FRACTIONAL FREQUENCY REUSE BASED INTERFERENCE MITIGATION IN IRREGULAR GEOMETRY MULTICELLULAR NETWORKS

RAHATULLAH

UNIVERSITI TEKNOLOGI MALAYSIA

FRACTIONAL FREQUENCY REUSE BASED INTERFERENCE MITIGATION IN IRREGULAR GEOMETRY MULTICELLULAR NETWORKS

RAHATULLAH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JULY 2016

To My Beloved Parents

(Abai & Baba)

ACKNOWLEDGEMENT

All praise and glory to the Almighty Allah (Subhanahu Wa Ta'ala) who gave me the courage and patience to carry out this work. Peace and blessings of Allah be upon His last Prophet Muhammad (Sallulaho-Alaihe-Wassalam).

I would like to express my sincere gratitude to my supervisor Prof. Dr. Norsheila bnt Fisal for not only being a supervisor, but a mother. May Allah reward you in many fold for your patience, support and invaluable advises.

I would also like to thank the Higher Education Commission (HEC) of Pakistan for sponsoring my studies and the FUUAST, Pakistan, for their support throughout the course of this study.

My thanks and appreciation is also for my friends, colleagues and fellow researchers in the UTM, for all their support and encouragement during the time we spent together doing our research.

I would like to thank my Family; my parents, wife, brothers and sister for all their love, understanding and support. Their prayers and encouragement always helps me to take the right steps in life.

Finally, my beautiful children; Sinan, Maria and Hassaan, for being my life, my happiness and my hope.

ABSTRACT

Recent drastic growth in the mobile broadband services specifically with the proliferation of smart phones demands for higher spectrum capacity of wireless cellular systems. Due to the scarcity of the frequency spectrum, cellular systems are seeking aggressive frequency reuse, which improve the network capacity, however, at the expense of increased Inter Cell Interference (ICI). Fractional Frequency Reuse (FFR) scheme has been acknowledged as an effective ICI mitigation scheme, however, in literature FFR has been used mostly in perfect geometry network. In realistic deployment, the cellular geometry is irregular and each cell experiences varying ICI. The main objective of this thesis is to develop ICI mitigation scheme that improves spectrum efficiency and throughput for irregular geometry multicellular network. Irregular Geometry Sectored-Fractional Frequency Reuse (IGS-FFR) scheme is developed that comprises of cell partitioning and sectoring, and dynamic spectrum partitioning. The cell-partitioning and sectoring allows full frequency reuse within an irregular geometry cell. Nevertheless, the sub-regions in an irregular cell have varying coverage areas and thus demands diverse spectrum requirements. The IGS-FFR scheme is designed to dynamically allocate the spectrum resources according to the traffic demands of each sub-region. An enhanced IGS-FFR has been developed to optimally allocate the spectrum resources to individual users of each sub-region. Enhanced IGS-FFR has been realized using two different approaches, Auction based Optimized IGS-FFR (AO-IGS-FFR) and Hungarian based Optimized IGS-FFR (HO-IGS-FFR). The results show that IGS-FFR has significantly improved the cell throughput by 89%, 45% and 18% and users' satisfaction by 112%, 65.8% and 38% compared to Reuse-1, Strict-FFR and FFR-3 schemes, respectively. The findings show that the ICI mitigation in IGS-FFR is reinforced by users' satisfaction. As the number of sectors in IGS-FFR increases from 3 to 4 and 6, the cell throughput increase by 21% and 33% because of spatial diversity exploitation along with orthogonal sub-band allocation. AO-IGS-FFR and HO-IGS-FFR have further improved the cell throughput of the basic FFR-3 by 65% and 72.2%, respectively. HO-IGS-FFR performs 7% better than the AO-IGS-FFR at the expense of 26.7% decrease in the users' satisfaction and excessive complexity. Although, AO-IGS-FFR compromises sub-optimal bandwidth allocation, it is a low complexity scheme and can mitigate ICI with high users' satisfaction. The enhanced IGS-FFR can be deployed in future heterogeneous irregular geometry multicellular OFDMA networks.

ABSTRAK

Pertumbuhan drastik dalam perkhidmatan terkini jalur lebar mudah alih terutamanya dengan percambahan telefon pintar memerlukan kapasiti spektrum sistem selular tanpa wayar yang lebih tinggi. Oleh kerana kekurangan spektrum frekuensi, sistem selular sedang mencari frekuensi guna semula yang agresif, yang mana meningkatkan keupayaan rangkaian, bagaimanapun dengan mengorbankan gangguan antara sel (ICI) yang meningkat. Skim frekuensi guna semula berperingkat (FFR) telah diiktiraf sebagai skim pencegahan ICI yang berkesan, namun begitu, dalam kajian FFR kebanyakan telah digunakan di dalam rangkaian geometri sempurna. Dalam penggunaan sebenar geometri selular adalah tidak teratur dan setiap sel mengalami ICI yang berbeza-beza. Objektif utama tesis ini adalah untuk membangunkan skim pengurangan ICI yang meningkatkan kecekapan spektrum dan daya pemprosesan untuk geometri tidak teratur bagi rangkaian multisel. Skim geometri tidak teratur bersektor-frekuensi guna semula berperingkat (IGS-FFR) dibangunkan yang terdiri daripada pembahagian dan persektoran sel, dan pembahagian spektrum dinamik. Pembahagian dan persektoran sel membolehkan penggunaan semula frekuensi penuh dalam sel geometri tidak teratur. Walau bagaimanapun, sub-kawasan dalam sel yang tidak teratur mempunyai pelbagai kawasan liputan dan dengan itu memerlukan keperluan spektrum yang pelbagai. Skim IGS-FFR direka untuk secara dinamik memperuntukkan sumber spektrum, mengikut permintaan trafik setiap sub-kawasan. IGS-FFR yang dipertingkatkan telah dibangunkan untuk berfungsi secara optimum dalam memperuntukkan sumber spektrum kepada pengguna individu bagi setiap sub-kawasan. IGS-FFR yang dipertingkatkan telah direalisasikan dengan menggunakan dua pendekatan yang berbeza, IGS-FFR yang dioptimum berdasarkan lelong (AO-IGS-FFR) dan IGS-FFR yang dioptimum berdasarkan Hungarian (HO-IGS-FFR). Keputusan menunjukkan bahawa IGS-FFR telah meningkatkan daya pemprosesan sel dengan ketara dengan pada 89%, 45% dan 18% dan kepuasan pengguna masing-masing pada 112%, 65.8% dan 38% berbanding dengan skim-skim Reuse-1, Strict-FFR dan FFR-3. Hasil kajian menunjukkan bahawa pengurangan ICI di IGS-FFR dikuatkan oleh kepuasan pengguna. Dengan kenaikan bilangan sektor di IGS-FFR dari 3 ke 4 dan 6, daya pemprosesan sel juga meningkat masing-masing sebanyak 21% dan 33% kerana eksploitasi kepelbagaian spatial bersama-sama dengan peruntukan sub-band ortogon. AO-IGS-FFR dan HO-IGS-FFR telah dipertingkatkan lagi pemprosesan sel daripada asas FFR-3 sehingga 65% dan 72.2%, masing-masing. HO-IGS-FFR berfungsi 7.1% lebih baik daripada AO-IGS-FFR dengan 26.7% penurunan dalam kepuasan pengguna dan kerumitan yang berlebihan. Walaupun, AO-IGS-FFR kompromi peruntukan jalur lebar sub-optimum, ianya merupakan skim kerumitan yang rendah dan boleh mengurangkan ICI dengan kepuasan pengguna yang tinggi. IGS-FFR teroptimum boleh digunakan dalam rangkaian OFDMA multisel geometri tidak teratur berbagai-bagai di masa depan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

