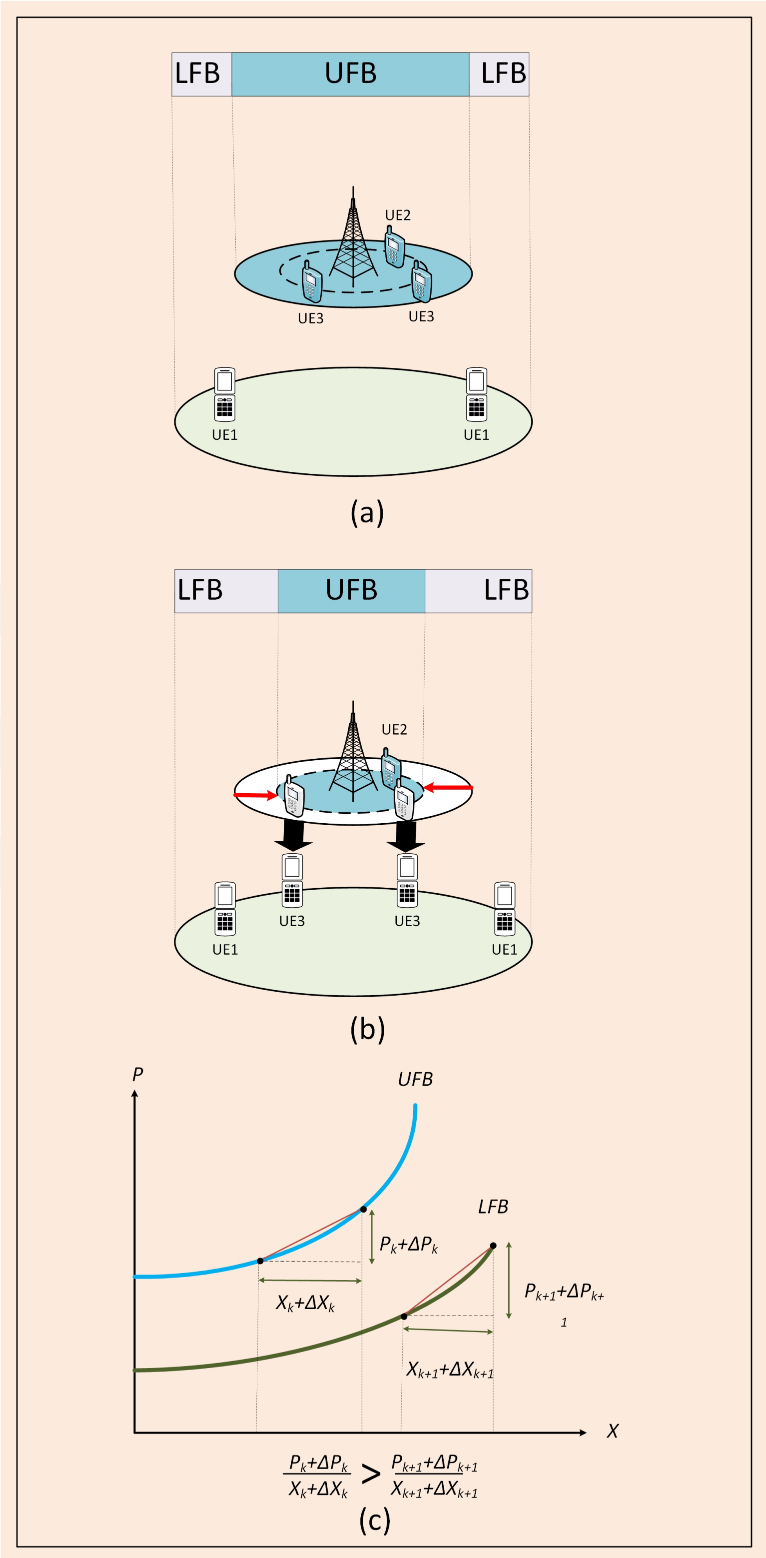

Figure 3.2 : Possible scenarios of the ICE technique with the help of dynamic coverage area of a BS: (a) UE1 takes service from LFB, and UE2 and UE3 take service from UFB; (b) UE3 is exiled from the UFB to the LFB by adjusting the UFB coverage area; (c) Graphical illustration of the ICE decision (X: Average output utilization rate, P: Radio unit power consumption).

3.2.1 User Association Probability in Intra-Cell Frequency Band Exiling

In general concept, it is supposed that one UE is served by one traffic cell. In the ICE technique, UE should be exiled from UFB to LFB into current cell, not other cells. Hence, we need to obtain user association probability in dynamic coverage adjustment environment. It is explained details of user association probability in [22]. The probability of association is derived, and typical user receives more power from $\{k-1\}$-th band in cell m than any other bands in cells. For simplicity, $R_{i,m}$ express receiving power which user i receives power $\{k-1\}$-th band in cell m. Also, $R_{i,j}$ is receiving power for cell j after exiling. Hence, we can get the following conclusion:

$$R_{i,m} > R_{i,j} \tag{3.9}$$

Downlink Received Signal Strength (DL-RSS) is considered main user association parameter [40]. According to power law, the receiving power after exiling can be expressed as follow:

$$R_m \left(\frac{x_{i,m}}{r_m} \right)^{-\alpha_m} > R_j \left(\frac{x_{i,j}}{r_j} \right)^{-\alpha_j} \tag{3.10}$$

where $x_{i,m}$ denotes the distance between user i and $\{k-1\}$-th band in cell m; $x_{i,j}$ denotes the distance between user i and cell j; r_m, and r_j are coverage adjustment parameters. Also, α_m and α_j are the path-loss factor of cell m and j. If r_j=1, the value of bias is 0. There are no adjustment effect and all UEs will be associated with the BS when the receiving power is R_j. If r_j>1, the value of bias is greater than 0. The area of cell expands and more users could associate with it. If r_j<1, the value of bias is less than 0. The area of cell shrinks, and when its coverage increases in a much smaller range, the cell may have the chance to turn into the sleeping state. The relationship among different distance is explained in (3.11).

$$x_{i,j} > \left(\frac{R_j}{R_m} \right)^{1/\alpha_j} \left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}} \right) x_{i,m}^{\frac{\alpha_m}{\alpha_j}} \tag{3.11}$$

$\mathbb{P}[n=m]$ shows the probability which user associated with $\{k-1\}$-th band in traffic cell m. The probability express as

$$\begin{aligned}
\mathbb{P}[n=m] &= \mathbb{E}_{x_m}\left[\mathbb{P}[R_{i,m} > \max_{j,j\neq m} R_{i,j}]\right] \\
&= \mathbb{E}_{x_m}\left[\prod_{j,j\neq m} \mathbb{P}[R_{i,m} > R_{i,j}]\right] \\
&= \mathbb{E}_{x_m}\left[\prod_{j,j\neq m} \mathbb{P}\left[x_{i,j} > \left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)x_{i,m}^{\frac{\alpha_m}{\alpha_j}}\right]\right] \\
&= \int_0^\infty \prod_{j,j\neq m} \mathbb{P}\left[x_{i,j} > \left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)x_{i,m}^{\frac{\alpha_m}{\alpha_j}}\right] f_{x_m}(l)dl
\end{aligned} \tag{3.12}$$

In the 2-D poisson process, there is conclusion in [41]:

$$\mathbb{P}[\text{No Cell Close than } l] = e^{-\pi\lambda l^2} \tag{3.13}$$

The transition length is Rayleigh distributed.

$$f_{x_m}(l) = \frac{1-\mathbb{P}[\text{No Cell Close than } l]}{dl} = 2\pi\lambda l e^{-\pi\lambda l^2} \tag{3.14}$$

At first, we derive part of formula (3.12), where (3.13) and (3.14) are substituted into below formula.

