J Y V Ä S K Y L Ä   S T U D I E S   I N   C O M P U T I N G

177

Zheng Chang

Spectrum and Energy Efficient Solutions For OFDMA Collaborative Wireless Networks

JYVÄSKYLÄN YLIOPISTO

JYVÄSKYLÄ STUDIES IN COMPUTING 177

Zheng Chang

Spectrum and Energy Efficient Solutions For OFDMA Collaborative Wireless Networks

Esitetään Jyväskylän yliopiston informaatioteknologian tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston Agora-rakennuksen auditoriossa 1
joulukuun 17. päivänä 2013 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Information Technology of the University of Jyväskylä,
in building Agora, auditorium 1, on December 17, 2013 at 12 o'clock noon.

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2013

Spectrum and Energy Efficient Solutions For OFDMA Collaborative Wireless Networks

JYVÄSKYLÄ STUDIES IN COMPUTING 177

Zheng Chang

Spectrum and Energy Efficient Solutions For OFDMA Collaborative Wireless Networks

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2013

Editors
Timo Männikkö
Department of Mathematical Information Technology, University of Jyväskylä
Pekka Olsbo, Sini Tuikka
Publishing Unit, University Library of Jyväskylä

URN:ISBN:978-951-39-5500-7
ISBN 978-951-39-5500-7 (PDF)

ISBN ISBN 978-951-39-5499-4 (nid.)
ISSN 1456-5390

Jyväskylä University Printing House, Jyväskylä 2013

To my family

ABSTRACT

Chang, Zheng
Spectrum and Energy Efficient Solutions For OFDMA Collaborative Wireless Networks
Jyväskylä: University of Jyväskylä, 2013, 58 p.(+included articles)
(Jyväskylä Studies in Computing
ISSN 1456-5390; **177**)
ISBN 978-951-39-5499-4 (nid.)
ISBN 978-951-39-5500-7 (PDF)
Finnish summary
Diss.

On the way towards providing gigabytes transmission, incorporation of OFDMA and relays is foreseen to offer a promising network infrastructure. This thesis concentrates on how to improve the spectrum efficiency and energy efficiency of cooperative relay-assisted OFDMA wireless networks. First, various radio resource allocation (RRA) schemes are proposed here in order to provide reliable transmissions. The goal of this research is to investigate relay selection, subcarrier allocation and power allocation in wireless relay networks with objective to maximize the system throughput. Various practical scenarios are considered including channel information imperfectness and link asymmetry. With a variety of mathematical tools, theoretical expressions for the presented algorithms and solutions are derived. Simulation results validate our expectation. Second, in order to reduce the energy consumption of networks, we make use of the concept of mobile relays in introducing the platform of collaborative mobile cloud (CMC) which is formed by a coalition of users. We examine the energy efficiency performance of CMC by using unicast and multicast as its transmission strategies. Two schemes, referred to as unicast supported multicast and multicast supported multicast are proposed to improve the energy efficiency performance of CMC.

Keywords: Spectrum Efficiency; Energy Efficiency, OFDMA, Cooperative Communications, Relay, Collaborative Mobile Cloud

Author Zheng Chang
Department of Mathematical Information Technology
University of Jyväskylä
Finland

Supervisor Professor Tapani Ristaniemi
Department of Mathematical Information Technology
University of Jyväskylä
Finland

Reviewers Professor Peter Han Joo Chong
School of Electrical & Electronic Engineering
Nanyang Technological University
Singapore

Professor Mohammad Elmusrati
Department of Computer Science
University of Vaasa
Finland

Opponent Professor Fu-Chun Zheng
School of Systems Engineering
University of Reading
UK

ACKNOWLEDGEMENTS

The research work for this doctoral thesis was carried out at Department of Mathematical Information Technology of the University of Jyväskylä and at Magister Solutions during 2010–2013. This manuscript would not have been possible in its current form without the support of many wonderful people. First and foremost, I would like to thank my supervisor Professor Tapani Ristaniemi for giving me the opportunities to pursue my Ph.D. studies at the university and relentlessly finding new funding opportunities. He gave me a lot of freedom to study the field I found myself attracted towards and he encouraged every small progress I ever made. His selflessness, goodness to students, and passion for work is the treasure that I will cherish for the rest of my life.