EB - ExaByte
CAGR - Compound Annual Growth Rate
IMT-A - International Mobile Telecommunication-Advanced
ITU - International Telecommunication Union
3GPP - 3rd Generation Partnership Project
4G - 4th Generation
5G - 5th Generation
LTE - Long Term Evolution
LTE-A - Long Term Evolution-Advanced
VNI - Visual Networking Index
OFDMA - Orthogonal Frequency Division Multiple Access
ICI - Inter Cell Interference
CCI - Co-Channel Interference
ICIC - Inter Cell Interference Coordination
FFR - Fractional Frequency Reuse
BS - Base Station
SINR - Signal to Interference plus Noise Ratio
SON - Self Organization Network
QoS - Quality of Service
HGM - Hexagon Geometry Model
IGS-FFR - Irregular Geometry Sectored-Fractional Frequency Reuse
AO-IGS-FFR - Auction based Optimized IGS-FFR
HO-IGS-FFR - Hungarian based Optimized IGS-FFR
FDD - Frequency Division Duplexing
HetNet - Heterogeneous Network
FBS - Femto Base Station
D2D - Device 2 Device

M2M	-	Machine 2 Machine
H2H	-	Human 2 Human
IoT	-	Internet of Things
WiMAX	-	Worldwide Interoperability for Microwave Access
ISI	-	Inter Symbol Interference
OFDM	-	Orthogonal Frequency Division Multiplexing
BER	-	Bit Error Rate
OPEX	-	Operational Expenditures
CAPEX	-	Capital Expenditures
PPP	-	Poisson Point Process
PHCP	-	Poisson Hard Core Process
MUD	-	Multi-user Detection
SIC	-	Successive Interference Cancellation
PIC	-	Parallel Interference Cancellation
AWGN	-	Additive White Gaussian Noise
FH	-	Frequency Hoppoing
CDMA	-	Code Division Multiple Access
IDMA	-	Interleave Division Multiple Access
MIMO	-	Multiple Input and Multiple Output
FRF	-	Frequency Reuse Factor
FFR	-	Fractional Frequency Reuse
VCG	-	Vickrey-Clarke-Groves
GFFR	-	Generalized Fractional Frequency Reuse
SSI	-	Spectrum Satisfaction Index
US	-	User Satisfaction
SORA	-	Self-Organized Resource Allocation
CDF	-	Commulative Density Function

LIST OF SYMBOLS

T_s	-	SINR threshold
S	-	Number of sectors
P^t	-	Transmit power
Φ	-	PHCP
R^2	-	Euclidean plane
d	-	Distance between BS and user
X	-	set of BSs
x	-	BS
$C(x)$	-	Coverage of the BS x
n	-	user
k	-	sub-carrier
N	-	Total number of users
K	-	Total number of sub-carriers
N^T	-	Total users in cell
B^T	-	Total bandwidth
$R^t_{n,k}$	-	Recieved power on k for n
$G^i_{n,k}$	-	Channel gain of i on k for n
$H^i_{n,k}$	-	Small scale fading gain
$PL(D^i_n)$	-	large scale path loss
D^i_n	-	Distan between BS i and user n
X_σ	-	log-normal shadowing
σ	-	standard deviation
X^i	-	Location of the BS i
X^n	-	Location of the user n
J	-	Set of interfering BS
$I_{n,k}$	-	interference received by a user n on sub-carrier k

$P_{n,k}^{j}$ - Transmit power of the BS j for n on sub-carrier k

$G_{n,k}^{j}$ - Channel gain of the BS j for n on sub-carrier k

$SINR_{(n,k)}$ - Recived SINR of user n on sub-carrier k

N_o - Power spectral density of additive noise

Δf - Sub-carrier spacing

US - User satisfaction

R_n - Throughput of the user n

R_{max} - Maximum user throughput

B^T - Total system bandwidth

$SE_{(n,k)}$ - Spectral efficiency of user n on sub-carrier k

B_n^a - Bandwidth allocated to user n

R_n - Achievable throughput of user n

$x_{(n,k)}$ - Sub-carrier allocation indicator

R_n^i - Throughput of a serving cell i

T_S - Threshold SINR

N^C - Number of users in cell-center region

N^E - Number of users in cell-edge region

N^s - Number of users in sector s

B_{req}^n - Bandwidth required by user n

K_{req}^n - Sub-carriers required by user n

R_d^n - Traffic demand of user n

B_{req}^c - Bandwidth required by cell-center region

B_{req}^e - Bandwidth required by cell-edge region

B_{req}^s - Bandwidth required by sector S

Γ^C - Cell-center region satisfaction index

Γ^E - Cell-edge region satisfaction index

Γ^T - Threshold satisfaction index

Γ_s^t - Sector satisfaction index

$B^{1,2,3}$ - Sub-band for sector 1,2,3

B^o - Open sub-band

B_s^o - Part of open sub-band B^o for sector S

B_a^s - bandwidth allocated to sector S

$B^o_{(s,i)}$ - Portion/part of the B^o initially allocated to setor S

$B^o_{(s,f)}$ - Final portion of the open sub-band for sector s

$B^{o'}$ - Remainig part of the open sub-band

B_t^S - Tatal bandwidth for sector S

K^S - Total number of sub-carriers in the sub-band for sector S

R^d_{max} - Maximum throughput demand

R_{max} - Maximum throughput

R^{mean} - Mean throughput

R^{mean}_{max} - Maximum mean throughput

R^{cell}_{total} - Cell throughput

K^c - Number of sub-carriers in cell-center sub-band

K^1 - Number of sub-carriers in sector 1 sub-band

K^2 - Number of sub-carriers in sector 2 sub-band

K^3 - Number of sub-carriers in sector 3 sub-band

C_n - bundle of sub-carriers requested by user n

Γ - Game

B_n - Bid of user n

U_n - Utility function of user n

V_n - Valuation of the user n

P_n - Payment by user n or price for user n

$R_n^{t,c}$ - Target date rate of cell-center user n

$B^C_{N^C}$ - Set of bids for cell center region

$B^1_{N^1}$ - Set of bids for sector 1

$a(n)$ - Approximate value of user n

$A(N)$ - List of approximate values for N users

$u_i(s_i)$ - Utility of user i for strategi s_i

G_n - Bundle of sub-carriers granted to user n

$H_{(N,K)}$ - Channel matrix for normalized SINR values of N users and K sub-carriers

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Future cellular systems are changing rapidly because of the proliferation of smart phones, tablets and other media hungry devices. Specifically with the advancement of the smart gadgets, the demand for broadband application services has dramatically increased over the past few years [1]. Recent Ericsson Mobility Report indicates that the exponential growth in the mobile data traffic will reach a nine-fold escalation by the year 2020 [2]. Global mobile data traffic was 1.5 Exabyte's (EB) per month by the end of 2013, raises up to 2.5 EB per month at the end of 2014, which translates to 66.6 percent growth in the global mobile data traffic recorded in the year 2014. Moreover, updated Cisco industry report for this year forecasts that the mobile data traffic is expected to grow up to 24.3 EB per month by 2019 [3]. Statistically, mobile data traffic will grow at a compound annual growth rate (CAGR) of 57 percent between 2014 and 2019, as shown in Figure 1.1.

Next generation wireless communication systems aim to meet the high data rates, increased capacity, extended coverage, low complexity and low latency requirements defined by International Mobile Telecommunications-Advanced (IMT-A) of the International Telecommunication Union (ITU). The formulation of the Long Term Evolution (LTE) into LTE-Advanced (LTE-A), make it possible to meet the IMT-A requirements (peak data rates of 1Gbit/s for the downlink and 500Mbits/s for the uplink, and extended bandwidth support up to 100MHz) for the fourth generation (4G) mobile communication [4]. According to the recent Cisco Visual Networking Index (VNI) report [5], 4G connection has generated 10 times more traffic than a non-4G connection in 2014 and is responsible for 40 percent of the total mobile data traffic. These statistics show that the 4G technology is going to be the most preferable choice for the mobile traffic in the near future.