$$\begin{aligned}
&\prod_{j,j\neq m} \mathbb{P}\left[x_{i,j} > \left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)x_{i,m}^{\frac{\alpha_m}{\alpha_j}}\right] \\
&= \prod_{j,j\neq m} \mathbb{P}[\text{No Cell Close than } l] \\
&= \prod_{j,j\neq m} e^{-\pi\lambda\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)x_{i,m}^{\frac{\alpha_m}{\alpha_j}}\right]^2} \\
&= e^{-\pi\lambda\sum_{j,j\neq m}\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)x_{i,m}^{\frac{\alpha_m}{\alpha_j}}\right]^2}
\end{aligned} \tag{3.15}$$

Then, we put above formula into (3.12),

$$\begin{aligned}
\mathbb{P}[n=m] &= \int_0^\infty e^{-\pi\lambda\sum_{j,j\neq m}\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)l^{\frac{\alpha_m}{\alpha_j}}\right]^2} 2\pi\lambda e^{-\pi\lambda l^2}dl \\
&= 2\pi\lambda\int_0^\infty l e^{-\pi\lambda\left[\sum_{j,j\neq m}\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)l^{\frac{\alpha_m}{\alpha_j}}\right]^2+l^2\right]}dl \\
&= \pi\lambda\int_0^\infty e^{-\pi\lambda\left[\sum_{j,j\neq m}\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha_j}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)l^{\frac{\alpha_m}{\alpha_j}}\right]^2+L^2\right]}dL
\end{aligned} \tag{3.16}$$

For calculation simplicity the above formula, it is considered that bands have similar configuration, which are all UEs have the same bandwidth allocation. Furthermore, path-loss exponents of UFB and LFB are almost equal to each other, which means α_m=α_j=α. This assumption is verified as very limited impacts for the performances [42]. Therefore, the main differences is the transmit power and standard cover radius of cell m.

$$
\begin{aligned}
\mathbb{P}[n=m] =& \pi\lambda \int_0^\infty e^{-\pi\lambda\left[\sum_{j,j\neq m}\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)\right]^2 + L^2\right]} dL \\
=& \int_0^\infty e^{-\pi\lambda L\left[\sum_{j,j\neq m}\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)\right]^2 + 1\right]} d\pi\lambda L \\
=& \frac{1}{\sum_{j,j\neq m}\left[\left(\frac{R_j}{R_m}\right)^{1/\alpha}\left(\frac{r_j}{r_m^{\alpha_m/\alpha_j}}\right)\right]^2 + 1} = \frac{(R_m^{1/\alpha} r_m)^2}{\sum_j (R_j^{1/\alpha} r_j)^2}
\end{aligned}
\qquad (3.17)
$$

The derived-closed-form expression shows the relationship between the probability which UE associated with $\{k-1\}$-th band in cell m and radius. The association probability is not only related with cell m but also with all other neighbour cells. In fact, it is considered neighbour cells conditions with the user association probability in this section.

3.2.2 Intra-cell Frequency Band Exiling Probability in Green Cellular Networks

During the network operations, neither CSO nor CZ approach is usually preferred because of service interruption possibility of mobile users in the field. Instead, it is possible to change the coverage area of the k-th band by ensuring the coverage area of the field by the $\{k-1\}$-th band. Thus, we eliminate the most significant disadvantages of CZ that are not only coverage holes but also computational complexity. If the power consumption of the k-th band is higher than the $\{k-1\}$-th band, the exiled users from the k-th band to $\{k-1\}$-th band decreases power consumption of the overall system. In other words, ICE technique can be used, if only the amount of decrease in UFB is greater than the amount of increase in LFB. Therefore, probability of the ICE is defined below and given in Figure 3.2c by considering the constraint as

$$\begin{aligned}\mathbb{P}[f_k \to f_{k-1}] &= \mathbb{P}\left(\frac{\partial P_k}{\partial x_k} > \frac{\partial P_{k-1}}{\partial x_{k-1}}\right)\mathbb{P}[n=m] \\ = \mathbb{P}\Bigg(x_k - \frac{2\alpha_{k-1}P_{k-1}^{(o)^2}}{2\alpha_k P_k^{(o)^2}}(x_{k-1}) &> \frac{\beta_{k-1}P_{k-1}^{(o)} - \beta_k P_k^{(o)}}{2\alpha_k P_k^{(o)^2}}\Bigg)\mathbb{P}[n=m],\end{aligned} \tag{3.18}$$

where $f_k \to f_{k-1}$ represents an exiled user from the k-th band to the $\{k-1\}$-th band carrier frequency. Cell traffic can be modeled by log-normal distribution as defined [43]

$$\mathbb{P}[x_k \text{ at the } k\text{-th band}] = \frac{1}{x_k\sigma_k\sqrt{2\pi}}e^{-\frac{[\ln(x_k)-\mu_k]^2}{2\sigma_k^2}}, \tag{3.19}$$

where μ_k and σ_k are the location and the scale parameters, respectively. Thus, $\mathbb{P}[f_k \to f_{k-1}]$ becomes a combination of log-normally distributed two random variables, x_k and scaled x_{k-1}. The closed-form expression of the sums of log-normal random variables has not been determined analytically yet. Furthermore, it is difficult to numerically calculate the distribution. Numerous approximations exist that are based on approximating a sum of log-normal random variables as another log-normal random variable. Wilkinson's method is widely used owing to allow the summation of log-normal distributions whose mean values and standard deviations are different [44]. According to Wilkinson's method, the mean value, μ_{ICE}, and the standard deviation, σ_{ICE}, of the log-normally distributed ICE probability are obtained as

$$\mu_{ICE} = 2\ \ln u_1 - \frac{1}{2}\ \ln u_2 \tag{3.20}$$

$$\sigma_{ICE} = \sqrt{\ln u_2 - 2\ \ln u_1} \tag{3.21}$$

respectively, where

$$u_1 = \sum_{i=0}^{K-1} \exp\left(\mu_{k-i} + \sigma_{k-i}^2/2\right) \tag{3.22a}$$

$$u_2 = \sum_{i=0}^{K-1} \exp\left(2\mu_{k-i} + 2\sigma_{k-i}^2\right) + 2\sum_{i=0}^{K-2}\sum_{j=i}^{K-1} \exp\left(\mu_{k-i} + \mu_{k-j}\right) \times \exp\left[\frac{1}{2}\left(\sigma_{k-i}^2 + \sigma_{k-j}^2 + 2r\sigma_{k-i}\sigma_{k-j}\right)\right]. \tag{3.22b}$$

3.3 Performance Metrics in Intra-Cell Frequency Band Exiling Technique

Signal-to-interference-plus-noise ratio (SINR) is commonly used performance criterion in wireless communications as a way to measure the quality of wireless connections. In this study, SINR is a main component for measuring quality of service (QoS). UE is associeted with its closest BS. To this aim, SINR is given by

$$\text{SINR} = \frac{P_t(1+r_i)^{-\alpha} \mid h_i \mid^2}{\sum_{j\varepsilon\phi_B\setminus i} P_t(1+r_j)^{-\alpha} \mid h_j \mid^2 + \sigma^2}, \tag{3.23}$$

where P_t is the total transmit power of the BS and the channel coefficient between the typical UE and l-th BS is denoted by h_l. Also, distance between UE to l-th BS is denoted by r_l [21]. In information-theoretical sense, ergodic capacity refers to the maximum rate that the communication system can achieve, assuming the communication duration is long enough to experience all channel states. The capacity achievable by each user is given by

$$\mathscr{C} = B[\log_2(1+\text{SINR})], \tag{3.24}$$

where B represents the system bandwidth. The ASE and EE are critical metrics for comparing various network designs [23], [45]. ASE measures the performance of ICE scenarios in green cellular networks. ASE is formulated as

$$\eta_{ASE} = \lambda_M \times \mathscr{C} , \tag{3.25}$$

where λ_M and $\mathscr{C}$ are the UE density and the ergodic capacity of each user, respectively. Additionally, the EE of an active BS can be expressed as

$$\eta_{EE} = \frac{B \times L \times \mathscr{C}}{P_{BS}} \tag{3.26}$$

where L stands for the total number of active users in a cell. Besides, in the denominator of (3.26), P_{BS} defines total power consumption of BS.