I would like to express my deepest appreciation to Professor Zhisheng Niu from Tsinghua University for providing me the warmest environment when I visited his lab in 2013. I also want to thank Dr. Jie Gong and Dr. Sheng Zhou for the kind help and meaningful discussions during my visit. Moreover I would like to thank all the other people who I worked with and who helped me in some of my publications: Olli Alanen, Timo Nihtilä, Toni Huovinen, Jaakko Kneckt, Eng-Hwee Ong. I want to thank all the great people who ever worked with me or had discussions with me.

I am very grateful to have Professor Peter Han Joo Chong from the Nanyang Technological University and Professor Mohammad Elmusrati from the University of Vaasa as the reviewers of this dissertation and Professor Fu-Chun Zheng from the University of Reading as my opponent. In addition, I would like to thank Magister Solutions Ltd and CEO Janne Kurjenniemi for the possibilities to work with the thesis. All the discussions, games and jokes with colleagues at Magister added color to my daily life , thanks so much!

I would like to thank for the financial support I have received from COMAS, the Academy of Finland and the Celtic-Plus Green-T project during these years. In addition, the generous funding support by Ulla Tuominen Foundation, NOKIA Foundation and Riitta ja Jorma J. Takanen Foundation is also greatly appreciated.

I want to express my unreserved gratitude to Dr. Fengyu Cong who is like a older brother and tutor for me. Without his help and encouragement, it would have been hard for me to finish the work in three years. I also would like to thank all my friends in Finland and in China for their support. Finally, I wish to express my warmest gratitude to my parents. Their permanent encouragement and support has been essential during the past years. Last and most importantly, I thank for my wife Dan for her love and support. The happiness she brought rescued me from exhaustion. I am sure that there are still persons who I failed to mention but in my heart. Kiitos! Thanks!

ACRONYMS

OFDMA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
QoS	Quality of Service
IEEE	Institute of Electrical and Electronics Engineers
LTE	Long Term Evolution
WiMAX	Worldwide Interoperability for Microwave Access
NLOS	Non-Line-Of-Sight
BS	Base Station
LOS	Line-Of-Sight
RN	Relay Node
3GPP	3rd Generation Partnership Project
MT	Mobile Terminal
RRA	Radio Resource Allocation
CSI	Channel State Information
AF	Amplify-Forwarding
DF	Decode-Forwarding
HD	Half-Duplex
FD	Full-Duplex
D2D	Device to Device
M2M	Machine to Machine
CMC	Collaborative Mobile Cloud
WSR	Weighted Sum Rate
BER	Bit Error Ratio
USM	Unicast Supported Multicast

LIST OF FIGURES

CONTENTS

LIST OF INCLUDED ARTICLES

PI Zheng Chang and Tapani Ristaniemi. Radio Resource Allocation for Relay-assisted OFDMA Wireless Networks. *Proc. of 3rd IEEE International Workshop on Cross-layer Design (IWCLD)*, 2011.

PII Zheng Chang and Tapani Ristaniemi. Resource Allocation for Cooperative Relay-assisted OFDMA Networks with Imperfect CSI. *Proc. of 2012 IEEE Military Communication Conference (MILCOM'12)*, 2012.

PIII Zheng Chang and Tapani Ristaniemi. Reducing Energy Consumption via Cooperative OFDMA Mobile Cluster. *Proc. of 17th IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD'12)*, 2012.

PIV Zheng Chang and Tapani Ristaniemi. Energy Efficiency of Collaborative OFDMA Mobile Cluster. *Proc. of 10th IEEE Consumer Communication and Networking Conference (CCNC'13)*, 2013.

PV Zheng Chang and Tapani Ristaniemi. Asymmetric Resource Allocation for OFDMA Networks with Collaborative Relays. *Proc. of 10th IEEE Consumer Communication and Networking Conference (CCNC'13)*, 2013.

PVI Zheng Chang and Tapani Ristaniemi. Efficient Use of Multicast and Unicast in Collaborative OFDMA Mobile Cluster. *Proc. of 77th IEEE Vehicular Technology Conference (VTC'13-spring)*, 2013.

