# JOINT RELAY SELECTION AND BANDWIDTH ALLOCATION FOR COOPERATIVE RELAY NETWORK

AIMI SYAMIMI BINTI AB GHAFAR

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

FEBRUARY 2015

*To my beloved parents; Ab Ghafar bin Ismail and Satariah binti Yong,*

*brothers; Annas Asqalanee and Aizad Ayasyi*

*and sisters; Husnul Hakimah, Amira Syazwani, Aina Saufi, and Alia Salwani ☺*

## ACKNOWLEDGEMENT

In the Name of Allah, the Most Gracious and the Most Merciful. I am grateful to Allah for His guidance and only by His strength that I have successfully completed my research works and the write up of this thesis.

I would like to express my sincere gratitude to my supervisor, Prof. Dr. Norsheila binti Fisal for her guidance, advice and support throughout the accomplishment of this research. Her inspiring comments and suggestions, broad range of ideas and experiences have been my motivation and encouragement during the research period. Not forgetting Dr. Anthony Lo, for his guidance and advice which were invaluable to me.

Recognition and thankfulness to all my colleagues and fellow researchers in UTM-MIMOS Center of Excellence in Telecommunication Technology for all of their helps, support and encouragement at all the times up to completion of this research. My special thanks to my friends Wangi, Nadiah, Farizah, Faiz, Kak Shida, Nuurul, Kak Nazirah, Kak Shikin, Kak Anis and all those who have contributed, reviewed and gave good feedbacks in realizing this research works.

Finally, I would like to express my deepest appreciation to my dearest family; my parents, Ab Ghafar bin Ismail and Satariah binti Yong, my brothers and sisters for their constant love, encouragement and support which have been my source of inspiration, motivation and strength. I am indebted to all these important people in my life.

# ABSTRACT

Cooperative communication that exploits multiple relay links offers significant performance improvement in terms of coverage and capacity for mobile data subscribers in hierarchical cellular network. Since cooperative communication utilizes multiple relay links, complexity of the network is increased due to the needs for efficient resource allocation. Besides, usage of multiple relay links leads to Inter-Cell Interference (ICI). The main objective of this thesis is to develop efficient resource allocation scheme minimizes the effect of ICI in cooperative relay network. The work proposed a joint relay selection and bandwidth allocation in cooperative relay network that ensures high achievable data rate with high user satisfaction and low outage percentage. Two types of network models are considered: single cell network and multicell network. Joint Relay Selection and Bandwidth Allocation with Spatial Reuse (JReSBA_SR) and Optimized JReSBA_SR (O_JReSBA_SR) are developed for single cell network. JReSBA_SR considers link quality and user demand for resource allocation, and is equipped with spatial reuse to support higher network load. O_JReSBA_SR is an enhancement of JReSBA_SR with decision strategy based on Markov optimization. In multicell network, JReSBA with Interference Mitigation (JReSBA_IM) and Optimized JReSBA_IM (O_JReSBA_IM) are developed. JReSBA_IM deploys sectored-Fractional Frequency Reuse (sectored-FFR) partitioning concept in order to minimize the effect of ICI between adjacent cells. The performance is evaluated in terms of cell achievable rate, Outage Percentage (OP) and Satisfaction Index (SI). The result for single cell network shows that JReSBA_SR has notably improved the cell achievable rate by 35.0%, with reduced OP by 17.7% compared to non-joint scheme at the expense of slight increase in complexity at Relay Node (RN). O_JReSBA_SR has further improved the cell achievable rate by 13.9% while maintaining the outage performance with reduced complexity compared to JReSBA_SR due to the effect of optimization. The result for multicell network shows that JReSBA_IM enhances the cell achievable rate up to 65.1% and reduces OP by 35.0% as compared to benchmark scheme. Similarly, O_JReSBA_IM has significantly reduced the RN complexity of JReSBA_IM scheme, improved the cell achievable rate up to 9.3% and reduced OP by 1.3%. The proposed joint resource allocation has significantly enhanced the network performance through spatial frequency reuse, efficient, fair and optimized resource allocation. The proposed resource allocation is adaptable to variation of network load and can be used in any multihop cellular network such as Long Term Evolution-Advanced (LTE-A) network.

# ABSTRAK

Komunikasi koperasi yang mengeksploitasi pelbagai pautan pengulang memberi peningkatan prestasi ketara dari segi liputan dan kapasiti untuk pelanggan data mudah alih dalam rangkaian selular hierarki. Memandangkan komunikasi koperasi menggunakan pelbagai pautan pengulang, kerumitan rangkaian meningkat disebabkan oleh perlunya peruntukan sumber yang cekap. Selain itu, penggunaan pelbagai pautan pengulang menyebabkan Gangguan Antara Sel (ICI). Objektif utama tesis ini adalah untuk membangunkan skim peruntukan sumber efisien dan mengurangkan ICI dalam rangkaian pengulang koperasi. Kerja ini mencadangkan pemilihan pengulang dan peruntukan jalur lebar bersama dalam rangkaian pengulang koperasi yang memastikan kadar data boleh capai tinggi, kepuasan pengguna tinggi dan peratus gangguan rendah. Dua jenis model rangkaian telah diambil kira: rangkaian sel tunggal dan rangkaian multisel. Pemilihan Pengulang dan Peruntukan Jalur Lebar Bersama dengan Guna-semula Ruang (JReSBA_SR) dan JReSBA_SR Teroptimum (O_JReSBA_SR) dibangunkan untuk rangkaian sel tunggal. JReSBA_SR mengambil kira kualiti pautan dan permintaan pengguna untuk peruntukan sumber, dan dilengkapi dengan penggunaan semula ruang untuk menyokong beban rangkaian lebih tinggi. O_JReSBA_SR merupakan pembaikkan JReSBA_SR dengan strategi berdasarkan pengoptimuman Markov. Dalam rangkaian multisel, JReSBA dengan Pengurangan Gangguan (JReSBA_IM) dan JReSBA_IM Teroptimum (O_JReSBA_IM) dibangunkan. JReSBA_IM menggunakan pembahagian Penggunaan Semula Frekuensi Pecahan-tersektor (FFR-tersektor) bagi mengurangkan ICI antara sel-sel berdekatan. Prestasi dinilai daripada segi kadar data boleh capai sel, Peratus Gangguan (OP) dan Indeks Kepuasan (SI). Hasil kajian untuk jaringan sel tunggal menunjukkan bahawa JReSBA_SR telah meningkatkan kadar data boleh capai sel sebanyak 35.0%, dengan OP berkurang sebanyak 17.7% berbanding dengan skim-tidak-bersama dengan sedikit peningkatan kerumitan di Nod Pengulang (RN). O_JReSBA_SR telah meningkatkan lagi kadar data boleh capai sel sebanyak 13.9% di samping mengekalkan prestasi gangguan dengan pengurangan kerumitan berbanding JReSBA_SR disebabkan oleh kesan pengoptimuman. Hasil kajian untuk rangkaian multisel menunjukkan JReSBA_IM meningkatkan kadar data boleh capai sel sehingga 65.1% dan mengurangkan OP sebanyak 35.0% berbanding dengan skim tanda aras. Begitu juga, O_JReSBA_IM telah mengurangkan kerumitan di pengulang dalam skim JReSBA_IM dengan ketara, meningkatkan kadar data boleh capai sel sehingga 9.3% dan mengurangkan OP sebanyak 1.3%. Peruntukan sumber bersama yang dicadangkan telah meningkatkan prestasi rangkaian dengan ketara melalui penggunaan semula frekuensi berdasarkan ruang, dan peruntukan sumber teroptimum yang cekap dan adil. Peruntukan sumber yang dicadangkan dapat disesuaikan dengan perubahan beban rangkaian dan boleh digunakan dalam mana-mana rangkaian selular pelbagai langkauan seperti rangkaian Evolusi Jangka Panjang-Lanjutan (LTE-A).

## TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| 3GPP | - | Third Generation Partnership Project |
| 4G | - | Fourth Generation |
| AF | - | Amplify-and-Forward |
| AL | - | Access Link |
| B4G | - | Beyond 4G |
| BA | - | Bandwidth Allocation |
| BER | - | Bit Error Rate |
| BO | - | Bandwidth Occupancy |
| BRS | - | Best Relay Selection |
| BRS+DBA | - | Best Relay Selection and Demand-based Bandwidth Allocation |
| CA | - | Carrier Aggregation |
| CapEx | - | Capital Expenditure |
| CC | - | Component Carrier |
| CoMP | - | Coordinated Multi-Point Transmission |
| CQI | - | Channel Quality Indicator |
| CSI | - | Channel State Information |
| D2D | - | Device-to-Device |
| DBA | - | Demand-based Bandwidth Allocation |
| DCF | - | Decode-and-Forward |
| DL | - | Direct Link |
| eNB | - | Evolved Node B |
| FDD | - | Frequency Division Duplexing |
| FDX | - | Full-duplex |
| FFR | - | Fractional Frequency Reuse |
| HDX | - | Half-duplex |
| HetNets | - | Heterogeneous Networks |

| | | |
|---|---|---|
| ICIC | - | Inter-Cell Interference Cancellation |
| ImpEx | - | Implementation Expenditure |
| IMT-A | - | International Mobile Telecommunications-Advanced |
| IP | - | Internet Protocol |
| ISD | - | Inter-Site Distance |
| JReSBA_IM | - | Joint Relay Selection and Bandwidth Allocation with Inter-cell Interference Mitigation |
| JReSBA_SR | - | Joint Relay Selection and Bandwidth Allocation with Spatial Reuse |
| L1 | - | Layer 1 |
| L2 | - | Layer 2 |
| L3 | - | Layer 3 |
| LTE | - | Long Term Evolution |
| LTE-A | - | Long Term Evolution-Advanced |
| MAC | - | Medium Access Control |
| MIMO | - | Multiple-Input Multiple-Output |
| MIMO-BC | - | Multiple-Input-Multiple-Output Broadcast Channel |
| MIMO-MAC | - | Multiple-Input-Multiple-Output Multiple Access Channel |
| MRC | - | Maximal Ratio Combining |
| MTC | - | Machine Type Communications |
| O&M | - | Operation and Maintenance |
| O_JReSBA_IM | - | Optimized Joint Relay Selection and Bandwidth Allocation with Inter-cell Interference Mitigation |
| O_JReSBA_SR | - | Optimized Joint Relay Selection and Bandwidth Allocation with Spatial Reuse |
| OFDMA | - | Orthogonal Frequency Division Multiple Access |
| OP | - | Outage Percentage |
| OpEx | - | Operational Expenditure |
| PA | - | Power Allocation |
| PDCCH | - | Physical Downlink Control Channel |
| PDSCH | - | Physical Downlink Shared Channel |
| PHY | - | Physical Layer |

| | | |
|---|---|---|
| PL | - | Path Loss |
| PRBs | - | Physical Resource Blocks |
| QoS | - | Quality of Service |
| RL | - | Relay Link |
| RN | - | Relay Node |
| RRM | - | Radio Resource Management |
| RS | - | Relay Selection |
| SC-FDMA | - | Single Carrier Frequency-Division Multiple Access |
| SE | - | Spectral Efficiency |
| SI | - | Satisfaction Index |
| SINR | - | Signal-to-Interference-plus-Noise Ratio |
| SNR | - | Signal-to-Noise Ratio |
| SON | - | Self-Organizing Network |
| SUP | - | Symbol-Based Superposition |
| TCO | - | Total Cost of Ownership |
| TDD | - | Time Division Duplexing |
| TTI | - | Transmission Time Interval |
| UE | - | User Equipment |
| UJRSP | - | Utility-based Joint Relay Selection and Spectrum Partitioning |
| WiMAX | - | Worldwide Interoperability for Microwave Access |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $T_{frame}$ | - | Frame duration |
| $T_{subframe}$ | - | Subframe duration |
| $T_{slot}$ | - | Duration of LTE time slot |
| $T_{\mathrm{u}}$ | - | Useful symbol time |
| $T_{\mathrm{S}}$ | - | Symbol time |
| $T_{CP}$ | - | Cyclic prefix length |
| $\ell_d^{AF}$ | - | Downlink spectral efficiency of AF relay |
| $\ell_u^{AF}$ | - | Uplink spectral efficiency of AF relay |
| $\ell_d^{DCF}$ | - | Downlink spectral efficiency of DCF relay |
| $\ell_u^{DCF}$ | - | Uplink spectral efficiency of DCF relay |
| $SNR_{R_{i,j}}$ | - | Relay link SNR from terminal $i$ to terminal $j$ |
| $SNR_{A_{i,j}}$ | - | Access link SNR from terminal $i$ to terminal $j$ |
| $\omega$ | - | Power allocation coefficient for signals from eNB and UE for AF two-way relay |
| $h_{A_{i,j}}$ | - | Access link channel gain from terminal $i$ to terminal $j$ |
| $h_{R_{i,j}}$ | - | Relay link channel gain from terminal $i$ to terminal $j$ |
| $\ell_d^{DCF-XOR}$ | - | Downlink spectral efficiency of DCF two-way relay with XOR signals combination |
| $\ell_u^{DCF-XOR}$ | - | Uplink spectral efficiency of DCF two-way relay with XOR signals combination |

| | | |
|---|---|---|
| $\ell_d^{DCF-SUP}$ | - | Downlink spectral efficiency of DCF two-way relay with SUP combination |
| $\ell_u^{DCF-SUP}$ | - | Uplink spectral efficiency of DCF two-way relay with SUP combination |
| $\varsigma$ | - | Power allocation coefficient for signals from eNB and UE for DCF two-way relay |
| $E_{D_{q,k}}$ | - | Average signal energy over one symbol period received at UE through the direct link (DL) |
| $E_{R_{q,m}}$ | - | Average signal energy over one symbol period received at UE through the relay link (RL) |
| $E_{A_{q,m,k}}$ | - | Average signal energy over one symbol period received at UE through the access link (AL) |
| $h_{D_{q,k}}$ | - | Independent frequency flat fading with complex valued, unit power channel gains for DL |
| $h_{R_{q,m}}$ | - | Independent frequency flat fading with complex valued, unit power channel gains for RL |
| $h_{A_{q,m,k}}$ | - | Independent frequency flat fading with complex valued, unit power channel gains for AL |
| $\sigma^2$ | - | Additive white Gaussian noise |
| $h_{mean_m}$ | - | Harmonic mean channel magnitude |
| $\mathcal{M}_q$ | - | Set of RNs in cell $q$ |
| $\left\Vert \mathcal{M}_q \right\Vert$ | - | Length of vector $\mathcal{M}_q$ |
| $\lvert \mathbf{h} \rvert$ | - | Modulus of a vector **h** |
| $\mathcal{M}_{q,j}$ | - | Set of RNs in sector $j$ of cell $q$ |
| $\mathcal{K}_q$ | - | Set of UEs in cell $q$ |
| $W_{tot}$ | - | Total bandwidth |
| $\mathcal{N}$ | - | Set of available subchannels |
| $\mathcal{Q}$ | - | Set of cells |
| $\mathcal{N}_{Cj}$ | - | Subchannel sets of inner regions sector $j$ |
| $\mathcal{N}_{Ej}$ | - | Subchannel sets of outer or edge regions sector $j$ |

| | | |
|---|---|---|
| $\gamma_{q,k}$ | - | Data rate requirement of user $k$ in cell $q$ |
| $\gamma_{\min}$ | - | Minimum data rate value |
| $\gamma_{\max}$ | - | Maximum data rate value |
| $R$ | - | Cell radius |
| $P_{eNB}$ | - | Maximum eNB transmit power |
| $P_{RN}$ | - | Maximum RN transmit power |
| $C_{q,k}$ | - | Achievable rate of UE $k$ in cell $q$ |
| $C_q^T$ | - | Total achievable rate of users in cell $q$ |
| $\mathcal{K}_{out_q}$ | - | Set of UEs which suffer outage in cell $q$ |
| $\mathcal{N}_j$ | - | Set of subchannels allocated for sector $j$ |
| $\theta$ | - | Angle for directional antenna coverage |
| $A(\theta)_{dB}$ | - | Antenna gain in decibels at angle $\theta$ |
| $\theta_{3dB}$ | - | Angle of which the antenna gain is 3 dB lower than the antenna gain at the main beam direction |
| $A_{\mathrm{m}}$ | - | Maximum attenuation for the sidelobe |
| $d_{D_{q,k}}$ | - | Distance (in km) between eNB $q$ to UE $k$ for DL |
| $d_{R_{q,m}}$ | - | Distance (in km) between eNB $q$ to RN $m$ for RL |
| $d_{A_{q,m,k}}$ | - | Distance (in km) between RN $m$ to UE $k$ for AL |
| $PL_{D_{q,k}}$ | - | Path loss for DL between eNB $q$ and UE $k$ |
| $PL_{R_{q,m}}$ | - | Path loss for RL between eNB $q$ and RN $m$ |
| $PL_{A_{q,m,k}}$ | - | Path loss for AL between RN $m$ and UE $k$ in cell $q$ |
| $P_{eNB_{q,k}}$ | - | Transmit power of eNB $q$ to UE $k$ |
| $P_{eNB_{q,m}}$ | - | Transmit power of eNB $q$ to RN $m$ |
| $P_{RN_{q,m,k}}$ | - | Transmit power of RN $m$ to UE $k$ |
| $\tau$ | - | Processing delay at relay node |
| $y_{r_{q,m,k}}$ | - | Received signal at UE $k$ from relay node |