Due to increasing number of smart mobile devices, main products transform voice and message service to data services. It is thought that serving more data increases the profits, however, power consumption of eNodeBs is dramatically raising cost. Also, more and more devices cause to spectral scarcity because of the limited and licensed frequency bands. It is worth noting that there is a trade-off between ASE and EE.

4. SIMULATIONS RESULTS

In simulations, the ICE techniques is evaluated in regard to previous chapter's outputs such as user association probability and performance metrics. The data-set details and the ICE probabilities are illustrated in figures. Finally, ASE and EE graphics are shown in both DL and UL scenarios.

4.1 Probability of Intra-Cell Frequency Band Exiling

In this thesis, data-set is obtained with locations of BSs from networks deployed in one of the east province in China where population is more than 9 million [4]. Also, a dense urban area and a rural area depicted in Figure 4.1 and 4.2. Nearly, 6297 cells are considered in data-set and evaluated as a input of probabilistic model.

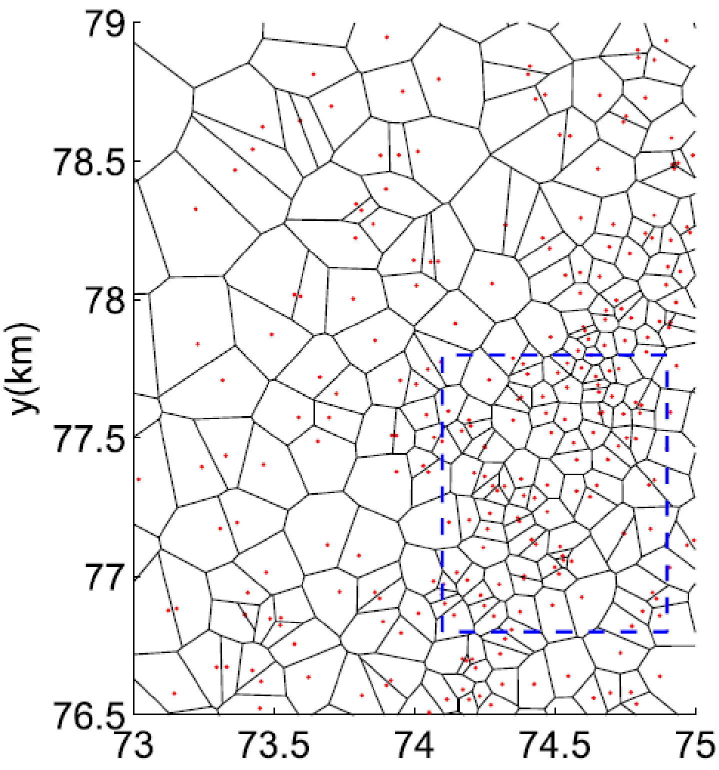

Figure 4.1 : Corresponding Voronoi cells (lines) in a urban area and BS locations (dots) [4].

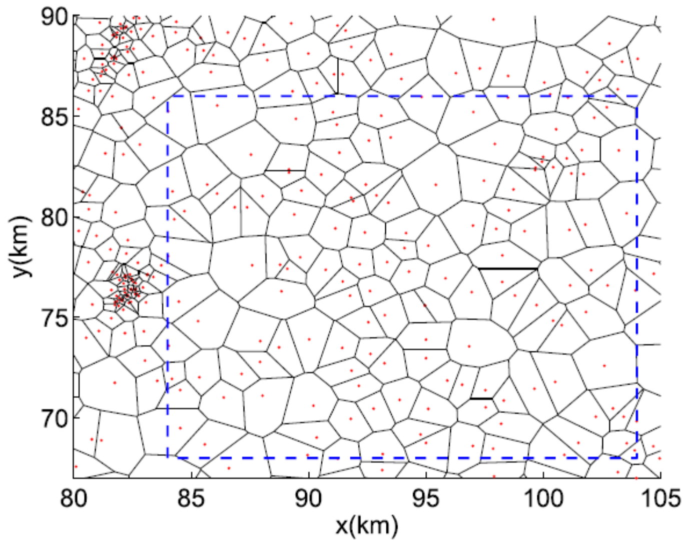

Figure 4.2 : Corresponding Voronoi cells (lines) in a rural area and BS locations (dots) [4].

In China, there is a variety of spatial structures among locations because, they faced rapid population growth and urbanization along 21st century. The structure of a urban area and population are key components of planning cellular networks. It is shown in Figure 4.1 and 4.2, location of BSs in an urban area is highly ultra-dense where the diameter of small size cells is even several tens of meters. Between May 1 and 14 in 2013, it is obtained traffic records in terms of packet-switched data traffic. Also, each BS actually transmitted during a one-hour time interval and measured in the unit of kilobyte (KB). It is introduced the traffic density (traffic load per unit area) which can be easily measured by using the data from BSs for the simulation of the traffic fluctuation.

In [4], log-normal, Weibull, gamma, and exponential distributions are tested with the K-S test and all the distributions should be denied at 5% significance level. The log-normal distribution shows the best fitting performance in terms of the Kolmogorov-Smirnov (K-S) test statistics. In the simulation scenario, higher mean values of traffic density distributions are chosen for the UFB (the k-th band) and lower mean values of traffic density distributions are chosen for the LFB (the $\{k-1\}$-th band). The location (μ) and the scale (σ) parameters of log-normal distributions for each region are obtained by the maximum likelihood estimation, and are listed in Table 4.1.

Table 4.1 : Parameters of log-normal distibutions.

	Uplink		Downlink	
Freq. bands	μ	σ	μ	σ
UFB	13.8401	1.4288	15.1738	1.2744
LFB	8.7435	1.5640	10.2637	1.3885

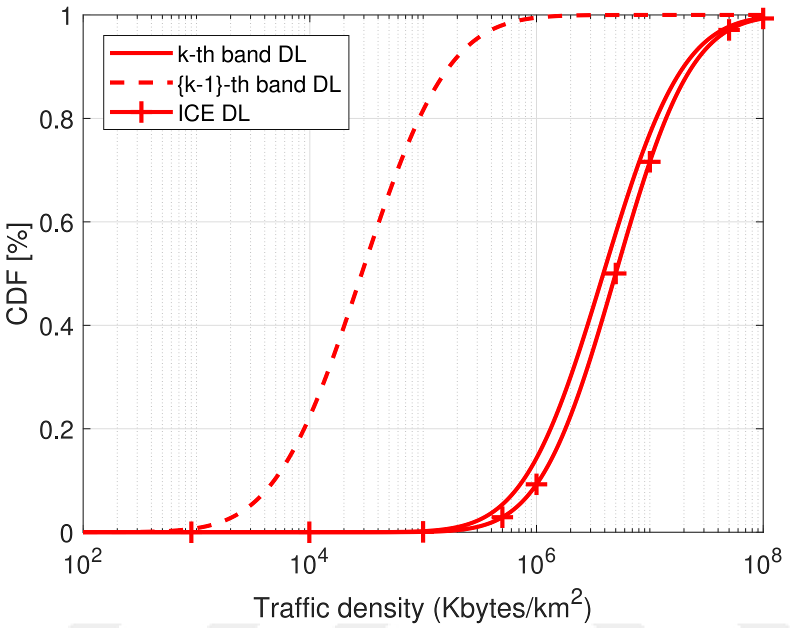

Figure 4.3 : DL traffic densities in the k-th and $k-1$-th bands, and the ICE probability.