PVII Zheng Chang and Tapani Ristaniemi. Asymmetric Radio Resource Allocation Scheme for OFDMA Wireless Networks with Collaborative Relays. *Springer/ACM Wireless Networks, Volume 19, Issue 5, Page 619-627*, 2013.

PVIII Zheng Chang and Tapani Ristaniemi. Energy Efficiency of Unicast Support Multicast with QoS Guarantee. *Proc. of 2nd IEEE/CIC International Conference on Communications in China (ICCC'13)*, 2013.

PIX Zheng Chang, Tapani Ristaniemi and Zhisheng Niu. Asymmetric Resource Allocation for Collaborative Relay OFDMA Networks with Imperfect CSI. *Proc. of 2nd IEEE/CIC International Conference on Communications in China (ICCC'13)*, 2013.

PX Zheng Chang and Tapani Ristaniemi. Power Efficient Multicast Transmission Framework with QoS Awareness. *Proc. of 2013 International Conference on Wireless Communications and Signal Processing (WCSP'13)*, 2013.

PXI Zheng Chang and Tapani Ristaniemi. Collaborative Mobile Clusters: An Energy-Efficient Emerging Paradigm. *book chapter in "Broadband Wireless Access Networks for 4G: Theory, Application, and Experimentation"* ***(Invited)***, 2013.

PXII Zheng Chang, Tapani Ristaniemi and Zhisheng Niu. Asymmetric Relay Selection and Resource Allocation for OFDMA multi-Relay Networks with Imperfect CSI. *Department Report, Department of Mathematical Information Technology, University of Jyväskylä, accepted by China Communication*, 2013.

1 INTRODUCTION

1.1 Motivation

During the past few years, there has been a tremendous growth in the global wireless market, evidenced especially by the explosive increase in smart phones, tablets, laptops and devices of that kind. All of these applications will doubtlessly accelerate and create new traffic demands in the form of additional functionalities and services, including wireless internet access, multimedia applications, such as video and music download/upload, mobile social networks, content sharing and storage, and many others. To support advanced services and applications, future wireless networks are expected to support peak aggregate data rates up to 1 Gbps with a spectrum bandwidth demand of approximately 100 MHz [1] [2].

On the way towards providing gigabytes transmission, Orthogonal Frequency Division Multiple Access (OFDMA) has been selected as the air interface for many current/upcoming wireless systems. OFDMA is known as an effective technique that exploits the benefits of Orthogonal Frequency Division Multiplexing (OFDM) to combat channel noise and multipath effects and to enable high data rate transmissions over fading channels. In addition, OFDMA is able to provide good bandwidth scalability, as the number of subcarriers can be flexibly configured [3]. Therefore, OFDMA is widely adopted in many standards of existing/upcoming wireless communication systems, such as IEEE 802.11ac [4], LTE/LTE-A [5] and WiMAX [6].

Unfortunately, to satisfy such a high data rate in demand for an OFDMA based system is indeed challenging, taking into account scarce/expensive radio resources, such as spectrum and power, and inescapable constraints, e.g., delay requirements, channel capacity, interference, Quality of Service (QoS) requirements, etc. Besides, since the spectrum allocated for future systems will be above the 2GHz frequency band, which is more vulnerable to Non-Line-Of-Sight (NLOS) scenarios, the traditional cellular architecture is not well-suited for providing uniform data-rate coverage due to the serve path loss effect. For service coverage, the conceived high data rate in wireless systems requires high transmit power, , which is usually highly regulated. Thus, cell edge users will have bad service experience and it will be more difficult for them to obtain the spectrum efficiency comparable to that of users near the Base Station (BS) or data transmitter that have Line-Of-Sight (LOS) transmission. One way to overcome the path loss problem is to divide a long transmission into different shorter hops. In light of these restrictions, a scenario with many small cells seems to be able to provide one potential solution, which, unfortunately, creates a considerable linear cost with respect to the number of cells [7]. One cost efficient alternative which has received much attention is the deployment of Relay Nodes (RNs) to forward data, which can extend the cell coverage of high capacity area [8]. It is shown that the usage of relay will not only enhance cell edge performance and cell coverage, but also improve the spectral efficiency as well as the power efficiency [9] [10]. Therefore, due to the enormous advantages aforementioned, the deployment of fixed relays has been studied as part of the infrastructure within the scope of the 3rd Generation Partnership Project (3GPP) [5].