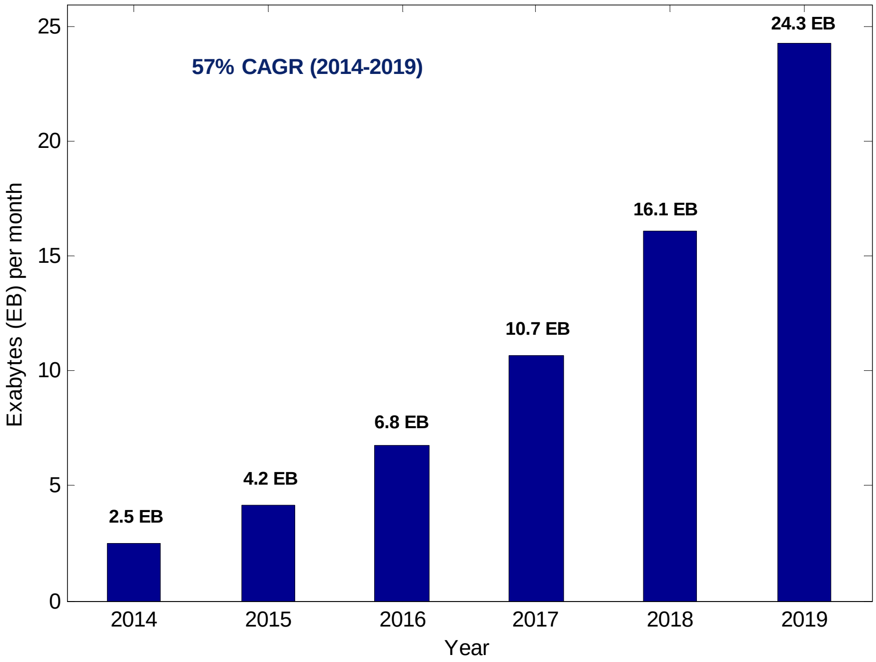

Figure 1.1: CISCO mobile data traffic growth forecast by 2019 [3]

The exponential growth in the mobile data traffic is forcing network operators to significantly enhance their system capacity and coverage. Therefore, efficient radio resource management is gaining more attention in the wireless communication as it could open up new prospects for the capacity and coverage enhancement [6]. These trends have triggered the development of new cellular standards, which incorporates the OFDMA as a radio access technique because of its capacity gain via frequency domain diversity as well as multi-user diversity [7].

Due to the scarcity of the frequency spectrum, spatial reuse is a promising technique to enhance network capacity by allowing spectrum reuse in the OFDMA based cellular network. However, the aggressive frequency reuse results in the inter cell interference (ICI) or co-channel interference (CCI), because of the co-channel deployment in neighboring cells. Therefore, there is always a trade-off between the support for improved network capacity offered by spatial reuse and the interference it introduced. Fractional Frequency Reuse (FFR) has been acknowledged as an effective interference mitigation technique in the OFDMA based cellular systems [8].The basic mechanism of FFR corresponds to the partitioning of the cell coverage area in spatial sub-regions and the frequency spectrum in sub-bands. In addition, the spectrum sub-bands are then allocated to each sub-region in way that avoids the ICI.

In the wireless networks, signal power and interference received at a typical user depends mainly on the distance between transmitter and receiver [9]. On the other hand, the position of the typical user with respect to other Base Stations (BSs) which are simultaneously using the same channel, highly affects the interference experience by that user. The Signal to Noise plus Interference Ratio (SINR) experienced by each user depends on its location, the positions of the interference sources as well as the instantaneous channel gains. Consequently, the network geometry has a significant impact on the received SINR and hence the performance of wireless cellular system crucially depends on the spatial configuration of BSs and network topology [10]. Therefore, it is important to consider the network topology while designing any interference mitigation scheme.

Finally, to realize the requirement of both cellular operators and users in a cost effective way, recent development has triggered the induction of intelligence and autonomous adaptivety (i.e. called self-organization) into the future cellular networks. Self-organization has been extensively explored and applied in wireless ad-hoc networks, wireless sensor networks and autonomic computer networks. However, from the perspective of wireless cellular networks, this concept has gained significant interest in the recent past [11]. Self-Organizing Networks (SON) concept appears as an efficient solution, where in the network is capable to autonomously observe and adjust to different conditions with minimal human intervention [12] and therefore, results in reduce operational cost [13].

1.2 Problem Statement

In order to meet the ever increasing capacity demand for the mobile broadband applications and services, next generation cellular systems are targeting aggressive frequency reuse due to the scarcity of frequency spectrum, [14]. The frequency reuse of one (Reuse-1) is the example of such aggressive frequency reuse, where in, all the available radio resources are allocated at every cell of the network. Such frequent frequency reuse increase the spatial spectrum efficiency and the network capacity, at the expense of increased ICI [8]. Therefore, ICI is the prominent limiting factors which affect the users' ability to achieve the desired quality-of-service (QoS) [13]. Furthermore, the ICI problem is more severe at the cell edges [15].

Due to the above mentioned challenge, interference mitigation is the primary interest of both the academic and industry communities [16]. Review on the present interference management approaches for OFDMA based cellular networks are presented in Chapter 2, section 2.5. It is found that, to enhance the performance of the cellular network, FFR is an effective ICI mitigation approach [8, 17]. FFR is attractive due to its low complexity and significant coverage improvement for cell edge users [18]. The main objective of FFR is to improve the SINR and system throughput by avoiding the ICI through orthogonal sub-band allocation specifically at the cell edge region. In FFR, each cell is allocating its resources in a way such that to minimize the overall interference experienced in the network and to maximize the spatial reuse [19].

In literature FFR has been used mostly with perfect cellular geometry models such as a hexagonal grid model (HGM), where each cell has a symmetrical coverage region [20]. However, in the realistic deployment of the cellular systems it is impractical to achieve an exact degree of symmetry [21]. In realistic deployment, where the cellular layout is irregular, not only propagation conditions vary significantly from cell to cell, but also, azimuths are not aligned and hence, cells experience vast difference of ICI [22]. As a consequence, the cell edge region may differ in terms of size and interference levels. Therefore, the performance of basic FFR techniques is poor in the irregular geometry cellular deployment [23].

Thus, network topology considered for any interference mitigation scheme plays an important role in the performance. The network topology consideration has triggered recent research on FFR with irregular geometry cellular networks [19, 24, 25]. However, almost all of the previous work on FFR on irregular geometry model only accounts for simplistic FFR with only two regions (cell-center and cell-edge) and the cell sectoring has not been taken into account [26]. Moreover, dynamic spectrum partitioning has not been adopted in the FFR configuration for irregular geometry multicellular networks in order to support the diverse users' traffic demands. Thus, there is a need to develop an ICI mitigation using FFR, which considers sectoring and dynamic spectrum partitioning for irregular cellular geometry based OFDMA multicellular networks while realizing full frequency reuse.

1.3 Research Objectives

The main goal of this research is to mitigate ICI in the irregular geometry OFDMA multicellular system through improving the system spectrum efficiency and enhancing the system throughput. The specific objectives of the research are;

- To develop FFR scheme which considers sectoring and dynamic spectrum partitioning for irregular geometry OFDMA multicellular network.
- To develop an enhanced FFR scheme for the irregular geometry multicellular network to optimize the system performance in terms of achievable throughput.

The proposed FFR scheme is defined as Irregular Geometry based Sectored- Fractional Frequency Reuse (IGS-FFR). The IGS-FFR scheme has been optimized by adopting two different techniques and defined as Enhanced-IGS-FFR (eIGS-FFR). In the first optimization approach auction mechanism is adopted to optimize IGS-FFR and is named as AO-IGS-FFR. Then in the second optimization approach, Hungarian method is adopted to optimize IGS-FFR and is named as HO-IGS-FFR scheme. The performance of the proposed FFR schemes is evaluated in terms of cell achievable throughput, user satisfaction, and throughput with respect to different load conditions.