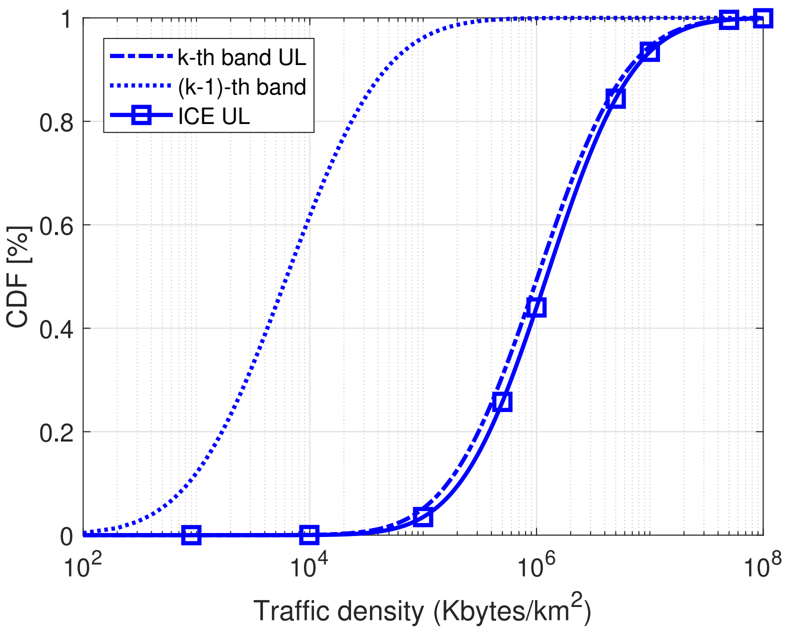

Figure 4.4 : UL traffic densities in the k-th and $k-1$-th bands, and the ICE probability.

Figure 4.3 shows the distributions of the traffic density in the k-th and the $\{k-1\}$-th band and the ICE probabilities in terms of DL CDF. Also, UL CDF is shown in Figure 4.4. It is obvious that traffic density of the UFB is higher than the LFB. Also, it has to be highlighted that DL traffic density is generally higher than the UL traffic density. Besides, UL and DL ICE CDFs are shown separately. For the calculation of ICE CDF from (3.20) and (3.21), we choose parameters as $\lambda_m = 1$ $[1/km^2]$, $\lambda_u = \{1000, 10000, 100000\}$ $[1/km^2]$, $n = 4$, $\alpha_k = -0.004$, $\alpha_{k-1} = 0.005$, $P_k^{(o)} = 40\ W$, and $P_{k-1}^{(o)} = 40\ W$ for simulations. Also, B_{DL}= 10 MHz and B_{UL}= 5 MHz are determined. All parameters are shown in Table 4.2. It can be inferred that ICE UL is preferable in lower traffic density. However, ICE technique is more beneficial in DL for higher traffic density.

Table 4.2 : Parameters of ICE.

Parameters	Values
Intensity of BSs (λ_m)	1 $[1/km^2]$
Intensity of UEs (λ_u)	10000 $[1/km^2]$
Path loss exponent (n)	4
Weighting coefficients of radio unit consumed power (α_k, α_{k-1})	{-0.004 , 0.005}
Output powers of radio unit ($P_k^{(o)}$, $P_k^{(o)}$)	40 W
Downlink bandwidth (B_{DL})	10 MHz
Uplink bandwidth (B_{UL})	5 MHz

4.2 Performance of Intra-Cell Frequency Band Exiling

ICE performance is evaluated in terms of ASE and EE according to DL and UL traffic density and shown in Figure 4.5, 4.6, 4.7, and 4.8. Since power consumption of UEs is quite low compared to BSs, the power consumption of UEs is neglected. In Figure 4.5 and 4.8, ASE performance in the $\{k-1\}$-th band increases with DL and UL traffic density. However, the k-th band ASE performance decreases. Also, they have very close ASE value after $10^7 Kbytes/km^2$. In the UFB, meanly the k-th band, performance improvement of ASE is lower than the LFB. In Figure 4.6 and 4.8, the ICE EE performance in DL and UL is shown. It can be observed that EE performance has similar pattern as ASE. However, EE decreases beyond a specific threshold especially for the values higher than $10^7 Kbytes/km^2$. The trade-off between ASE and EE is shown in Figure 4.9, 4.10, and 4.11 for different user intensity scenarios. It can be seen that from Figure 4.10, concavity of the curves proves that there is an optimum point at $10^7 Kbytes/km^2$. In other words, increasing ASE degrades EE after passing the top point of the curve. Also, the optimum point is a proof of the ICE technique can be alternative technique for green cellular networks change in regard to DL and UL traffic densities. It can be inferred that ICE UL can be selected in lower traffic density. However, ICE technique is more beneficial in DL for higher traffic density.

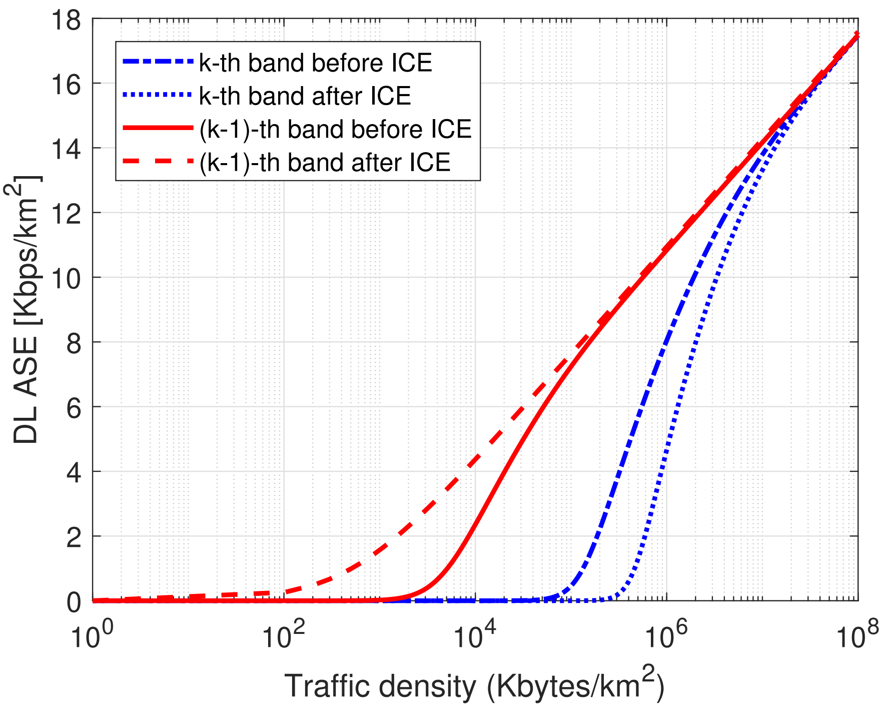

Figure 4.5 : Intra-cell frequency band exiling DL ASE performance.

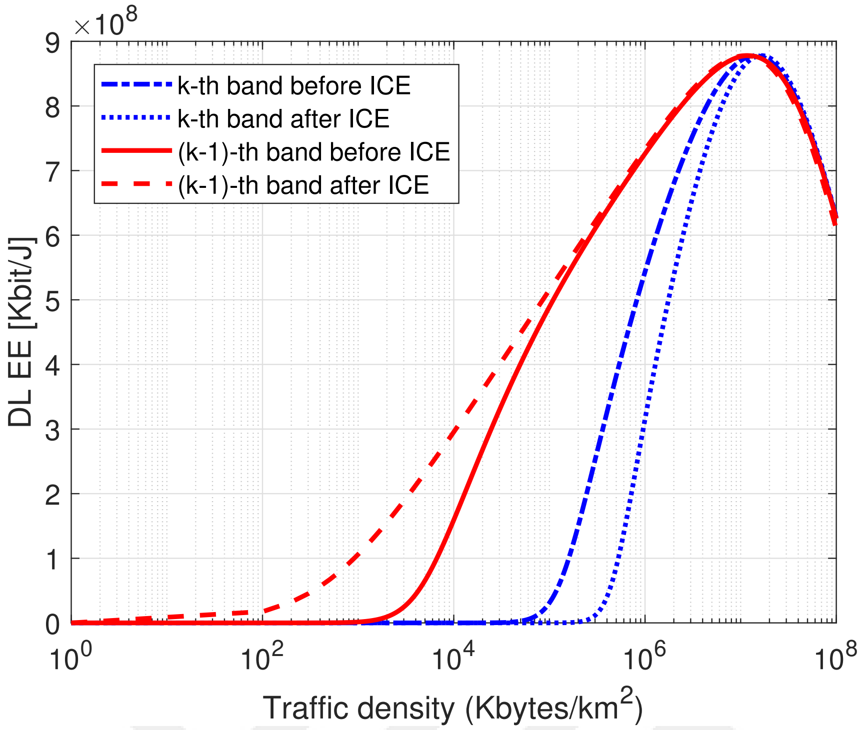

Figure 4.6 : Intra-cell frequency band exiling DL EE performance in PVT cellular network.