| | | |
|---|---|---|
| $x_{q,k}$ | - | Intended signal for UE $k$ |
| $n_{R_{q,m}}$ | - | Additive white Gaussian noise at RN with variance $\sigma^2$ |
| $y_{u_{q,k}}$ | - | Received signal at UE $k$ from both eNB and relay node |
| $\alpha_{q,m,k}$ | - | Binary indicator for cooperation of RN $m$ |
| $\boldsymbol{\alpha}_{q,k}$ | - | Node selection vector |
| $y_{I_{q,k}}$ | - | Interference signals received by UE $k$ in cell $q$ |
| $x_{q,k'}$ | - | Transmitted signal for UE $k'$ |
| $\psi_{q,m',k}$ | - | Binary indicator showing that RN $m'$ is reusing same subchannel as UE $k$ to serve UE $k'$ in other sector |
| $\ell^{d}_{q,k}$ | - | Spectral efficiency over DL for one-hop UE $k$ |
| $\ell^{co}_{q,k}$ | - | Maximum achievable SE for UE $k$ with multiple cooperating RNs |
| $\rho_{eff_{q,k}}$ | - | Number of effective subchannels allocated to each UE $k$ |
| $W_{eff_{q,k}}$ | - | Size of effective bandwidth assigned to the UEs |
| $\varphi_{q,k}$ | - | User binary indicator |
| $\gamma^{n}_{q,k}$ | - | Indicator for subchannel $n$ reuse by UE $k$ |
| $\ell^{a}_{q,m,k}$ | - | Access links spectral efficiency values |
| $\mathcal{M}c_{q,k}$ | - | Candidate RNs matrix for UE $k$ |
| $W_{q,k}$ | - | Estimated size of bandwidth needed to meet UE $k$ demand |
| $\rho_{q,k}$ | - | Number of requested subchannels $\rho_{q,k}$ needed to satisfy UE $k$ demand |
| $\rho_{th_{q,k}}$ | - | Subchannel allocation threshold |
| $\rho_{q_{sum}}$ | - | Summation of UEs required subchannels |

| | | |
|---|---|---|
| $\beta_{q,k}$ | - | Bandwidth weightage |
| $W_{th_{q,k}}$ | - | Bandwidth allocation threshold |
| $\mathcal{K}_{q,j}$ | - | Set of UEs in sector $j$ of cell $q$ |
| $\eta_{q,k}^{n}$ | - | Binary indicator for allocation of subchannel $n$ for UE $k$ in cell $q$ |
| $\mathcal{R}_q$ | - | List of ranked UEs based on their spectral efficiency |
| $r_{q,m,k}$ | - | Relay subchannel reuse indicator |
| $\mathcal{R}_k$ | - | Subchannel reuse vector UE $k$ |
| $\mathcal{N}_{RN_m}$ | - | Set of subchannels used by each RN $m$ to serve its UEs |
| $\mathcal{N}_{reuse_m}$ | - | Candidate subchannels from RN $m$ for UE $k$ in sector $j$ |
| $\mathcal{N}_{cand_{q,j,k}}$ | - | Set of candidate subchannels for UE $k$ |
| $\left\Vert \mathcal{K}_q^{\max} \right\Vert$ | - | Highest number of UEs that is evaluated in the numerical evaluation |
| $Outage_q$ | - | Outage percentage |
| $SI_q$ | - | User satisfaction index |
| $\gamma_{mean}$ | - | Mean of user demanded rate range |
| $\gamma_{mean}^{\max}$ | - | Maximum mean of user demanded rate range |
| $S_{q,k}^{s}$ | - | Markov state indicating cooperative structure |
| $\mathcal{S}$ | - | State spaces defining set of cooperative structures |
| $Po\left(S_{q,k}^{s}\right)$ | - | Payoff function |
| $\ell_{q,k}\left(S_{q,k}^{s}\right)$ | - | Spectral efficiency for current state $S_{q,k}^{s}$ |
| $\xi$ | - | Cost of a relay |
| $W_{q,k}^{s}$ | - | Requested bandwidth for each state |
| $\rho_{q,k}^{s}$ | - | Number of requested subchannels needed to satisfy UE $k$ demand with current state $S_{q,k}^{s}$ |

| | | |
|---|---|---|
| $\mathbf{P}_{q,k}$ | - | Transition probability matrix for the cooperative structure |
| $P_{S^{s}_{q,k},S^{s'}_{q,k}}$ | - | Transition probability from state $S^{s}_{q,k}$ to $S^{s'}_{q,k}$ |
| $\delta_{q,k}$ | - | Probability that eNB makes decision for joint relay selection and bandwidth allocation of a user $k$ |
| $\hat{\theta}\left(S^{s'}_{q,k} \middle\| S^{s}_{q,k}\right)$ | - | Best-reply rule for eNB decision for a user $k$ |
| $\Theta$ | - | Constant value representing the probability transition from state $S^{s}_{q,k}$ to $S^{s'}_{q,k}$ |
| $\mathcal{B}s^{s}_{q,k}$ | - | Set of better states |
| $\boldsymbol{\pi}_{q,k}$ | - | Steady state distribution vector |
| $\pi_{S^{s}_{q,k}}$ | - | Probability that eNB decides on cooperation structure $S^{s}_{q,k}$ |
| $y^{adj}_{I_{q,k}}$ | - | Interference signals received by UE $k$ from adjacent cells $q'$ |
| $\vartheta_{q',k}$ | - | Binary indicator showing that eNB $q'$ has UEs to be served on same subchannel as UE $k$ |
| $\psi_{q',m',k}$ | - | Binary indicator of whether RN $m'$ of cell $q'$ is serving its UEs on the same subchannel as UE $k$ or not |
| $d_{c}$ | - | Centre radius of cell |
| $\mathcal{N}_{RN^{adj}_{m'}}$ | - | List of subchannels used by adjacent relay $m'$ to serve its UEs |
| $\mathcal{N}_{reuse^{adj}_{m}}$ | - | Candidate subchannels from adjacent relay $m'$ for UE $k$ in sector $j$ |
| $\mathcal{N}_{cand^{adj}_{q,j,k}}$ | - | List of subchannels that can be used from all non-interfering relays of adjacent cells |

# LIST OF APPENDIX

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Global mobile data traffic is growing rapidly over the past few years with the increasing number of smartphones and tablets around the world and has already overtaken the total monthly traffic of voice traffic since 2009. It is also observed that the growth of voice traffic is almost flat [1]. There is no doubt that increment on the number of mobile smartphones and mobile broadband subscription is the key factor for the rapid data traffic growth. In 2013 alone, according to Cisco Visual Networking Index for Global Mobile Data Traffic Forecast Update [2], over half a billion mobile devices and connections were added, where the number grew from 6.5 billion in 2012 to 7 billion in 2013. From that extensive growth, 77% of it is accounted from smartphones. Moreover, based on the forecast done by Cisco, mobile data traffic is expected to grow from 1.5 exabytes in 2013 to 15.9 exabytes per month by 2018. Statistically, mobile data traffic will grow at a compound annual growth rate (CAGR) of 61% from 2013 to 2018, as shown in Figure 1.1.