1.4 Scope of the Research

In the multicellular OFDMA network, the ICI occurs when the overlapping cells are utilizing the same frequency spectrum. This research mainly focuses on the ICI issue in the OFDMA based multicellular network operating in the downlink. The OFDMA is selected as a multiple access technique in the downlink as it offers the flexibility while allocating the frequency spectrum resources based on the channel quality, through its inherent feature of multi-user diversity. Specifically, the Frequency Division Duplexing (FDD) [27] access mode of the OFDMA downlink transmission is assumed in this thesis.

This research focuses on mitigating ICI in the irregular geometry based OFDMA multicellular network. Stochastic geometry based model is used to abstract the position of the BSs, which enables the realistic interference computation by considering the random distances between the neighboring cells. The users are assumed to be connected to the nearest BSs. Consequently, the coverage region of each cell is irregular or Voronoi tessellation. Self-organized ICI mitigation schemes are developed for the irregular geometry based OFDMA multicellular network. The proposed schemes are self-organized in the scope that each cell of the network autonomously decides its spectrum partition based on the load condition, spectrum requirement and channel conditions. Therefore, the proposed interference mitigation schemes are aware of the diverse user traffic demands and the channel quality.

First, the IGS-FFR scheme is developed to mitigate the ICI in the irregular geometry based OFDMA multicellular network. The objective of this scheme is to achieve the full frequency reuse (Reuse-1) to meet the capacity demand. To achieve the full frequency reuse, the proposed scheme divides the cell into cell-center and cell-edge region, where the cell-edge region is further divided into a number of sectors. The resultant cell-center and sectors are defined as sub-region of the cell, and will be used throughout this thesis. Due to the irregular geometry, the resultant sub-regions are different in terms of coverage area and hence, in load distribution. The IGS-FFR scheme dynamically allocates the frequency spectrum (sub-band) to each sub-region of the cell, according to the traffic demand of each sub-region. Moreover, to mitigate the ICI, the proposed scheme maintains the orthogonality in the spectrum sub-band allocation.

The eIGS-FFR schemes is the enhancement of the IGS-FFR scheme in terms of optimal bandwidth allocation to the individual users of each sub-region of the cell. First, AO-IGS-FFR scheme is developed based on the game theoretic auction mechanism for optimal sub-carrier allocation in the irregular geometry OFDMA multicellular network. The AO-GOS-FFR is distributive in nature, where users are allowed to request for multiple sub-carriers, according to their traffic demand and channel condition. However, in order to avoid the complexity issue, the users are restricted to request for only one combination of the sub-carriers of their choice in one allocation time. On the other hand in the second approach, HO-IGS-FFR is developed based on Hungarian method to optimally allocate the sub-carriers to users in each sub-region based Channel Quality Information (CQI).

In this research, the BSs are considered to be equipped with an omni-directional transmission antenna configuration for the cell-center region, and a directional antenna transmission configuration for the cell-edge region. The directional antenna pattern depends on the number of sectors in the cell-edge region, for example, for the a three sectors cell, the BS is equipped with 120^o directional antenna. Moreover, the antenna configurations are considered without any power control ability. This is due to the fact that the total transmission power of the BS is considered to be uniformly distributed across the amount of spectrum. Furthermore, this research considered the network users with heterogeneous traffic demand. The proposed schemes are evaluated by MATLAB simulation, considering the 3GPP model for the parameter settings.

1.5 Research Contribution

The major contributions of the thesis are listed as follows;

- **Development of Sectored-FFR for the Irregular Geometry Multicellular Network**

  FFR has been acknowledged as an efficient scheme to avoid the ICI in OFDMA multicellular systems. The basic mechanism of FFR corresponds to the partitioning of the cell coverage area in spatial regions, where each sub-region is assigned with different frequency sub-bands in order to avoid the interference. However, in case of irregular geometry cellular network, partitioning of the cell resultants in sub-regions of varying coverage, number of users and load conditions. Therefore, each sub-region has a different spectrum requirement. In literature, almost all of the previous works on FFR with irregular geometry network models account for two sub-regions, cell-center and cell-edge. Cell sectoring has not been included in the FFR for irregular geometry networks. In this thesis, the sectored FFR scheme is developed for irregular geometry network, where the cell coverage area is partitioned into cell-center and cell-edge region, the cell edge is further divided into a number of sectors. The frequency spectrum is accordingly partition into a number of sub-bands, for each sub-region of the cell. The sectoring of the cell-edge region make it possible to fully utilize the frequency spectrum, by orthogonaly allocating the spectrum sub-band to each cell-edge region sector in the neighboring cells, in order to mitigate ICI in multicelluar network.

- **Dynamic Spectrum Allocation**

  The developed IGS-FFR and eIGS-FFR scheme are designed to dynamically allocate the spectrum resource to each sub-region, according to the spectrum requirement and traffic demand.

- **Optimized bandwidth allocation**

  The IGS-FFR is optimized in terms of optimal bandwidth allocation to the individual users of each sub-region of the cell. In the IGS-FFR scheme the sub-bands are specified for each sub-region of the cell. However, the optimized bandwidth resources for the individual users are not specified. The eIGS-FFR is developed to optimally allocate the bandwidth resources to the users using two different approaches. AO-IGS-FFR is developed based on game theoretic auction mechanism whereas, HO-IGS-FFR is developed based on Hungarian method. In both, AO-IGS-FFR and HO-IGS-FFR, the sub-carriers are optimally allocated to maximize the throughput of every users in the cell, and hence the overall throughput is maximized.

1.6 Significance of the Research

The proposed FFR schemes for the irregular geometry based OFDMA cellular system can contribute towards realizing self-organizing networks (SON). This is because the proposed IGS-FFR scheme is able to adapt to the network variations and automatically implement the proposed spectrum allocation according to the requirement when the current spectrum partition is no longer valid. Note that the deployment of the proposed self-organized spectrum assignment schemes are not limited for single tier macro-cell network.The proposed scheme can be an excellent fit to the successful deployment of the Heterogeneous Network (HetNet).

In the femtocell network, Femto Base Stations (FBSs) are randomly deployed by end users within the macrocell coverage area. The number and locations of FBSs can continuously vary. Classical network planning tools would not be able to configure and optimize a femtocell network. Therefore, the FBSs need to be self-organized in order to autonomously integrate into the radio access network [28]. Moreover, to efficiently utilize the available resources in the femtocell network, frequency spectrum is shared by macrocell and femtocell. However, this type of deployment results in cross-tier interference because of the co-channel deployment. The proposed interference mitigation scheme can be applied to avoid the interference by allocating orthogonal spectrum band to macro and femto users. Therefore, the proposed scheme is feasible in the successful deployment of the HetNets.

The proposed interference mitigation scheme can also be applied to Device-to-Device (D2D) communications [29], where the co-channel deployment will cause interference that would limit the performance gain of this technology. In D2D communication, the implementation of the proposed self-organized spectrum allocation schemes is feasible by ensuring the orthogonal sub-band allocation in the multi-tier devices. Similarly, in the Machine-to-machine (M2M) communication [30], which has been acknowledged to provide ubiquitous connectivity among communication-enabled devices in an unprecedented way, thus enabling in parts the Internet of Things (IoT) [31]. To improve the spectral efficiency, the same spectrum utilized for H2H (Human-to-human) communications can be reused for

M2M communications. This will increase the spatial spectrum efficiency and network capacity at the expense of increased interference. The proposed IGS-FFR scheme can be utilized to mitigate the interference in the M2M communication and 5G technology [32], by dynamically allocate the spectrum resources in the self-organized fashion.

1.7 Thesis Outlines

This thesis is organized as follows. Chapter 2 can be mainly composed of two main discussions, the theoretical background and the literature review. The theoretical background elaborates the technical aspects and fundamental features of OFDMA based systems, cellular network modeling, auction theory and Hungarian method. The literature review part of the chapter 2 covers the discussions on the existing interference mitigation approaches available in the literature, both for regular and irregular cell geometry OFDMA networks. The prior ICI approaches are analyzed based on their potentials and shortcomings which eventually leads towards the research motivations of this thesis.