In Fig. 4.12, ICE performance is evaluated in terms of ASE and EE according to DL and UL traffic density and shown. Also, we compare the ASE and EE of the CZ technique which derive a tractable expression for the ergodic capacity in a PVT random cellular network. In both techniques BSs' and UEs' locations are drawn randomly from two independent PPPs. Also, the CZ technique is evaluated for only DL not for UL traffic density in [21]. Thus, we show only the CZ DL performance in Fig. 4.12 As power consumption of UEs is quite low compared to BSs, it is neglected. The trade-off between the ASE and EE is shown in Fig. 4.12. It can be seen from Fig. 4.12 that concavity of the curves proves that there is an optimum point for different UE density scenarios for DL and UL. In other words, an increase in ASE degrades EE after passing the top point (i.e., max efficiency) of the curve. In addition, the ICE optimum points for both DL and UL provide higher efficiencies than the CZ technique. It is also shown that the ICE technique is more suitable than CZ for different UE density levels.

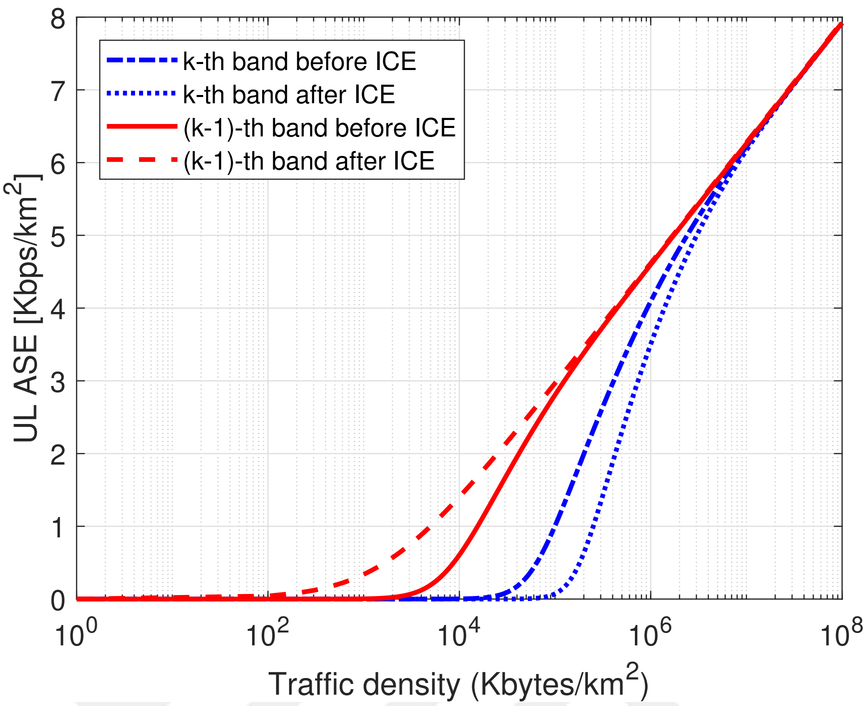

Figure 4.7 : Intra-cell frequency band exiling UL ASE performance in PVT cellular network.

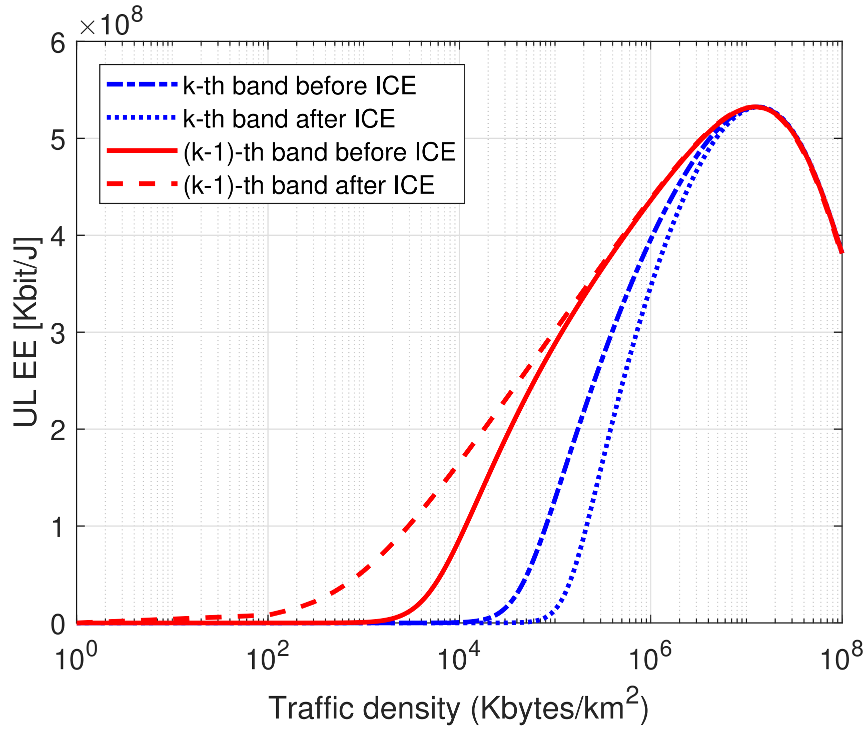

Figure 4.8 : Intra-cell frequency band exiling UL EE performance in PVT cellular network.

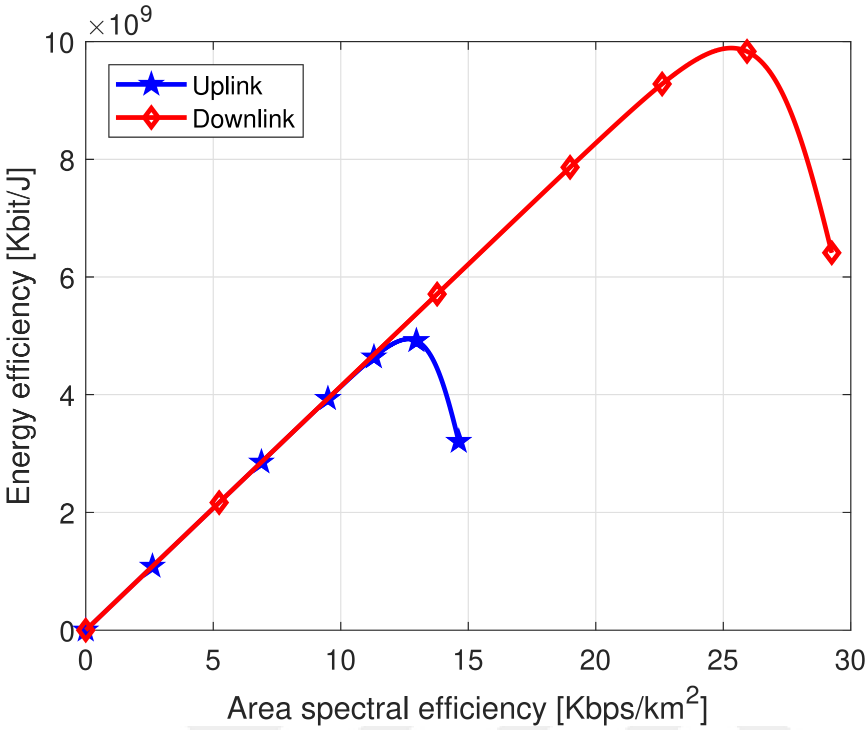

Figure 4.9 : Trade-off between energy and area spectral efficiency in λ_u=1000 [$1/km^2$].