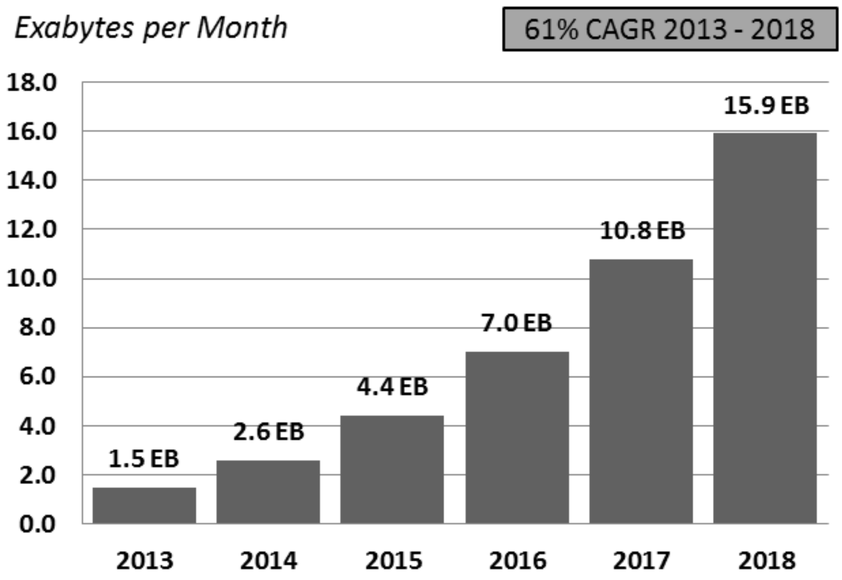


**Figure 1.1** Cisco forecasts for monthly growth of mobile data traffic by 2018 [2]

In response to the explosive demands for mobile data, the entire world is moving towards next generation wireless broadband network in order to meet the requirements of high throughput, extended coverage and low latencies which are defined in International Mobile Telecommunications-Advanced (IMT-A) requirements [3], [4]. As an enhancement to the formerly developed Long Term Evolution (LTE) Release 8 standard, the Third Generation Partnership Project (3GPP) working group has carried out studies for LTE-Advanced (or LTE Release 10). LTE-Advanced development should be backward compatible to LTE as to enable LTE terminal to work in LTE-Advanced network and vice versa. It also aims to fulfil or even exceed the IMT-A requirements including peak data rates of 1Gbit/s for the downlink and 500Mbits/s for the uplink, and extended bandwidth support up to 100MHz [5], [6]. Key technologies of LTE-Advanced are carrier aggregation, enhanced multiple-input multiple-output (MIMO) transmission (spatial multiplexing of eight layers for downlink and four layers for uplink), coordinated multi-point transmission (CoMP), relaying and heterogeneous networks.

Relay assisted cellular network is a form of multi-tier or hierarchical network that offers coverage extension and capacity enhancement. The usage of relaying is very useful in densely populated cellular network. Relay deployment is also a cost-efficient solution to improve network performance. This is because the installation of relay node does not require expensive cost for planning, construction, and maintenance. In practical network scenario, the usage of relaying can be applied to improve the performance of cell edge users, provide coverage to areas affected by shadowing, support temporary network deployments, and also to support group mobility [5], [7], [8]. In wireless networks, cooperative communication has been widely considered as an extension to relay networks to improve diversity gain [9]. Basically, virtual MIMO concept is applied where an Evolved Node B (eNB) exploits multiple relay nodes (RNs) to cooperatively transmit the data to the destination by taking advantage of multiple antennas that belongs to a pool of individual relay terminals. Cooperative relaying has been considered as an efficient solution because it offers dramatic performance gains by taking advantage of space or multiple antenna diversity techniques which can be readily combined with other diversity techniques such as time and frequency diversity.

Spatial reuse is a promising technique to enhance network capacity by means of allowing spectrum reusing among multiple nodes in the network. The nature of multi-tier network provides more rooms for simultaneous transmission on same spectrum band by taking the advantage of directional antenna of the transmitter [10], [11]. There is a trade-off between the support for high network capacity offered by spatial reuse and the interference it introduced. One of the eminent methods to mitigate interference is sectored-Fractional Frequency Reuse (sectored-FFR). Sectored-FFR technique involves partitioning of the spectrum band according to cell sectors and proper planning of the spectrum reuse which efficiently mitigate interference leading to good network performance [12].

## 1.2 Problem Statement

The deployment of cooperative relay to enhance network performance poses technical challenges. The main challenge in hierarchical cooperative network is to provide efficient resource allocation to meet user demands in order to obtain high cell achievable rate and low outage percentage.

The problem with conventional transmission where the source is transmitting directly to its destination is that if link is broken, then the transmission will fail and retransmission is needed leading to longer delay. Therefore, cooperative relaying is introduced where multiple relay nodes are used to forward signals for the source-destination pair [9], [13]–[15]. The destination then combines the signals coming from source and multiple relays, which created spatial diversity by taking the advantage of sending redundant data through multipath transmission. Thus, cell throughput is improved significantly. However, it is not optimal to use all available RNs in the network in assisting the transmission to users because it incurs cost of additional resources and power [16], [17]. Besides, some relays may be far-away from a particular user which will result in waste of power resources if it assists the transmission to that user. Hence, there is a need for relay selection in the network.

Bandwidth sharing is also one of the challenges concerned throughout the literature [18]–[21]. In a network with large number of users with their own traffic demand, bandwidth allocation is crucial. Ineffective bandwidth allocation that is unaware of user traffic demand leads to user dissatisfaction. The service providers need to differentiate users based on their requirements in order to ensure fair resource allocation while maintaining high network performance. Thus, efficient bandwidth allocation technique is needed.

Explosive data rate demand of users and high network load due to large number of users leads to shortage of spectral resources. One of the ways to handle the problem is to provide more spectrum resources which are very expensive. In order to overcome this problem without the need for additional spectrum resources, spatial reuse technique is introduced by means of exploiting the space dimension to enable concurrent transmissions on the same spectrum channel [10]. Following this, inter-cell interference (ICI) issue arises among adjacent cells as the effect of spectrum reusing by relay nodes [10], [22]. Therefore, the spatial reuse technique needs to be designed such that ICI is kept minimal while simultaneously provides high cell achievable rate.

Currently, few research works tackle the problem of spectrum resources shortage by considering spatial reuse technique to mitigate ICI in densely populated network. In contrary, most of the research works limit the number of users for each RN utilizing the same frequency band [23], [24]. In densely populated network, limiting the number of users entering the network may lead to inefficient usage of bandwidth utilization. Since the main goal of resource allocation is to maximize the achievable rate to cater for various users demand, there must be an optimal solution to ensure fair bandwidth allocation among participating users while taking advantage of spatial reuse.

As mentioned earlier, allowing concurrent transmissions of multiple relay nodes in the network may lead to interference problem. Therefore, in order to use the cooperative communication effectively, there is a need for efficient resource allocation which leverages the trade-off between achieving the diversity gain benefit and interference caused by the concurrent transmission.

## 1.3 Research Objectives

The main objective of this research is to develop an optimal joint relay selection and bandwidth allocation strategy for cooperative relay network that provides high achievable rate and can efficiently allocate resources with high user satisfaction and very outage percentage. The specific objectives of the work are:

i) to develop joint relay selection and bandwidth allocation scheme with spatial frequency reuse for single cell network.

ii) to develop joint relay selection and bandwidth allocation scheme with interference mitigation for multicell network.

iii) to optimize the joint relay selection and bandwidth allocation schemes in both single cell and multicell network.

In this thesis, the joint relay selection and bandwidth allocation scheme for single cell is developed to mitigate the interference that occurs among adjacent sectors within the cell. On the other hand, the joint relay selection and bandwidth allocation scheme for multicell is developed to mitigate the interference that occurs among adjacent cells. Optimization of the relay selection and bandwidth allocation decision aims to enhance the cell achievable rate and satisfy user traffic demand.

## 1.4 Scope of Research

This research mainly focuses on relay assisted hierarchical cooperative network based on LTE-Advanced system. Two network scenarios are considered. Firstly, single cell network scenario is considered where two strategies are proposed, namely JReSBA_SR and O_JReSBA_SR. The first one is a heuristic algorithm, while the second one is equipped with optimization using Markov chain technique to reduce the complexity of the former. Both strategies are aware of diverse users traffic demand and link quality. In order to overcome the problem of spectrum resources shortage due to high network load, spatial reuse is implemented. For the second scenario, multicell scenario consisting of seven adjacent cells is considered. Similarly, another two strategies are proposed, namely JReSBA_IM in heuristic manner, while the other is an optimized version of it, O_JReSBA_IM. Sectored-FFR based spatial reuse technique is proposed to mitigate the effect of ICI, while at the same time maximizing network performance. In this research, equal power allocation is adapted where the total transmit power is divided to all the served users of eNB and RN.

This research considers only two-hop cellular network with infrastructure mode. Centralized resource allocation mechanism is considered, where eNB is responsible in making all the allocation decisions. The performance evaluation is done for downlink transmission only. The RN is assumed to be Type 1 full-duplex relay and implementing Decode-and-Forward (DCF) operation. Apart from that, this research also considers multi-users scenario with asymmetric traffic demand. Performance evaluation is done in MATLAB, considering evaluation settings based on 3GPP case 1 urban macro scenario. Throughout the research, frequency division duplexing (FDD) mode is considered.