Chapter 3 presents the design approach of the proposed ICI mitigation scheme for irregular geometry based OFDMA multicellular network. The basic design concept of IGS-FFR and eIGS-FFR schemes are presented in detail. The algorithmic flow charts for the proposed schemes are provided and discuss in detail. Moreover, chapter 3 also provides the specific detail of the system model, network topology and channel model. System performance metrics used to evaluate the network performance of the proposed schemes are provided and described. Furthermore, the chapter includes the description of the numerical and simulation tool using MATLAB, whereas its implementation concept is elaborated using functional blocks.

The formulation of the IGS-FFR for the ICI mitigation in the irregular geometry multicellular network is presented in the Chapter 4. The formulation is followed by the detail description of the IGS-FFR scheme. Then, the performance analysis of IGS-FFR scheme in comparison to the basic FFR schemes, when applied to irregular geometry networks, is presented.

Chapter 5 presents the formulation of the eIGS-FFR scheme. The formulation is followed by the detail description of AO-IGS-FFR and and HO-IGS-FFR. Then, the performance analysis of the AO-IGS-FFR and HO-IGS-FFR schemes in comparison to the basic FFR-3 scheme is provided.

Finally, Chapter 6 summarizes the significant achievements of IGS-FFR and eIGS-FFR schemes along with the recommendations for the future works.

REFERENCES

1. ICT Facts & Figures. The World in 2015. *International Telecommunication Union (ITU)*, 2015.
2. *Ericsson Mobility Report: On the pulse of the Networked society*. Technical Report June. 2015.
3. Networking, C. V. *Forecast and Methodology, 2014-2019 White Paper*. Technical report. Cisco Technical Report. 2015.
4. Parkvall, S., Furuskär, A. and Dahlman, E. Evolution of LTE toward IMT-advanced. *IEEE Communications Magazine*, 2011. 49(2): 84–91.
5. Cisco. Global mobile data traffic forecast update, 2014–2019. *white paper*, 2015.
6. Zander, J., Kim, S.-L., Almgren, M. and Queseth, O. *Radio resource management for wireless networks*. Artech House, Inc. 2001.
7. Srikanth, S., Pandian, P. and Fernando, X. Orthogonal frequency division multiple access in WiMAX and LTE: a comparison. *IEEE Communications Magazine*, 2012. 50(9): 153–161.
8. Himayat, N., Talwar, S., Rao, A. and Soni, R. Interference management for 4g cellular standards [wimax/lte update]. *IEEE Communications Magazine*, 2010. 48(8): 86–92.
9. Błaszczyszyn, B., Karray, M. K. and Klepper, F.-X. Impact of the geometry, path-loss exponent and random shadowing on the mean interference factor in wireless cellular networks. *Third Joint IFIP Wireless and Mobile Networking Conference*. IEEE. 2010. 1–6.
10. Andrews, J. G., Ganti, R. K., Haenggi, M., Jindal, N. and Weber, S. A primer on spatial modeling and analysis in wireless networks. *IEEE Communications Magazine*, 2010. 48(11): 156–163.
11. Aliu, O. G., Imran, A., Imran, M. A. and Evans, B. A survey of self organisation in future cellular networks. *IEEE Communications Surveys & Tutorials*, 2013. 15(1): 336–361.

12. Álvarez, F. B. *Contribution to Dynamic Spectrum Assignment in Multicell OFDMA Networks*. Ph.D. Thesis. Universitat Politècnica de Catalunya. 2010.

13. López-Pérez, D. *Practical models and optimization methods for intercell interference coordination in self-organizing cellular networks*. Ph.D. Thesis. University of Bedforshire Luton UK, Ph. D. dissertation. 2011.

14. Cho, Y. H., Seo, S., Song, J.-s., Lee, S.-H. and Lee, H. S. Adaptive fractional time reuse for multi-cell OFDMA networks. *IEEE Communications Letters*, 2013. 17(9): 1798–1801.

15. Saquib, N., Hossain, E., Le, L. B. and Kim, D. I. Interference management in OFDMA femtocell networks: issues and approaches. *IEEE Wireless Communications*, 2012. 19(3): 86–95.

16. ElSawy, H., Hossain, E. and Haenggi, M. Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: A survey. *IEEE Communications Surveys & Tutorials*, 2013. 15(3): 996–1019.

17. Bai, D., Park, C., Lee, J., Nguyen, H., Singh, J., Gupta, A., Pi, Z., Kim, T., Lim, C., Kim, M.-G. *et al.* LTE-advanced modem design: challenges and perspectives. *IEEE Communications Magazine*, 2012. 50(2): 178–186.

18. Saquib, N., Hossain, E. and Kim, D. I. Fractional frequency reuse for interference management in LTE-advanced hetnets. *IEEE Wireless Communications*, 2013. 20(2): 113–122.

19. Novlan, T. D., Ganti, R. K., Andrews, J. G. and Ghosh, A. A new model for coverage with fractional frequency reuse in OFDMA cellular networks. *IEEE Global Telecommunications Conference*. IEEE. 2011. 1–5.

20. Andrews, J. G., Baccelli, F. and Ganti, R. K. A tractable approach to coverage and rate in cellular networks. *IEEE Transactions on Communications*, 2011. 59(11): 3122–3134.

21. Andrews, J. G. Seven ways that HetNets are a cellular paradigm shift. *IEEE Communications Magazine*, 2013. 51(3): 136–144.

22. González, D., García-Lozano, M., Ruiz, S. and Olmos, J. On the performance of static inter-cell interference coordination in realistic cellular layouts. In: *Mobile Networks and Management*. Springer. 163–176. 2010.

23. Gonzalez, D. G., Garcia-Lozano, M., Ruiz Boque, S. and Lee, D. S. Optimization of soft frequency reuse for irregular LTE macrocellular networks. *IEEE Transactions on Wireless Communications*, 2013. 12(5):

2410–2423.

24. Novlan, T. D., Ganti, R. K., Ghosh, A. and Andrews, J. G. Analytical evaluation of fractional frequency reuse for OFDMA cellular networks. *IEEE Transactions on Wireless Communications*, 2011. 10(12): 4294–4305.

25. Novlan, T. D., Ganti, R. K., Ghosh, A. and Andrews, J. G. Analytical evaluation of fractional frequency reuse for heterogeneous cellular networks. *IEEE Transactions on Communications*, 2012. 60(7): 2029–2039.

26. Guo, A. and Haenggi, M. Spatial stochastic models and metrics for the structure of base stations in cellular networks. *IEEE Transactions on Wireless Communications*, 2013. 12(11): 5800–5812.

27. Han, Z.-H. and Lee, Y.-H. Opportunistic scheduling with partial channel information in OFDMA/FDD systems. *60th IEEE Vehicular Technology Conference*. IEEE. 2004, vol. 1. 511–514.

28. Andrews, J. G., Claussen, H., Dohler, M., Rangan, S. and Reed, M. C. Femtocells: Past, present, and future. *IEEE Journal on Selected Areas in Communications*, 2012. 30(3): 497–508.

29. Xu, C., Song, L., Han, Z., Zhao, Q., Wang, X. and Jiao, B. Interference-aware resource allocation for device-to-device communications as an underlay using sequential second price auction. *IEEE International Conference on Communications (ICC)*. IEEE. 2012. 445–449.

30. Lien, S.-Y., Chen, K.-C. and Lin, Y. Toward ubiquitous massive accesses in 3GPP machine-to-machine communications. *IEEE Communications Magazine*, 2011. 49(4): 66–74.

31. Lee, I.-G. and Kim, M. Interference-aware self-optimizing Wi-Fi for high efficiency internet of things in dense networks. *Computer Communications*, 2016.

32. Chin, W. H., Fan, Z. and Haines, R. Emerging technologies and research challenges for 5G wireless networks. *IEEE Wireless Communications*, 2014. 21(2): 106–112.