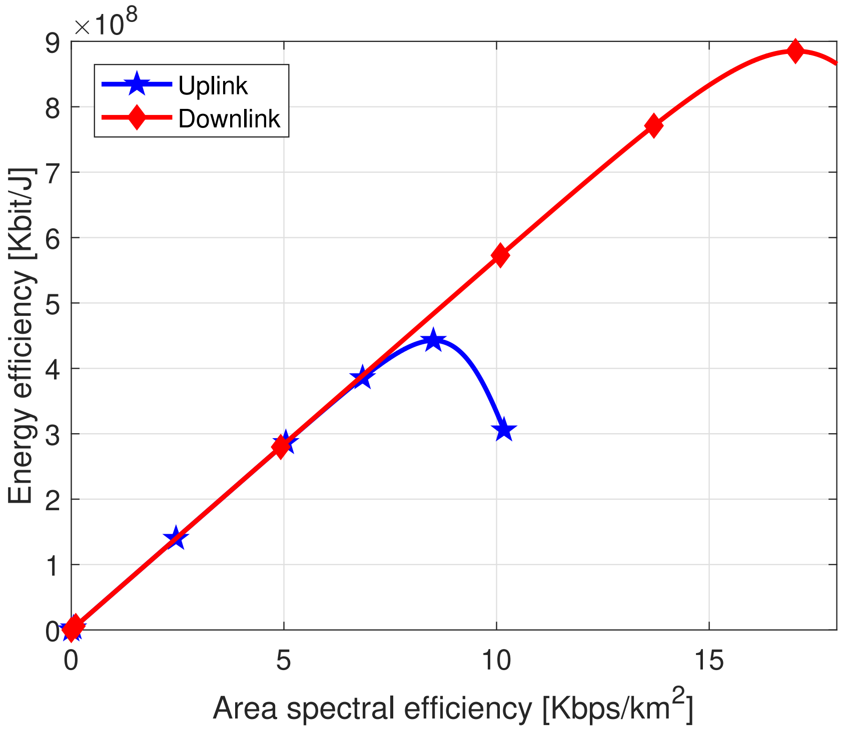

Figure 4.10 : Trade-off between energy and area spectral efficiency in λ_u=10000 [$1/km^2$].

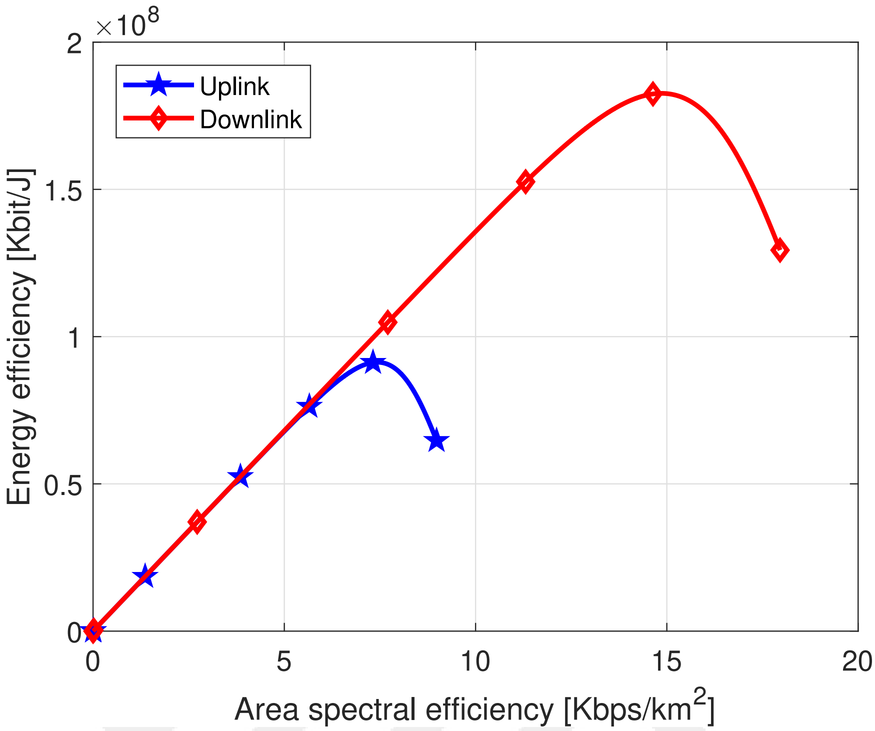

Figure 4.11 : Trade-off between energy and area spectral efficiency in λ_u=100000 [$1/km^2$].

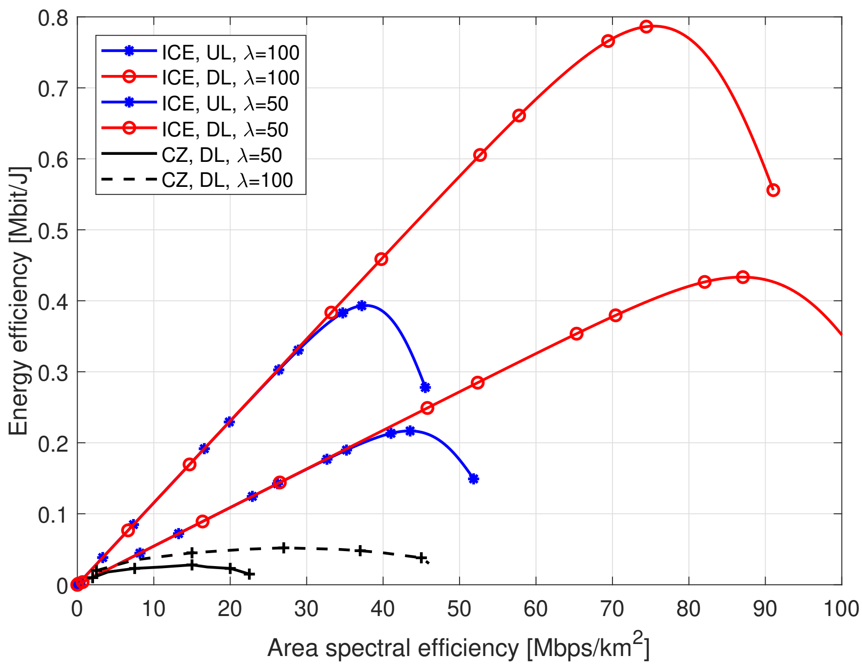

Figure 4.12 : The trade-off between energy and area spectral efficiency of a PVT random cellular network employing the ICE and CZ technique.

5. CONCLUSIONS AND RECOMMENDATIONS

Increasing energy consumption through rapidly evolving mobile communication systems is indicative of the demand for energy efficient systems. According to previous study, information and communication technology (ICT) sector is responsible of 10% of the total energy consumption and 2% of global CO_2 emissions. Among the main ICT sectors, 37% of the total ICT energy consumption are due to communication equipments. Also, many communication technology companies taking actions for decreasing harmful effects of ICT tools including a worldwide mobile operator, which have announced that their 2025 goals are to reduce greenhouse gas emissons by 40%. The drive to make cellular networks more "green" starts with base stations (BSs) because, around 60% percent of the power is consumed by base stations. Thus, smallest improvement in power consumption will bring huge saving in energy. As an example, Information and Communications Technologies Authority of the Republic of Turkey (BTK) reported in September 2018 that 181.972 base station (BS) are deployed all over the country and average base stations consume nearly 2500 Wh.