## 1.5 Research Contributions

The proposed joint resource allocation schemes aim to enhance the performance of relay network. The proposed joint relay selection and bandwidth allocation scheme is furnished with interference mitigation competency and is optimized to deliver high cell achievable rate with low probability of denying users demand. The major contributions of this thesis include:

**i) Joint relay selection and bandwidth allocation for single cell and multicell cooperative relay network**

In this work, the proposed resource allocation schemes JReSBA_SR for single cell network and JReSBA_IM for multicell network will be able to select good quality cooperative links and allocate adequate bandwidth to meet user demands. The selected cooperative relay links in single and multicell network will ensure high cell achievable rate due to the cooperative diversity gain.

**ii) Optimized joint relay selection and bandwidth allocation for single cell and multicell cooperative relay network**

Both JReSBA_SR and JReSBA_IM allow as many users as possible to be served by a RN. Without the limitation on the number of participating users, the algorithm tends to burden RN which may lead to lower power allocation to participating users. The optimization based on Markov process in O_JReSBA_SR and O_JReSBA_IM generate optimal relay selection and bandwidth allocation that maximizes cell achievable rate by compromising spectral efficiency enhancement with the cost of cooperative relay links. Consequently, more efficient power can be allocated to reduced number of participating users.

**iii) Support for higher network load through spatial reuse**

In a densely populated network with limited resources, satisfying every user demand is competitive. In this work, spatial reuse technique is utilized along with O_JReSBA_SR and O_JReSBA_IM to further enhance network capacity in order to support higher network load by providing rooms for more concurrent transmissions on the limited spectrum band.

**iv) Interference mitigation by adopting sectored-FFR partitioning**

In practical network scenario, spectrum reuse leads to ICI problem which deeply affects the performance of cell edge users. The deployment of sectored-FFR spectrum partitioning along with the spatial reuse technique in O_JReSBA_SR and O_JReSBA_IM enable the network to maximize cell achievable rate and minimize the effect of ICI.

## 1.6 Significance of Research

The proposed joint relay selection and bandwidth allocation is suitable for any multihop cellular network (MCN). MCN is a cutting edge technology which is heavily considered in next generation wireless broadband network such as LTE-Advanced and Worldwide Interoperability for Microwave Access (WiMAX) IEEE 802.16m that utilizes the advantage of relay to provide coverage extension and capacity enhancement. Cooperative communication utilizing multiple relay nodes is a cost-efficient solution to enhance the network performance because relay node does not incur expensive installation and operational costs. In addition, the proposed schemes are also suitable for implementation in ad-hoc network such as multi-tier Wireless Fidelity (WiFi) and clustered Wireless Sensor Network (WSN) that operates in centralized manner.

Furthermore, the proposed scheme will work efficiently in both urban and rural area. The proposed scheme is capable to support densely populated network with limited spectrum resources by means of using spatial reuse. On top of that, the proposed scheme will be able to meet user traffic demands which includes various types of application such as web browsing – Hyper Text Transfer Protocol (HTTP), File Transfer Protocol (FTP), online video streaming, and Voice over Internet Protocol (VoIP).

## 1.7 Thesis Outline

The thesis elaborates the development of joint relay selection and bandwidth allocation for hierarchical relay network. Chapter 2 highlights the technology features of LTE-Advanced system, which includes relaying as one of its key technologies. The issues in cooperative relay network which includes relay selection, bandwidth allocation and power allocation are discussed, and the related approaches to solve the relay network problems are presented and analysed. Several loopholes are identified which become the driver for this research work.

Chapter 3 mainly focuses on the design framework of the proposed joint resource allocation schemes. It covers the basic design concept of all four schemes, namely JReSBA_SR, O_JReSBA_SR, JReSBA_IM and O_JReSBA_IM. The algorithms of the proposed schemes are described and differences between the schemes are highlighted by using flowcharts. In addition, the considered network model, which include single cell and multicell scenarios are described, along with the network parameters and assumptions for numerical simulation study. Performance metrics used to justify network performance are listed and described. Then, numerical simulation tool using MATLAB and its implementation concept is depicted by using functional blocks and the consistency of the numerical simulation result is validated.

Chapter 4 presents the formulation for JReSBA_SR followed by its algorithm design which includes link quality and user traffic demand parameters in its decision making block. In addition, implementation of spatial reuse technique is also described. Then, performance analysis of the proposed JReSBA_SR scheme in comparison to non-joint scheme and JReSBA_B scheme without spatial reuse is presented. Following that, by identifying the drawback of JReSBA_SR, development of O_JReSBA_SR with optimization based on Markov process and method to determine the optimization solution are also described. Then, the performance of O_JReSBA_SR is analysed in comparison to JReSBA_SR.

Chapter 5 describes the detail algorithm design for JReSBA_IM scheme. Formulation of JReSBA_IM by incorporating sectored-FFR spectrum partitioning concept is described, followed by the algorithm description which includes the joint relay selection and bandwidth allocation scheme with centre and edge regions spatial reuse technique. The performance of JReSBA_IM is the analysed in comparison to Soft Frequency Reuse (SFR) based scheme in the literature.

Chapter 6 presents the detail of O_JReSBA_IM algorithm. Markov process representation of joint relay selection and bandwidth allocation with sectored-FFR is described. Similar to Chapter 4, stable cooperation structure for two-hop users are determined. Performance analysis is done to compare O_JReSBA_IM performance with JReSBA_IM and JReSBA_SR schemes.

Finally, Chapter 7 concludes the thesis with summary of the research work, significant achievements, together with recommendations for future work.

## REFERENCES


1. Ericsson. *Interim Ericsson Mobility Report*. Technical Report. Stockholm, Sweden. 2013.
2. T. Cisco. *Cisco Visual Networking Index : Global Mobile Data Traffic Forecast Update , 2013 – 2018*. White Paper. 2014.
3. Nakamura T., Nagata S., Benjebbour A., Kishiyama Y., Hai T., Xiaodong S., Ning Y., and Nan L. Trends in small cell enhancements in LTE advanced. *IEEE Commun. Mag.* 2013. 51(2): 98–105.
4. 3GPP. *Requirements related to technical performance for IMT-Advanced radio interface(s)*. Technical Report ITU-R M.2134. 2008.
5. Akyildiz I. F., Gutierrez-Estevez D. M., Balakrishnan R., and Chavarria-Reyes E. LTE-Advanced and the evolution to Beyond 4G (B4G) systems. *Phys. Commun.* 2014. 10: 31–60.
6. 3GPP. *Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA).* Technical Report TR 36.913. 2009.
7. Ghosh A., Ratasuk R., Mondal B., Mangalvedhe N., and Thomas T. LTE-advanced: next-generation wireless broadband technology. *IEEE Wirel. Commun.* 2010. 17(3): 10–22.
8. Yuan Y. *LTE-Advanced Relay Technology and Standardization*. Springer. 2013.
9. Laneman J. N., Tse D. N. C., and Wornell G. W. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Trans. Inf. Theory*. 2004. 50(12): 3062–3080.
10. Wu Y. and Niu Z. Exploiting cooperative diversity and spatial reuse in multihop cellular networks. *Proceedings of 2009 IEEE International Conference on Communications (ICC'09)*. IEEE. 2009. 1–5.

11. Najjar A., Hamdi N., and Bouallegue A. Efficient frequency reuse scheme in cooperative relaying for multi-cell OFDMA systems. *Proceedings of 2010 15th IEEE Mediterranean Electrotechnical Conference (MELECON 2010).* IEEE. 2010. 466–469.

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

13. Nam Y-H., Liu L., and Zhang J. Cooperative communications for LTE-advanced—relay and CoMP. *Int. J. Commun. Syst.* 2012.

14. Jia J., Zhang J., and Zhang Q. Cooperative relay for cognitive radio networks. *Proceedings of 2009 IEEE 28th Conference on Computer Communications (INFOCOM 2009).* April 19-25, 2009. Rio de Janeiro, Brazil. IEEE. 2009. 2304–2312.

15. Zhang Q., Jia J., and Zhang J. Cooperative relay to improve diversity in cognitive radio networks. *IEEE Commun. Mag.* 2009. 47(2): 111–117.

16. Zhang S. and Lau V. K. N. Multi-Relay Selection Design and Analysis for Multi-Stream Cooperative Communications. *IEEE Trans. Wirel. Commun.* 2011. 10(4): 1082–1089.

17. Bel A., Vicario G. S-G. J. L., and Seco-Granados G. The benefits of relay selection in WiMAX networks. *Proceedings of ICT-MobileSummit'08*. June 10-12,2008. Stockholm, Sweden. 2008.