33. Stefania, S., Issam, T. and Matthew, B. LTE-the UMTS long term evolution: From theory to practice. *A John Wiley and Sons, Ltd*, 2009. 6: 136–144.

34. Wannstrom, J. LTE-advanced. *Third Generation Partnership Project (3GPP)*, 2012.

35. Ghosh, A., Ratasuk, R., Mondal, B., Mangalvedhe, N. and Thomas, T. LTE-advanced: next-generation wireless broadband technology [Invited Paper].

IEEE Wireless Communications, 2010. 17(3): 10–22.

36. Aliu, O. G., Imran, M. A. and Evans, B. Self organised cellular networks as the future of wireless communications. *Networking & Broadcasting 11th Annual Postgraduate Symposium on the Convergence of Telecommunications*. 2010.

37. Al-Ayyoub, M., Buddhikot, M. M. and Gupta, H. Self-regulating spectrum management: a case of fractional frequency reuse patterns in LTE networks. *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum*. IEEE. 2010. 1–12.

38. Marchetti, N., Prasad, N. R., Johansson, J. and Cai, T. Self-organizing networks: state-of-the-art, challenges and perspectives. *8th International Conference onCommunications*. IEEE. 2010. 503–508.

39. Döttling, M. and Viering, I. Challenges in mobile network operation: Towards self-optimizing networks. *IEEE International Conference on Acoustics, Speech and Signal Processing*. IEEE. 2009. 3609–3612.

40. Goldsmith, A. *Wireless communications*. Cambridge university press. 2005.

41. Wyner, A. D. Shannon-theoretic approach to a Gaussian cellular multiple-access channel. *IEEE Transactions on Information Theory*, 1994. 40(6): 1713–1727.

42. Somekh, O. and Shamai, S. Shannon-theoretic approach to a Gaussian cellular multiple-access channel with fading. *IEEE Transactions on Information Theory*, 2000. 46(4): 1401–1425.

43. Xu, J., Zhang, J. and Andrews, J. G. On the accuracy of the Wyner model in downlink cellular networks. *IEEE International Conference on Communications (ICC)*. IEEE. 2011. 1–5.

44. Shamai, S. and Wyner, A. D. Information-theoretic considerations for symmetric, cellular, multiple-access fading channels. I. *IEEE Transactions on Information Theory*, 1997. 43(6): 1877–1894.

45. Viterbi, A. J., Viterbi, A. M. and Zehavi, E. Other-cell interference in cellular power-controlled CDMA. *IEEE Transactions on Communications*, 1994. 42(234): 1501–1504.

46. Baert, A.-E. and Seme, D. Voronoi mobile cellular networks: topological properties. *Parallel and Distributed Computing Third International Symposium on/Algorithms, Models and Tools for Parallel Computing on Heterogeneous Networks*. IEEE. 2004. 29–35.

47. Gonzalez, G. D. and Hamalainen, J. Topology and irregularity in cellular networks. *IEEE Wireless Communications and Networking Conference*. IEEE. 2015. 1719–1724.

48. Sengoku, M., Tamura, H., Shinoda, S. and Abe, T. Graph & network theory and cellular mobile communications. *ISCAS'93 IEEE International Symposium on Circuits and Systems*. IEEE. 1993. 2208–2211.

49. González G, D. and Hämäläinen, J. Looking at Cellular Networks Through Canonical Domains and Conformal Mapping. *arXiv preprint arXiv*, 2015.

50. Haenggi, M. *Stochastic geometry for wireless networks*. Cambridge University Press. 2012.

51. Lee, C.-H., Shih, C.-Y. and Chen, Y.-S. Stochastic geometry based models for modeling cellular networks in urban areas. *Wireless networks*, 2013. 19(6): 1063–1072.

52. Lee, C.-h. and Haenggi, M. Interference and outage in doubly Poisson cognitive networks. *19th International Conference on Computer Communications and Networks*. IEEE. 2010. 1–6.

53. ElSawy, H., Hossain, E. and Kim, D. I. HetNets with cognitive small cells: user offloading and distributed channel access techniques. *IEEE Communications Magazine*, 2013. 51(6): 28–36.

54. Ganti, R. K. and Haenggi, M. Interference and outage in clustered wireless ad hoc networks. *IEEE Transactions on Information Theory*, 2009. 55(9): 4067–4086.

55. Han, Z. *Game theory in wireless and communication networks: theory, models, and applications*. Cambridge University Press. 2012.

56. Krishna, V. *Auction theory*. Academic press. 2009.

57. Zhang, Y., Niyato, D., Wang, P. and Hossain, E. Auction-based resource allocation in cognitive radio systems. *IEEE Communications Magazine*, 2012. 50(11): 108–120.

58. Benmammar, B., Amraoui, A. and Krief, F. A survey on dynamic spectrum access techniques in cognitive radio networks. *International Journal of Communication Networks and Information Security*, 2013. 5(2): 68.

59. Han, Z. An optimization theoretical framework for resource allocation over wireless networks. 2003.

60. Vickrey, W. Counterspeculation, auctions, and competitive sealed tenders. *The Journal of finance*, 1961. 16(1): 8–37.

61. Clarke, E. H. Multipart pricing of public goods. *Public choice*, 1971. 11(1): 17–33.

62. Groves, T. Incentives in teams. *Econometrica: Journal of the Econometric Society*, 1973: 617–631.

63. Wang, S. and Liu, D. A Truthful Multi-Channel Double Auction Mechanism for Heterogeneous Spectrums. *Wireless personal communications*, 2014. 77(3): 1677–1697.

64. Ji, Z. and Liu, K. Cognitive radios for dynamic spectrum access-dynamic spectrum sharing: A game theoretical overview. *IEEE Communications Magazine*, 2007. 45(5): 88–94.

65. Cramton, P., Shoham, Y. and Steinberg, R. Combinatorial auctions. *MIT Press*, 2006. doi:10.7551/mitpress/9780262033428.001.0001. URL `http://eprints.lse.ac.uk/23623/`.

66. De Vries, S. and Vohra, R. V. Combinatorial auctions: A survey. *INFORMS Journal on computing*, 2003. 15(3): 284–309.

67. Lehmann, D., Müller, R. and Sandholm, T. The winner determination problem. *Combinatorial auctions*, 2006: 297–318.

68. Sandholm, T., Suri, S., Gilpin, A. and Levine, D. Winner determination in combinatorial auction generalizations. *Proceedings of the first international joint conference on Autonomous agents and multiagent systems: part 1*. ACM. 2002. 69–76.

69. Iosifidis, G. and Koutsopoulos, I. Auction driven market mechanisms for dynamic spectrum management. *Mechanisms and Games for Dynamic Spectrum Allocation*, 2013.

70. Gai, Y., Gong, P., Lv, J. and Wu, W. Auction-based radio resource allocation for OFDMA systems. *5th International Conference on Wireless Communications, Networking and Mobile Computing*. IEEE. 2009. 1–4.

71. Deng, J., Zhang, R., Song, L., Han, Z., Yang, G. and Jiao, B. Joint power control and subchannel allocation for OFDMA femtocell networks using distributed auction game. *International Conference on Wireless Communications & Signal Processing*. IEEE. 2012. 1–6.

72. Milgrom, P. R. *Putting auction theory to work*. Cambridge University Press. 2004.

73. Zhang, Y., Lee, C., Niyato, D. and Wang, P. Auction approaches for resource allocation in wireless systems: A survey. *IEEE Communications Surveys &*

Tutorials, 2013. 15(3): 1020–1041.

74. Mu’Alem, A. and Nisan, N. Truthful approximation mechanisms for restricted combinatorial auctions. *Games and Economic Behavior*, 2008. 64(2): 612–631.

75. Kuhn, H. W. The Hungarian method for the assignment problem. *Naval research logistics quarterly*, 1955. 2(1-2): 83–97.

76. Munkres, J. Algorithms for the assignment and transportation problems. *Journal of the Society for Industrial and Applied Mathematics*, 1957. 5(1): 32–38.