In next generation wireless network systems, it is envisaged to increase the energy efficiency by changing the coverage area of BSs by two basic methods: cell switch on-off (CSO) and cell zooming (CZ). Many researches have been done in the literature on CZ. However, neither CSO nor CZ are sufficient solutions for energy efficiency in wireless networks. These techniques may not guarantee to meet the demands such as covering whole service area, computational simplicity, and fast processing. In this thesis, ICE is proposed as a promising energy-efficient technique due to the fact that radio units of lower frequency bands (LFBs) consume less power than radio units of upper frequency bands (UFBs). In ICE scenarios, we reduce the power consumed by a BS through switching the frequency bands. Hence, energy efficiency can be improved by assigning user equipments (UEs) from UFBs to LFBs. The ICE can not only solve the problem of traffic imbalance, but also reduce the energy consumption in cellular networks.

In introduction part, the necessity of green communication systems and the economic impacts of ICT in future is discussed. Besides, it was explained that the decision of cell zooming will be done in a central way or with a distributed decision making algorithm. Continuous, discrete and fuzzy CZ methods used to determine cell boundaries when adjusting coverage area. In energy-efficient cellular network design chapter, fundamental trade-offs in network resource utilization is explained. Also, energy-efficient homogeneous and heterogeneous network deployment are evaluated. After that, the most promising cellular operation techniques are examined. In the third chaper, our new technique which name is intra-cell frequency band exiling is explained. Poisson-Voronoi tesellation of cellular network and more realistic BS power consumption is used for system model. Besides, performance metrics in technique are introduced. In the fourth section, it is showed that the technique save a large amount of energy when traffic load is light, which can achieve the purpose of green cellular network in a cost efficient way. The developed technique is applied on the traffic intensity in one of a China district. In areas where user and data traffic change throughout the day, it is envisaged that energy efficiency will increase even more with the use of the proposed algorithm. It can be seen that concavity of the curves proves that there is an optimum point at $10^7 Kbytes/km^2$. In other words, increasing ASE degrades EE after passing the top point of the curve. It is aimed to further improve the energy efficiency by developing the existing technique.

In this work, a new technique is proposed for providing energy efficiency in a green cellular network which utilizes ICE in transmission strategy. Thanks to ICE technique, users are assigned from UFB to LFB owing to adjusting the BS coverage area. Thus, it contributes to less power consumption. To this purpose, we derived an expression for the ICE in networks, which is less complex and faster to simulate. Also, we evaluated ICE performance in terms of ASE and EE. As a result, it is shown that ICE technique can be applied until achievable ICE rate without considering performance measures. In future works, ICE technique can be evaluated on real implementation and performance indicators.

REFERENCES

[1] **Malmodin, J.**, **Bergmark, P. and Lundén, D.** (2013). The future carbon footprint of the ICT and E&M sectors, *on Information and Communication Technologies*, 12.

[2] **López-Pérez, D.**, **Valcarce, A.**, **De La Roche, G. and Zhang, J.** (2009). OFDMA femtocells: A roadmap on interference avoidance, *IEEE Communications Magazine*, *47*(9), 41–48.

[3] **Miao, G. and Song, G.** (2014). *Energy and spectrum efficient wireless network design*, Cambridge University Press.

[4] **Zhou, S.**, **Lee, D.**, **Leng, B.**, **Zhou, X.**, **Zhang, H. and Niu, Z.** (2015). On the Spatial Distribution of Base Stations and Its Relation to the Traffic Density in Cellular Networks., *IEEE Access*, *3*, 998–1010.

[5] **Fettweis, G. and Zimmermann, E.** (2008). ICT energy consumption-trends and challenges, *Proceedings of the 11th international symposium on wireless personal multimedia communications*, volume 2, (Lapland, p. 6.

[6] **Webb, M.** *et al.* (2008). Smart 2020: Enabling the low carbon economy in the information age, *The Climate Group. London*, *1*(1), 1–1.

[7] **Vidal, J.** (2017). Tsunami of data could consume one fifth of global electricity by 2025, *Climate Home News*, *12*(2).

[8] **Han, C.**, **Harrold, T.**, **Armour, S.**, **Krikidis, I.**, **Videv, S.**, **Grant, P.M.**, **Haas, H.**, **Thompson, J.S.**, **Ku, I.**, **Wang, C.X.** *et al.* (2011). Green radio: radio techniques to enable energy-efficient wireless networks, *IEEE communications magazine*, *49*(6).

[9] **Correia, L.M.**, **Zeller, D.**, **Blume, O.**, **Ferling, D.**, **Jading, Y.**, **Gódor, I.**, **Auer, G. and Van Der Perre, L.** (2010). Challenges and enabling technologies for energy aware mobile radio networks, *IEEE Communications Magazine*, *48*(11).

[10] **Teknolojileri, B. and Kurumu, İ.** (2018). Türkiye Elektronik Haberleşme Sektörü Üç Aylık Pazar Verileri Raporu 2018 Yılı 3, *Çeyrek Temmuz–Ağustos-Eylül*.

[11] **Ericsson** (June 2017). Power Consumption Guideline for RBS 6000, *User Guide*.

[12] **Auer, G.**, **Giannini, V.**, **Desset, C.**, **Godor, I.**, **Skillermark, P.**, **Olsson, M.**, **Imran, M.A.**, **Sabella, D.**, **Gonzalez, M.J.**, **Blume, O.** *et al.* (2011). How much energy is needed to run a wireless network?, *IEEE wireless communications*, *18*(5), 40–49.

[13] **Zhang, Z.**, **Liu, F. and Zeng, Z.** (2017). The cell zooming algorithm for energy efficiency optimization in heterogeneous cellular network, *Wireless Communications and Signal Processing (WCSP), 2017 9th International Conference on*, IEEE, pp.1–5.

[14] **Niu, Z.**, **Wu, Y.**, **Gong, J. and Yang, Z.** (2010). Cell zooming for cost-efficient green cellular networks, *IEEE communications magazine*, *48*(11).

[15] **Beitelmal, T. and Yanikomeroglu, H.** (2014). A set cover based algorithm for cell switch-off with different cell sorting criteria, *Communications Workshops (ICC), 2014 IEEE International Conference on*, IEEE, pp.641–646.

[16] **Weng, X.**, **Cao, D. and Niu, Z.** (2011). Energy-efficient cellular network planning under insufficient cell zooming, *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, IEEE, pp.1–5.

[17] **Balasubramaniam, R.**, **Nagaraj, S.**, **Sarkar, M.**, **Paolini, C. and Khaitan, P.** (2013). Cell zooming for power efficient base station operation, *Wireless Communications and Mobile Computing Conference (IWCMC), 2013 9th International*, IEEE, pp.556–560.

[18] **Hasan, Z.**, **Boostanimehr, H. and Bhargava, V.K.** (2011). Green cellular networks: A survey, some research issues and challenges, *IEEE Communications surveys & tutorials*, *13*(4), 524–540.

[19] **Beitelmal, T.** (2017). The Cell Switch-Off Approach for Energy Efficient Cellular Networks, *Ph.D. thesis*, Carleton University.

[20] **Elbassiouny, S.O.**, **Elhamy, A. and Ibrahim, A.S.** (2015). Traffic-aware user association technique for dynamic on/off switching of small cells, *Wireless Communications and Networking Conference (WCNC), 2015 IEEE*, IEEE, pp.866–871.

[21] **Khamesi, A.R. and Zorzi, M.** (2016). Energy and area spectral efficiency of cell zooming in random cellular networks, *Global Communications Conference (GLOBECOM), 2016 IEEE*, IEEE, pp.1–6.

[22] **Xu, X.**, **Yuan, C.**, **Chen, W.**, **Tao, X. and Sun, Y.** (2018). Adaptive Cell Zooming and Sleeping for Green Heterogeneous Ultradense Networks, *IEEE Transactions on Vehicular Technology*, *67*(2), 1612–1621.