18. Erwu L., Dongyao W., Jimin L., Gang S., and Shan J. Performance evaluation of bandwidth allocation in 802.16j mobile multi-hop relay networks. *Proceedings of IEEE 65th Vehicular Technology Conference, 2007 (VTC2007-Spring).* April 22-25,2007. Dublin, Ireland. IEEE. 2007. 939–943.

19. Awad M. K. and Shen X. OFDMA based two-hop cooperative relay network resources allocation. *Proceedings of IEEE International Conference on Communications, 2008 (ICC'08).* May 19-23,2008. Beijing, China. IEEE. 2008. 4414–4418.

20. Chen K., Zhang B., Liu D., Li J., and Yue G. Fair resource allocation in OFDMA two-hop cooperative relaying cellular networks. *Proceedings of 2009 IEEE 70th Vehicular Technology Conference Fall (VTC 2009-Fall).* September 20-23, 2009. Alaska, USA. IEEE. 2009. 1–5.

21. Yang X., Zhang T., Feng C., and Li Z. Zone based downlink frequency planning scheme in relay enhanced cellular systems. *Proceedings of 2011 International Conference on Wireless Communications and Signal Processing (WCSP)*. November 9-11, 2011. Nanjing, China. IEEE. 2011. 1–5.
22. Sundaresan K. and Rangarajan S. On exploiting diversity and spatial reuse in relay-enabled wireless networks. *Proceedings of the 9th ACM iInternational Symposium on Mobile Ad Hoc Networking and Computing*. May 26-30, 2008. Hong Kong, China. ACM. 2008. 13–22.
23. Liu Y., Tao M., Li B., and Shen H. Optimization framework and graph-based approach for relay-assisted bidirectional OFDMA cellular networks. *IEEE Trans. Wirel. Commun.* 2010. 9(11): 3490–3500.
24. Zhang D., Wang Y., and Lu J. QoS aware relay selection and subcarrier allocation in cooperative OFDMA systems. *IEEE Commun. Lett.* 2010. 14(4): 294–296.
25. Parkvall S. and Astely D. The evolution of LTE towards IMT-advanced. *Journal of Communications.* 2009. 4(3): 146–154.
26. Mogensen P. E., Koivisto T., Pedersen K. I., Kovacs I. Z., Raaf B., Pajukoski K., and Rinne M. J. LTE-advanced: the path towards gigabit/s in wireless mobile communications. *Proceedings of the 1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology, 2009 (Wireless VITAE 2009)*. February 28-March 3, 2011. Chennai, India. IEEE. 2009. 147–151.
27. 3GPP. *Evolved Universal Terrestrial Radio Access (E-UTRA); Further Advancements for E-UTRA Physical Layer Aspects*. Technical Report TR 36.814. 2010.
28. 3GPP. Overview of 3GPP Release 12 V0.1.3. Technical Report. 2014.
29. 3GPP. Overview of 3GPP Release 13 V0.0.6. Technical Report. 2014.
30. Yuan G., Zhang X., Wang W., and Yang Y. Carrier aggregation for LTE-advanced mobile communication systems. *IEEE Commun. Mag.* 2010. 48(2): 88–93.
31. Pedersen K. I., Frederiksen F., Rosa C., Nguyen H., Garcia L. G. U., and Wang Y. Carrier aggregation for LTE-advanced: functionality and performance aspects. *IEEE Commun. Mag.* 2011. 49(6): 89–95.

32. Iwamura M., Etemad K., Fong M-H., Nory R., and Love R. Carrier aggregation framework in 3GPP LTE-advanced [WiMAX/LTE Update]. *IEEE Commun. Mag.* 2010. 48(8): 60–67.
33. Ratasuk R., Tolli D., and Ghosh A. Carrier aggregation in LTE-Advanced. *Proceedings of 2010 IEEE 71st Vehicular Technology Conference (VTC 2010-Spring).* May 16–19, 2010. Taipei, Taiwan. IEEE. 2010. 1–5.
34. Shen Z., Papasakellariou A., Montojo J., Gerstenberger D., and Xu F. Overview of 3GPP LTE-advanced carrier aggregation for 4G wireless communications. *IEEE Commun. Mag.* 2012. 50(2): 122–130.
35. Juho L., and Jin-Kyu H. MIMO technologies in 3GPP LTE and LTE-advanced. *EURASIP Journal on Wirel. Commun. Netw.* 2009.
36. Li Q., Li G., Lee W., Lee M., Mazzarese D., Clerckx B., and Li Z. MIMO techniques in WiMAX and LTE: a feature overview. *IEEE Commun. Mag.* 2010. 48(5): 86–92.
37. Chu S. and Wang X. Opportunistic and cooperative spatial multiplexing in MIMO ad hoc networks. *IEEE/ACM Trans. Netw.* 2010. 18(5): 1610–1623.
38. Liu L., Chen R., Geirhofer S., Sayana K., Shi Z., and Zhou Y. Downlink MIMO in LTE-Advanced: SU-MIMO vs. MU-MIMO. *IEEE Commun. Mag.* 2012. 50(2): 140–147.
39. Chung W-C., Chen C-Y., Huang C-Y., Chang C-J., and F. Ren. Ant colony-based radio resource allocation for LTE-A systems with MIMO and CoMP transmission. *Proceedings of 2013 IEEE/CIC International Conference on Communications in China (ICCC).* August 12-14, 2013. Xi'an, China. IEEE. 2013. 780–785.
40. Park C. S., Wang Y-P. E., Jöngren G., and Hammarwall D. Evolution of uplink MIMO for LTE-Advanced. *IEEE Commun. Mag.* 2011. 49(2): 112–121.
41. Duplicy J., Badic B., Balraj R., Ghaffar R., Horváth P., Kaltenberger F., Knopp R., Kovács I., Nguyen H., and Tandur D. MU-MIMO in LTE Systems. *EURASIP J. Wirel. Commun. Netw.* 2011. 1-13.
42. Lim C., Yoo T., Clerckx B., Lee B., and Shim B. Recent trend of multiuser MIMO in LTE-advanced. *IEEE Commun. Mag.* 2013. 51(3): 127–135.
43. Choi D., Lee D., and Lee J. H. Resource allocation for CoMP with multiuser MIMO-OFDMA. *IEEE Trans. Veh. Technol.* 2011. 60(9): 4626–4632.

44. Gao Y., Li Y., Yu H., Zhao T., and Gao S. Implementation and analysis of CoMP in 3GPP LTE system level simulator. *Proceedings of 2011 International Conference on Electronic and Mechanical Engineering and Information Technology (EMEIT)*, August 12-14, 2011. Heilongjiang, China. IEEE. 2011. 9: 4809–4811.

45. Sun S., Gao Q., Peng Y., Wang Y., and Song L. Interference management through CoMP in 3GPP LTE-advanced networks. *IEEE Wirel. Commun.* 2013. 20(1): 59–66.

46. Sawahashi M., Kishiyama Y., Morimoto A., Nishikawa D., and Tanno M. Coordinated multipoint transmission/reception techniques for LTE-Advanced [Coordinated and Distributed MIMO]. *IEEE Wirel. Commun.* 2010. 17(3): 26–34.

47. Irmer R., Droste H., Marsch P., Grieger M., Fettweis G., Brueck S., Mayer H-P., Thiele L., and Jungnickel V. Coordinated multipoint: Concepts, performance, and field trial results. *IEEE Commun. Mag.* 2011. 49(2): 102–111.

48. Lee D., Seo H., Clerckx B., Hardouin E., Mazzarese D., Nagata S., and Sayana K. Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges. *IEEE Commun. Mag.* 2012. 50(2): 148–155.

49. Khandekar A., Bhushan N., Tingfang J., and Vanghi V. LTE-Advanced: heterogeneous networks. *Proceedings of 2010 European Wireless Conference (EW)*. April 12-15, 2010. Lucca, Italy. IEEE. 2010. 978–982.

50. Damnjanovic A., Montojo J., Wei Y., Ji T., Luo T., Vajapeyam M., Yoo T., Song O., and Malladi D. A survey on 3GPP heterogeneous networks. *IEEE Wirel. Commun.* 2011. 18(3): 10–21.

51. Holma H. and Toskala A. *LTE for UMTS: Evolution to LTE-advanced*. John Wiley & Sons. 2011.

52. Dahlman E., Parkvall S., and Skold J., *4G: LTE/LTE-Advanced for Mobile Broadband*. Academic Press. 2013.

53. 3GPP. *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 11)*. Technical Specification (TS 36.211). 2012.