77. Rahman, M. and Yanikomeroglu, H. Enhancing cell-edge performance: a downlink dynamic interference avoidance scheme with inter-cell coordination. *IEEE Transactions on Wireless Communications*, 2010. 9(4): 1414–1425.

78. Alavi, S. M., Zhou, C. and Gen, W. W. Distributed resource allocation scheme for multicell ofdma networks based on combinatorial auction. *Vehicular Technology Conference (VTC Fall), 2012 IEEE*. IEEE. 2012. 1–5.

79. Stiakogiannakis, I. N. and Kaklamani, D. I. A combinatorial auction based subcarrier allocation algorithm for multiuser OFDMA. *IEEE 73rd Vehicular Technology Conference (VTC Spring)*. IEEE. 2011. 1–5.

80. Hamza, A. S., Khalifa, S. S., Hamza, H. S. and Elsayed, K. A survey on inter-cell interference coordination techniques in OFDMA-based cellular networks. *IEEE Communications Surveys & Tutorial*, 2013. 15(4): 1642–1670.

81. Boudreau, G., Panicker, J., Guo, N., Chang, R., Wang, N. and Vrzic, S. Interference coordination and cancellation for 4G networks. *Communications Magazine, IEEE*, 2009. 47(4): 74–81.

82. Hoeher, P. A., Badri-Hoeher, S., Xu, W. and Krakowski, C. Single-antenna co-channel interference cancellation for TDMA cellular radio systems. *IEEE Wireless Communications*, 2005. 12(2): 30–37.

83. Axnäs, J., Wang, Y.-P. E., Kamuf, M. and Andgart, N. Successive interference cancellation techniques for LTE downlink. *IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications*. IEEE. 2011. 1793–1797.

84. Berardinelli, G., Manchón, C. N., Deneire, L., Sørensen, T. B., Mogensen, P. and Pajukoski, K. Turbo receivers for single user MIMO LTE-A uplink.

IEEE 69th Vehicular Technology Conference. IEEE. 2009. 1–5.

85. Xie, Z. and Walke, B. Resource allocation and reuse for inter-cell interference mitigation in OFDMA based communication networks. *The 5th Annual ICST Wireless Internet Conference (WICON)*. IEEE. 2010. 1–6.

86. Wu, W. Performance evaluation of inter-cell interference mitigation techniques for OFDMA cellular networks. 2010.

87. Rahman, M., Yanikomeroglu, H. and Wong, W. Interference avoidance with dynamic inter-cell coordination for downlink LTE system. *IEEE Wireless Communications and Networking Conference*. IEEE. 2009. 1–6.

88. Necker, M. A. *Novel Algorithm for Distributed Dynamic Interference Coordination in Cellular OFDMA Networks-Communication Networks and Computer Engineering*. Ph.D. Thesis. Ph. D. dissertation, Universit&aumlt Stuttgart. 2009.

89. Cao, F. and Fan, Z. The tradeoff between energy efficiency and system performance of femtocell deployment. *7th International Symposium on Wireless Communication Systems*. IEEE. 2010. 315–319.

90. Yeh, S.-p., Talwar, S., Himayat, N. and Johnsson, K. Power control based interference mitigation in multi-tier networks. *IEEE GLOBECOM Workshops (GC Wkshps)*. IEEE. 2010. 701–705.

91. Li, X., Qian, L. and Kataria, D. Downlink power control in co-channel macrocell femtocell overlay. *43rd Annual Conference on Information Sciences and Systems*. IEEE. 2009. 383–388.

92. Morozov, G., Davydov, A. and Papathanassiou, A. A novel combined CSI feedback mechanism to support multi-user MIMO beamforming schemes in TDD-OFDMA systems. *International Congress on Ultra Modern Telecommunications and Control Systems and Workshops*. IEEE. 2010. 896–900.

93. He, C., Liu, F., Yang, H., Chen, C., Sun, H., May, W. and Zhang, J. Co-channel interference mitigation in MIMO-OFDM system. *International Conference on Wireless Communications, Networking and Mobile Computing*. IEEE. 2007. 204–208.

94. Raghavendra, M., Juntti, M. and Myllylä, M. Co-channel interference mitigation for 3G LTE MIMO-OFDM systems. *ICC'09 IEEE International Conference on Communications*. IEEE. 2009. 1–5.

95. Fodor, G., Koutsimanis, C., Rácz, A., Reider, N., Simonsson, A. and Müller,

W. Intercell interference coordination in OFDMA networks and in the 3GPP long term evolution system. *Journal of Communications*, 2009. 4(7): 445–453.

96. Cho, K., Lee, W., Yoon, D., Hyun, K. and Choi, Y.-S. Resource alloation for orthogonal and co-channel femtocells in a hierarchical cell structure. *IEEE 13th International Symposium on Consumer Electronics*. IEEE. 2009. 655–656.

97. Zyoud, A.-H., Habaebi, M. H., Chebil, J. and Islam, M. R. Femtocell interference mitigation. *IEEE Control and System Graduate Research Colloquium (ICSGRC)*. IEEE. 2012. 94–99.

98. Jeon, W. S., Kim, J. and Jeong, D. G. Downlink radio resource partitioning with fractional frequency reuse in femtocell networks. *IEEE Transactions on Vehicular Technology*, 2014. 63(1): 308–321.

99. Dinc, E. and Koca, M. On dynamic fractional frequency reuse for OFDMA cellular networks. *IEEE 24th International Symposium on Personal Indoor and Mobile Radio Communications*. IEEE. 2013. 2388–2392.

100. Xiang, Y., Luo, J. and Hartmann, C. Inter-cell interference mitigation through flexible resource reuse in OFDMA based communication networks. *European wireless*. 2007, vol. 2007. 1–7.

101. Khalifa, S. S., Hamza, H. S. and Elsayed, K. Inter-cell interference coordination for highly mobile users in lte-advanced systems. *77th IEEE Vehicular Technology Conference*. IEEE. 2013. 1–5.

102. Chen, L. and Yuan, D. Generalized frequency reuse schemes for OFDMA networks: optimization and comparison. *IEEE 71st Vehicular Technology Conference*. IEEE. 2010. 1–5.

103. Qian, M., Hardjawana, W., Li, Y., Vucetic, B., Shi, J. and Yang, X. Inter-cell interference coordination through adaptive soft frequency reuse in LTE networks. *IEEE Wireless Communications and Networking Conference*. IEEE. 2012. 1618–1623.

104. Liu, S., Chang, Y., Wang, G. and Yang, D. Distributed resource allocation in two-hierarchy networks. *ETRI Journal*, 2012. 34(2): 159–167.

105. Zheng, Z., Dowhuszko, A. A. and Hämäläinen, J. Interference management for LTE-Advanced Het-Nets: stochastic scheduling approach in frequency domain. *Transactions on Emerging Telecommunications Technologies*, 2013. 24(1): 4–17.

106. Daeinabi, A. *Intercell Interference Mitigation in Long Term Evolution (LTE) and LTE-Advanced*. Ph.D. Thesis. University of Technology, Sydney. 2015.

107. González, D., García-Lozano, M., Ruiz, S. and Olmos, J. Static inter-cell interference coordination techniques for LTE networks: a fair performance assessment. In: *Multiple Access Communications*. Springer. 211–222. 2010.

108. Elayoubi, S.-E., Ben Haddada, O. and Fourestié, B. Performance evaluation of frequency planning schemes in OFDMA-based networks. *IEEE Transactions on Wireless Communications*, 2008. 7(5): 1623–1633.

109. Chang, R. Y., Tao, Z., Zhang, J. and Kuo, C.-C. J. Dynamic fractional frequency reuse (D-FFR) for multicell OFDMA networks using a graph framework. *Wireless Communications and Mobile Computing*, 2013. 13(1): 12–27.