[23] **Hsu, C.C.**, **Chang, J.M.**, **Chou, Z.T. and Abichar, Z.** (2014). Optimizing spectrum-energy efficiency in downlink cellular networks, *IEEE Transactions on Mobile Computing*, *13*(9), 2100–2112.

[24] Evolved Universal Terrestrial Radio Access (E-UTRA); Mobility and Radio Resource Management (Release 8)" version 2014.

[25] **U. Garcia, L.G.**, **Pedersen, K.I. and Mogensen, P.E.** (2009). Autonomous component carrier selection: interference management in local area environments for LTE-advanced, *IEEE Commun. Mag.*, *47*(9), 110–116.

[26] **Li, G. and Liu, H.** (2006). Downlink Radio Resource Allocation for Multi-Cell OFDMA System, *IEEE Trans. Wireless Commun.*, *5*(12), 3451–3459.

[27] **Akyildiz, I.F.**, **Lee, W.**, **Vuran, M.C. and Mohanty, S.** (2008). A survey on spectrum management in cognitive radio networks, *IEEE Commun. Mag.*, *46*(4), 40–48.

[28] **Mangharam, R.**, **Rajkumar, R.**, **Pollin, S.**, **Catthoor, F.**, **Bougard, B.**, **Van der Perre, L. and Moeman, I.** (2005). Optimal fixed and scalable energy management for wireless networks, *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.*, volume 1, IEEE, pp.114–125.

[29] **Xiong, C.**, **Li, G.Y.**, **Zhang, S.**, **Chen, Y. and Xu, S.** (2011). Energy-and spectral-efficiency tradeoff in downlink OFDMA networks, *IEEE transactions on wireless communications*, *10*(11), 3874–3886.

[30] **Amin, O.**, **Bedeer, E.**, **Ahmed, M.H. and Dobre, O.A.** (2015). Energy efficiency–spectral efficiency tradeoff: A multiobjective optimization approach, *IEEE Transactions on Vehicular Technology*, *65*(4), 1975–1981.

[31] **Miao, G.**, **Himayat, N.**, **Li, G.Y. and Talwar, S.** (2011). Distributed interference-aware energy-efficient power optimization, *IEEE Transactions on Wireless Communications*, *10*(4), 1323–1333.

[32] **Han, T. and Ansari, N.** (2014). Powering mobile networks with green energy, *IEEE Wireless Communications*, *21*(1), 90–96.

[33] **Zhang, Z.**, **Li, Y.**, **Huang, K.**, **Zhou, S. and Wang, J.** (2015). Energy efficiency analysis of cellular networks with cooperative relays via stochastic geometry, *China Communications*, *12*(9), 112–121.

[34] **Arvanitakis, G.** (2014). Distribution of the number of poisson points in poisson voronoi tessellation, *Tech. Rep. RR-15-304*.

[35] **Zhong, Y. and Zhang, W.** (2012). Downlink analysis of multi-channel hybrid access two-tier networks, *Communications (ICC), 2012 IEEE International Conference on*, IEEE, pp.2479–2484.

[36] **Soh, Y.S.**, **Quek, T.Q.**, **Kountouris, M. and Shin, H.** (2013). Energy efficient heterogeneous cellular networks, *IEEE Journal on Selected Areas in Communications*, *31*(5), 840–850.

[37] **Wu, S.** *et al.* (2018). Stochastic Geometry-based Analysis of Emerging Network Technologies: from Millimeter-wave Cellular to Nano-optical Networks, *Ph.D. thesis*, State University of New York at Buffalo.

[38] **Last, G. and Penrose, M.** (2017). *Lectures on the Poisson process*, volume 7, Cambridge University Press.

[39] **Haenggi, M.** (2012). *Stochastic geometry for wireless networks*, Cambridge University Press.

[40] **Xu, X.**, **Zhang, Y.**, **Sun, Z.**, **Hong, Y. and Tao, X.** (2016). Analytical modeling of mode selection for moving D2D-enabled cellular networks, *IEEE Communications Letters*, *20*(6), 1203–1206.

[41] **Jo, H.S.**, **Sang, Y.J.**, **Xia, P. and Andrews, J.G.** (2012). Heterogeneous cellular networks with flexible cell association: A comprehensive downlink SINR analysis, *IEEE Transactions on Wireless Communications*, *11*(10), 3484–3495.

[42] **Hong, Y.**, **Xu, X.**, **Tao, M.**, **Li, J. and Svensson, T.** (2015). Cross-tier handover analyses in small cell networks: A stochastic geometry approach, *2015 IEEE International Conference on Communications (ICC)*, IEEE, pp.3429–3434.

[43] **Lee, D.**, **Zhou, S.**, **Zhong, X.**, **Niu, Z.**, **Zhou, X. and Zhang, H.** (2014). Spatial modeling of the traffic density in cellular networks, *IEEE Wireless Communications*, *21*(1), 80–88.

[44] **Cardieri, P. and Rappaport, T.S.** (2000). Statistics of the sum of lognormal variables in wireless communications, *IEEE 51st Veh. Technol. Conf.*, volume 3, pp.1823–1827.

[45] **Keenan, T. and Villing, R.** (2013). Optimizing area power consumption in LTE type cells.

CURRICULUM VITAE

Name Surname: Ahmet Burak ÖZYURT

Place and Date of Birth: Çaycuma, Zonguldak, 17th November 1994

E-Mail: aburakozyurt@gmail.com

EDUCATION:

- **B.Sc.:** Istanbul Technical University, Management Engineering [September, 2014-June, 2018]
- **B.Sc.:** Istanbul Technical University, Electronics and Communication Engineering [September, 2012-January, 2018]
- **B.Sc.:** Institut Supérieur D'électronique de Paris, Electronics and Communication Engineering [January, 2016-June,2016 (Erasmus Exchange Program)]

PROFESSIONAL EXPERIENCES:

- Network Researcher, Ericsson Research, Istanbul September, 2019-Present
- Graduate Student Researcher, İTÜ-Vodafone Future Lab, Istanbul, July 2018—August 2019.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Ozyurt Ahmet Burak, Ardanuc Mine, Basaran Mehmet, Durak-Ata Lutfiye " Intra-Cell Frequency Band Exiling for Green Cellular Networks" IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), İstanbul, Turkey, 2019, September. (Accepted but witdrawn for submission as an article)
- Ozyurt Ahmet Burak, Basaran Mehmet, Durak-Ata Lutfiye, Aselsan 4th Communications Technologies Workshop Presantation- "Dynamic Coverage Management in Mobile Networks" (February 2019)
- Ozyurt Ahmet Burak, Hiz Arda, Durak-Ata Lutfiye "Energy-Efficient Utilization of Different Frequency Bands for Green Cellular Networks" IEEE 26th Signal Processing and Communications Applications Conference (SIU), İzmir, Turkey, 2018, May.
- Ozyurt Ahmet Burak, Durak-Ata Lutfiye, Scientific and Technological Research Council of Turkey (TÜBİTAK) Universities Project Competition - National 3rd Place-"Dynamic Coverage Management in Mobile Networks" (November 2018) (http://www.itu.edu.tr/ogrenci/%C3%B6grencimizden-bilisim-uygulamalarindatubitak-derecesi-)

- A.B. Ozyurt, A. Hiz, L.Durak-Ata, " Environmental Using Of Mobile Network Frequency Bands for Energy Efficiency", Turkish Patent Institute, TR 2017/22027.
- “Dynamic Coverage Management in Mobile Networks” Scientific and Technological Research Council of Turkey (TÜBİTAK) 2209-B Undergraduate Graduation Thesis Support Program for Industrialization Project No.1139B411701084 (11.2017- 06.2018)

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- Ozyurt Ahmet Burak, Basaran Mehmet, Durak-Ata Lutfiye "Impact of Self-Configuration on Handover Performance in Green Cellular Networks" IEEE Advances in Wireless and Optical Communications (RTUWO), Riga, Latvia, 2018, November.