54. Pramudiwati D. *LTE System Performance In Relation To Wideband Channel Properties*. Master of Science. Thesis. Delft University of Technology. 2011.

55. Odeh N. Multi-Hop Relay vs. Mesh. *Wirel. Commun. Clust. MIMOS Berhad*. 2009.

56. Lang E., Redana S., and Raaf B. Business impact of relay deployment for coverage extension in 3GPP LTE-Advanced. *Proceedings of 2009 IEEE International Conference on Communications Workshops (ICC 2009)*. June 14-18, 2009. Dresden, Germany. IEEE. 2009. 1-5.

57. Martins A., Rodrigues A., and Vieira P. Analyzing the economic impact of fixed relaying deployment in a LTE network. *Proceedings of 2013 16th International Symposium on Wireless Personal Multimedia Communications (WPMC),* June 24-27, 2013. NJ, USA. IEEE. 2013. 1–5.

58. Zolotukhin M., Hamalainen T., and Garnaev A. A Relay Deployment Mechanism for One Scenario of Cost-Effective Coverage Extension in IEEE 802.16j Networks. *Proceedings of 2012 5th International Conference on New Technologies, Mobility and Security (NTMS)*. May 7-10, 2012. Istanbul, Turkey. IEEE. 2012. 1–6.

59. Khirallah C., Thompson J. S., and Rashvand H. Energy and cost impacts of relay and femtocell deployments in Long-Term-Evolution Advanced. *IET Commun.* 2011. 5(18): 2617–2628.

60. Peters S. W., Panah A. Y., Truong K. T., and Heath R. W. Relay architectures for 3GPP LTE-Advanced. *Eurasip J. Wirel. Commun. Netw.* 2009.

61. Yang Y., Hu H., Xu J., and Mao G. Relay technologies for WiMAX and LTE-Advanced mobile systems. *IEEE Commun. Mag.* 2009. 47(10): 100–105.

62. Hoymann C., Chen W., Montojo J., Golitschek A., Koutsimanis C., and Shen X. Relaying operation in 3GPP LTE: challenges and solutions. *IEEE Commun. Mag.* 2012. 50(2): 156–162.

63. Zheng K., Fan B., Ma Z., Liu G., Shen X., and Wang W. Multihop cellular networks toward LTE-Advanced. *IEEE Veh. Technol. Mag.* 2009. 4(3): 40–47.

64. Lo A. and Niemegeers I. Multi-hop Relay Architectures for 3GPP LTE-Advanced. *Proceedings of IEEE 9th Malaysia International Conference on Communications (MICC)*. December 15-17, 2009. Kuala Lumpur, Malaysia. IEEE. 2009. 123–127.

65. Nam Y-H., Liu L., Wang Y., Zhang C., Cho J., and Han J-K. Cooperative Communication Technologies for LTE-Advanced. *Proceedings of 2010 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. March 14-19, 2010. Texas, USA. IEEE. 2010. 5610–5613.

66. Popovski P. and Yomo H. Physical network coding in two-way wireless relay channels. *Proceedings of 2007 IEEE International Conference on Communications (ICC'07)*. June 24-28, 2007. Glasgow, Scotland. IEEE. 2007. 707–712.

67. Rankov B. and Wittneben A. Spectral efficient protocols for half-duplex fading relay channels. *IEEE J. Sel. Areas Commun.* 2007. 25(2): 379–389.

68. Oechtering T. J. and Boche H. Stability region of an optimized bidirectional regenerative half-duplex relaying protocol. *IEEE Trans. Commun.* 2008. 56(9): 1519–1529.

69. Lo A. and Guan P. Performance of In-band Full-Duplex Amplify-and-Forward and Decode-and-Forward Relays with Spatial Diversity for Next-Generation Wireless Broadband. *Proceedings of 2011 International Conference on Information Networking (ICOIN)*. January 26-28, 2011. Kuala Lumpur, Malaysia. IEEE. 2011. 290–294.

70. Shende N., Gurbuz O., and Erkip E. Half-duplex or full-duplex relaying: A capacity analysis under self-interference. *Proceedings of 2013 47th Annual Conference on Information Sciences and Systems (CISS)*. March 20-22, 2013. MD, USA. IEEE. 2013. 1–6.

71. Telatar E. Capacity of Multi-antenna Gaussian Channels. *Eur. Trans. Telecommun.* 1999. 10(6): 585–595.

72. Foschini G. J. and Gans M. J. On limits of wireless communications in a fading environment when using multiple antennas. *Wirel. Pers. Commun.* 1998. 6(3): 311–335.

73. Lozano A. and Jindal N. Transmit Diversity vs. Spatial Multiplexing in Modern MIMO Systems. *IEEE Trans. Wirel. Commun.* 2010. 9(1): 186–197.

74. Zhang S. and Lau V. K. N. Design and analysis of multi-relay selection for cooperative spatial multiplexing. *Proceedings of 2008 IEEE International Conference on Communications (ICC'08)*. May 19-23, 2008. Beijing, China. IEEE. 2008. 1129–1133.

75. Jing Y. and Jafarkhani H. Single and Multiple Relay Selection Schemes and their Achievable Diversity Orders. *IEEE Trans. Wirel. Commun.* 2009. 8(3): 1414–1423.

76. Zhao Y., Adve R., and Lim T. J. Improving amplify-and-forward relay networks: optimal power allocation versus selection. *Proceedings of 2006 IEEE International Symposium on Information Theory*. July 9-14, 2006. Seattle, WA, USA. IEEE. 2006. 1234–1238.

77. Sadek A. K., Han Z., and Liu K. J. R. A distributed relay-assignment algorithm for cooperative communications in wireless networks. *Proceedings of 2006 IEEE International Conference on Communications (ICC'06)*. June 11-15, 2006. Istanbul, Turkey. IEEE. 2006. 4: 1592–1597.

78. Bletsas A., Khisti A., Reed D. P., and Lippman A. A simple cooperative diversity method based on network path selection. *IEEE J. Sel. Areas Commun.* 2006. 24(3): 659–672.

79. Tang X., Mou W., Fang F., Cai Y., Yang W., and Zhang T. Partial Relay Selection with Feedback Delay and Cochannel Interference: Performance Analysis and Power Optimization. *Int. J. Distrib. Sens. Networks*. 2014.

80. Rui X. Decode-and-forward with partial relay selection. *Int. J. Commun. Syst.* 2010. 23(11): 1443–1448.

81. Ibrahim A. S., Sadek A. K., Su W., and Liu K. J. R. Cooperative communications with relay-selection: When to cooperate and whom to cooperate with? *IEEE Trans. Wirel. Commun.* 2008. 7(7): 2814–2827.

82. Niyato D., Zhou X., Hjørungnes A., Wang P., and Li Y. Hierarchical coalition formation game of relay transmission in IEEE 802.16m. *Lect. Notes Inst. Comput. Sci. Soc. Telecommun. Eng.* 2012. 75: 490–505.

83. Zhang D., Shinkuma R., and Mandayam N. B. Bandwidth exchange: an energy conserving incentive mechanism for cooperation. *IEEE Trans. Wirel. Commun.* 2010. 9(6): 2055–2065.

84. Ben Chaabane I., Hamouda S., Tabbane S., and Vicario J. L. A New PRB Sharing Scheme in Dual-hop LTE-Advanced System Using Game Theory. *Proceedings of 2012 IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*. September 9-12, 2012. Sydney, Australia. IEEE. 2012. 375–379.

85. Lee S-H., Lin Y-Y., Yao Y-C., and Wen J-H. Power Allocation for Multi-relay Amplify-and-Forward Cooperative OFDM. *Proceedings of 2013 Seventh International Conference on Complex, Intelligent, and Software Intensive Systems (CISIS)*. July 3-5, 2013. Taichung, Taiwan. IEEE. 2013. 356–360.

86. Phan K. T., Le L. B., Vorobyov S. A., and Le-Ngoc T. Centralized and distributed power allocation in multi-user wireless relay networks. *Proceedings of 2009 IEEE International Conference on Communications (ICC'09)*. June 14-18, 2009. Dresden, Germany. IEEE. 2009. 1–5.

87. Kadloor S. and Adve R. Optimal relay assignment and power allocation in selection based cooperative cellular networks. *Proceedings of 2009 IEEE International Conference on Communications (ICC'09)*. June 14-18, 2009. Dresden, Germany. IEEE. 2009. 1–5.

88. Ma K., Liu Z., and Guan X. Joint Relay Selection and Power Allocation for Cooperative Cellular Networks. *Wirel. Pers. Commun.* 2010. 64(2): 1–17.