110. Mohamed, A. S., Abd-Elnaby, M. and El-Dolil, S. A. Self-organized dynamic resource allocation using fraction frequency reuse scheme in long term evolution networks. *Computers & Electrical Engineering*, 2015. 48: 174–186.

111. Novlan, T., Andrews, J. G., Sohn, I., Ganti, R. K. and Ghosh, A. Comparison of fractional frequency reuse approaches in the OFDMA cellular downlink. *IEEE Global Telecommunications Conference*. IEEE. 2010. 1–5.

112. Lee, I., Hwang, J. H., Jang, S. J. and Kim, J. M. Improved Resource Allocation Scheme in LTE Femtocell Systems based on Fractional Frequency Reuse. *KSII Transactions on Internet and Information Systems*, 2012. 6(9): 2153–2169.

113. Bilios, D., Bouras, C., Kokkinos, V., Papazois, A. and Tseliou, G. Selecting the optimal fractional frequency reuse scheme in long term evolution networks. *Wireless personal communications*, 2013. 71(4): 2693–2712.

114. Ali, S. H. and Leung, V. Dynamic frequency allocation in fractional frequency reused OFDMA networks. *IEEE Transactions on Wireless Communications*, 2009. 8(8): 4286–4295.

115. Boddu, S. R., Mukhopadhyay, A., Philip, B. V., Das, S. S. and Rajakumar, R. V. Bandwidth partitioning and SINR threshold analysis of fractional frequency reuse in OFDMA cellular networks for real time and best effort traffic. *Wireless personal communications*, 2014. 75(1): 325–347.

116. Mitran, P. and Rosenberg, C. On fractional frequency reuse in imperfect cellular grids. *IEEE Wireless Communications and Networking Conference*. IEEE. 2012. 2967–2972.

117. Chen, L. and Yuan, D. Generalizing and optimizing fractional frequency reuse in broadband cellular radio access networks. *EURASIP Journal on Wireless Communications and Networking*, 2012. 2012(1): 1–15.

118. Begain, K., Rozsa, G. I., Pfening, A. and Telek, M. Performance analysis of GSM networks with intelligent underlay-overlay. *Seventh International Symposium on Computers and Communications*. IEEE. 2002. 135–141.

119. Assaad, M. Optimal fractional frequency reuse (FFR) in multicellular OFDMA system. *IEEE 68th Vehicular Technology Conference*. IEEE. 2008. 1–5.

120. *3GPP TSG RAN WG142 R1-050764, Inter-cell interference handling for E-UTRA, Ericsson, Technical Report*. Technical report.

121. Chang, R., Tao, Z., Zhang, J. and Kuo, C. A graph approach to dynamic fractional frequency reuse (FFR) in multi-cell OFDMA networks, In proceedings of IEEE international conference on communications (ICC 2009)(pp. 1–6). *Dresden, Germany*, 2009.

122. Khan, F. *LTE for 4G mobile broadband: air interface technologies and performance*. Cambridge University Press. 2009.

123. Fujii, H. and Yoshino, H. Capacity and outage rate of OFDMA cellular system with fractional frequency reuse. *IEICE transactions on communications*, 2010. 93(3): 670–678.

124. Lei, H., Zhang, L., Zhang, X. and Yang, D. A novel multi-cell OFDMA system structure using fractional frequency reuse. *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE. 2007. 1–5.

125. Lee, S., Yoon, J., Lee, S. and Shin, J. Interference management in OFDMA femtocell systems using fractional frequency reuse. *Circuits and Systems 2010 International Conference on Communications*. IEEE. 2010. 176–180.

126. Lee, T., Yoon, J., Lee, S. and Shin, J. Resource allocation analysis in OFDMA femtocells using fractional frequency reuse. *IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications*. IEEE. 2010. 1224–1229.

127. Xiao, H. and Feng, Z. A novel fractional frequency reuse architecture and interference coordination scheme for multi-cell OFDMA networks. *IEEE 71st Vehicular Technology Conference (VTC 2010-Spring)*. IEEE. 2010. 1–5.

128. Sheu, T.-L. and Liu, K.-L. A capacity degradation model for sectorized FFR networks. *16th International Symposium on Wireless Personal Multimedia Communications (WPMC)*. IEEE. 2013. 1–6.

129. Hashima, S., Shalaby, H., Alghoniemy, M., Muta, O. and Furukawa, H. Performance analysis of Fractional Frequency Reuse based on worst case Signal to Interference Ratio in OFDMA downlink systems. *IEEE 24th International Symposium on Personal Indoor and Mobile Radio Communications*. IEEE. 2013. 616–620.

130. Lee, T., Kim, H., Park, J. and Shin, J. An efficient resource allocation in OFDMA femtocells networks. *IEEE 72nd Vehicular Technology Conference Fall*. IEEE. 2010. 1–5.

131. Li, M., Li, J., Gao, W., Li, N., Fei, Z. and Kuang, J. Enhanced dynamic spectrum sharing for multi-cell heterogeneous networks. *International Conference on Wireless Communications and Signal Processing*. IEEE. 2011. 1–5.

132. Amer, M. Optimal configuration of fractional frequency reuse system for LTE cellular networks. *IEEE Vehicular Technology Conference*. IEEE. 2012. 1–5.

133. Landstro?m, A., Jonsson, H. and Simonsson, A. Voronoi-based ISD and site density characteristics for mobile networks. *IEEE Vehicular Technology Conference*. IEEE. 2012. 1–5.

134. Chen, L. and Yuan, D. Beyond conventional fractional frequency reuse for networks with irregular cell layout: An optimization approach and performance evaluation. *ICST 5th Annual Wireless Internet Conference*. IEEE. 2010. 1–7.

135. Chen, L. and Yuan, D. Generalizing FFR by flexible sub-band allocation in OFDMA networks with irregular cell layout. *IEEE Wireless Communications and Networking Conference Workshops*. IEEE. 2010. 1–5.

136. Chen, L. and Yuan, D. Enhanced Fractional Frequency Reuse for large-scale OFDMA networks with heterogeneous cell layout: Optimization and performance evaluation. *IEEE International Conference on Communication Systems*. IEEE. 2010. 279–283.

137. Akoum, S. and Heath, R. W. Interference coordination: Random clustering and adaptive limited feedback. *IEEE Transactions on Signal Processing*, 2013. 61(7): 1822–1834.

138. Haenggi, M., Andrews, J. G., Baccelli, F., Dousse, O. and Franceschetti,

M. Stochastic geometry and random graphs for the analysis and design of wireless networks. *IEEE Journal on Selected Areas in Communications*, 2009. 27(7): 1029–1046.

139. Karavu Buloo Rao Jaya, B. *Analysis of Spectrum Efficiency and Energy Efficiency of Heterogeneous Cellular Networks*. Ph.D. Thesis. University of Calgary. 2014.

140. *TR 25.996 V10.0.0 (2011-03). Release 10.* Technical report. 3GPP. 2011.

141. Shannon, C. E. Communication in the presence of noise. *Proceedings of the IRE*, 1949. 37(1): 10–21.

142. Ko, C.-H. and Wei, H.-Y. On-demand resource-sharing mechanism design in two-tier OFDMA femtocell networks. *IEEE Transactions on Vehicular Technology*, 2011. 60(3): 1059–1071.

143. Chen, Y., Farley, T. and Ye, N. QoS requirements of network applications on the Internet. *Information Knowledge Systems Management*, 2004. 4(1): 55–76.

144. Kong, Z., Kwok, Y.-K. and Wang, J. Auction-based scheduling in non-cooperative multiuser OFDM systems. *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*. IEEE. 2009. 1–4.

145. Zhou, W., Jing, T., Cheng, W., Chen, T. and Huo, Y. Combinatorial auction based spectrum allocation under heterogeneous supply and demand. *Computer Communications*, 2015. 60: 109–118.

146. Lehmann, D., Oćallaghan, L. I. and Shoham, Y. Truth revelation in approximately efficient combinatorial auctions. *Journal of the ACM (JACM)*, 2002. 49(5): 577–602.