89. Yu Y., Wang W., Wang C., Yan F., and Zhang Y. Joint relay selection and power allocation with QoS support for cognitive radio networks. *Proceedings of 2013 IEEE Wireless Communications and Networking Conference, (WCNC 2013)*. April 7-10, 2013. Shanghai, China. IEEE. 2013. 4516–4521.

90. Chen D., Ji H., Li X., and Zhao K. A novel multi-relay selection and power allocation optimization scheme in cooperative networks. *Proceedings of 2010 IEEE Wireless Communications and Networking Conference (WCNC 2010)*. April 18-21, 2010. Sydney, Australia. IEEE. 2010. 1–6.

91. Chen D., Ji H., and Li X. Energy-efficient joint relay node selection and power allocation over multihop relaying cellular networks toward LTE-Advanced. *J. China Univ. Posts Telecommun.* 2011. 18(3): 1–7.

92. Wang R., Ji H., and Li X. Energy efficiency based multi-relay selection and power allocation in OFDM cooperation networks. *J. China Univ. Posts Telecommun.* 2014. 21(3): 10–17.

93. Vardhe K., Reynolds D., and Woerner B. D. Joint power allocation and relay selection for multiuser cooperative communication. *IEEE Trans. Wirel. Commun.* 2010. 9(4): 1255–1260.

94. Mapar F. and Abolhassani B. A fair power-efficient cross-layer relay selection based on priority and buffer management. *Proceedings of 2012 IEEE Consumer Communications and Networking Conference (CCNC)*. January 14-17, 2012. Las Vegas, Nevada, USA. IEEE. 2012. 711–713.

95. Lou S. and Yang L. Joint Relay Selection and Power Allocation for Two-way Relay Channels with Asymmetric Traffic Requirements. *KSII Trans. Internet Inf. Syst.* 2013. 7(8): 1955–1971.

96. Cao G., Yang D., Zhu X., and Zhang X. A joint resource allocation and power control algorithm for heterogeneous network. *Proceedings of 2012 19th International Conference on Telecommunications (ICT)*. April 23-25, 2012. Jounieh, Lebanon. IEEE. 2012. 1–5.

97. Prasetyo W. A., Lu H., and Nikookar H. Optimal relay selection and power allocation using game theory for cooperative wireless networks with interference. *Proceedings of 2011 41st European Microwave Conference (EuMC)*. October 10-13, 2011. Manchester, UK. IEEE. 2011. 37–40.

98. Uddin M. F., Assi C., and Ghrayeb A. Joint Relay Assignment and Power Allocation for Multicast Cooperative Networks. *IEEE Commun. Lett.* 2012. 16(3): 368–371.

99. Uddin M. F., Assi C., and Ghrayeb A. Joint optimal AF relay assignment and power allocation in wireless cooperative networks. *Comput. Networks*. 2014. 58(1): 58–69.

100. Hesketh T., de Lamare R. C., and Wales S. Joint partial relay selection, power allocation and cooperative maximum likelihood detection for mimo relay systems with limited feedback. *Proceedings of 2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*. June 2-5, 2013. Dresden, Germany. IEEE. 2013. 1–5.

101. Zhou Z. K. and Zhu Q. Power Allocation and Relay Selection Algorithm in Multi-Relay Amplify-and-Forward Networks. *Appl. Mech. Mater.* 2014. 3: 3423–3428.

102. Liu T. and Rong M. Utility-based joint routing and spectrum partitioning in relay LTE-advanced networks. *Proceedings of 2011 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC).* September 11-14, 2011. Toronto, Canada. IEEE. 2011. 1914–1918.

103. Dong L., Zhu X., and Huang Y. Optimal asymmetric resource allocation for multi-relay based LTE-advanced systems. *Proceedings of 2011 IEEE Global Telecommunications Conference (GLOBECOM 2011)*. December 5-9, 2011. Texas, USA. IEEE. 2011. 1–5.

104. Zhao G., Yang C., Li G. Y., Li D., and Soong A. C. K. Power and channel allocation for cooperative relay in cognitive radio networks. *IEEE J. Sel. Top. Signal Process.* 2011. 5(1): 151–159.

105. Huang G., Zhang G., Zhang P., Tang D., and Qin J. Resource allocation for OFDM relay systems with statistical QoS guarantees. *Int. J. Commun. Syst.* 2012. 27(7): 991–1008.

106. Krishnan N., Yates R. D., Mandayam N. B., and Panchal J. S. Bandwidth sharing for relaying in cellular systems. *IEEE Trans. Wirel. Commun.* 2012. 11(1): 117–129.

107. Al-Tous H. and Barhumi I. Joint Power and Bandwidth Allocation for Amplify-and-Forward Cooperative Communications Using Stackelberg Game. *IEEE Trans. Veh. Technol.* 2013. 62(4): 1678–1691.

108. Lang H-S., Yeh F-T., Lin S-C., and Fang W-H. Joint subcarrier pairings and power allocations with interference management in cognitive relay networks based on genetic algorithms. *Proceedings of 2014 International Conference on Intelligent Green Building and Smart Grid (IGBSG 2014).* April 23-25, 2014. Taipei, Taiwan. IEEE. 2014. 1–5.

109. Ng T. and Yu W. Joint optimization of relay strategies and resource allocations in cooperative cellular networks. *IEEE J. Sel. Areas Commun.* 2007. 25(2): 328–339.

110. Ruangchaijatupon N. and Yusheng J. OFDMA Resource allocation based on traffic class-oriented optimization. *IEICE Trans. Commun.* 2009. 92(1): 93–101.

111. Yu-ming H., Mao X., and Fan W. QoS-Aware Resource Allocation Algorithm for Cooperative Relay-based OFDM Cellular Networks. *J. Electron. Inf. Technol.* 2011. 32(12): 2948–2953.

112. Xie B., Zhou W., Hao C., Chen W., and Song J. Joint channel-aware and queue-aware relay selection and resource allocation in cooperative OFDMA networks. *Proceedings of 2010 IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*. September 26-29, 2010. Istanbul, Turkey. IEEE. 2010. 2139–2144.

113. Chen R., Leng S., and Huang X. A joint resource allocation algorithm for cooperative communications. *Proceedings of 2011 3rd International Conference on Advanced Computer Control (ICACC)*. January 18-20, 2011. Harbin, China. IEEE. 2011. 311–315.

114. Alam M. S., Mark J. W., and Shen X. S. Relay Selection and Resource Allocation for Multi-User Cooperative OFDMA Networks. *IEEE Trans. Wirel. Commun.* 2013. 12(5): 2193–2205.

115. Cover T. M. and El Gamal A. Capacity theorems for the relay channel. *IEEE Trans. Inf. Theory*. 1979. 25(5): 572–584.

116. B. Sklar. *Digital Communications: Fundamentals and Applications*. 2nd. ed. Prentice Hall NJ. 2001.

117. Wang L-C. and Yeh C-J. 3-cell network MIMO architectures with sectorization and fractional frequency reuse. *IEEE J. Sel. Areas Commun.* 2011. 29(6): 1185–1199.

118. Guan P. Combining relaying and base station coordination for improving cell-edge multi-user performance in 3GPP LTE-Advanced networks. Master of Science. Thesis. Delft University of Technology. 2011.

119. Liu C. and Wang W. Performance analysis of a sectorized distributed antenna system with reduced co-channel interference. *J. China Univ. Posts Telecommun.* 2006. 13(1): 20–24.

120. Cooper M. and Goldburg M. Intelligent antennas: Spatial division multiple access. *Annu. Rev. Commun.* 1996. 4: 2–13.

121. Ko C-H. and Wei H-Y. On-demand resource-sharing mechanism design in two-tier OFDMA femtocell networks. *IEEE Trans. Veh. Technol.* 2011. 60(3): 1059–1071.

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

123. Gebali F. *Analysis of computer and communication networks*. Springer. 2008.

124. Arnold T. and Schwalbe U. Dynamic coalition formation and the core. *J. Econ. Behav. Organ.* 2002. 49(3): 363–380.

125. Lo A. and Guan P. Joint Cooperative Shared Relaying and Multipoint Coordination for Network MIMO in 3GPP LTE-Advanced Multihop Cellular Networks. *Recent Developments in Mobile Communications - A Multidisciplinary Approach*. J. P. Maícas, Ed. InTech. 2011. 217–232.

126. Wang X., Giannakis G. B., and Marques A. G. A unified approach to QoS-guaranteed scheduling for channel-adaptive wireless networks. *Proceedings of IEEE*. 2007. 95(12): 2410–2431.