In addition, mobile relays which may consist of either relays or users can also be used to exploit the diversity and multiplexing advantages to benefit the spectrum efficiency and energy efficiency without infrastructure support [11]. In such systems, users can cooperate with BS or other source nodes and act as geometrically distributed mobile relays to assist the transmission from source to other receivers. Such wireless cooperative networking, which takes advantage of spatial diversity and multiplexing, has been shown to have potential to meet the needs of increased system capacity and coverage [12]. Therefore, one can notice that relay-aided cooperative transmission in OFDMA networks has gained considerable attention and is envisaged to be a promising technology towards realizing future communication infrastructures. An example of the relay-assisted networks can be found in Fig. 1 where the system consists of both fixed relays and mobile relays.

Since many new features are brought into the future OFDMA networks, sophisticated radio resource management strategies are of supreme importance and are to be designed carefully. To handle such problems, mathematical optimization is an important, trusty tool for its ability to provide general frameworks and systematic guidelines. Traditional research on the OFDMA relay network has quite often focused on spectrum efficiency enhancement; through Radio Resource Allocation (RRA) algorithm design, the objective has been to improve spectrum efficiency in terms of $bit/s/Hz$ of users. Recently, there has been increased interest in green communications techniques aiming to design energy efficient communication networks. Since the escalation of energy consumption in wireless networks directly results in the increased greenhouse gas emission, which has been recognized as a major threat to environmental protection and sustainable development [13], energy efficiency can be seen as a mature field of research in communications. Moreover, energy efficiency is also crucial for battery-operated system. Therefore, utilizing the energy saving potential of RN network is also a promising research direction in the evolution of future wireless architectures and it has already come into focus in both the academy and industry.

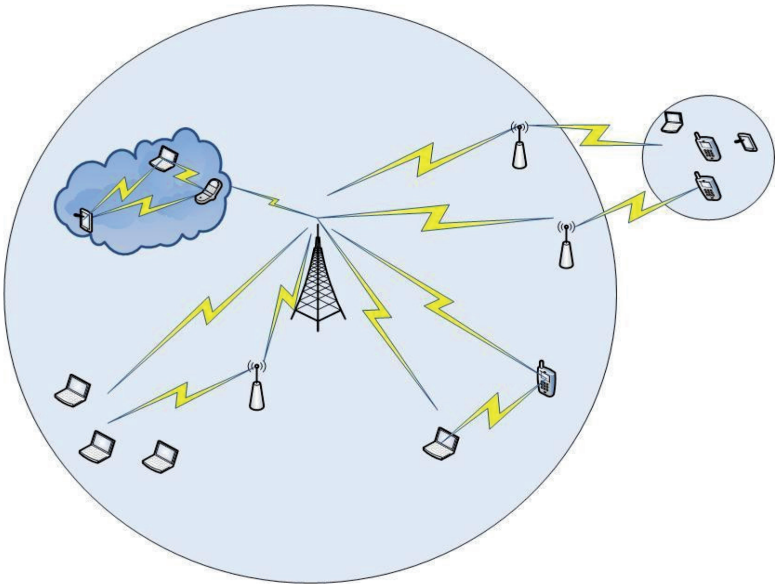


FIGURE 1 Relay-assisted Wireless Networks

Motivated by the importance of spectrum efficiency and energy efficiency in the OFDMA collaborative wireless relay networks, this thesis addresses both issues with different novel methods. The objective of this thesis is to establish a theoretical framework and to develop efficient algorithms for OFDMA collaborative networks. It is hoped that the research conducted in this study will shed more light on improving spectrum energy and energy efficiency solutions for future networks.

1.2 Research Problems

This thesis describes research into the development of the spectrum efficient and energy efficient algorithms in OFDMA collaborative relay networks. Future OFDMA networks are expected to be deployed in any area where users are located. As different areas may have different types of terrain profile (e.g. rural, suburban and urban), wireless channels in each of these profiles may not face the same wireless propagation challenges. Therefore, to meet the challenges for providing data services to users, relays are needed. Since, in the future OFDMA relay networks, there will be different radio resource existed, such as relay, subcarriers and power, cautious design of RRA scheme is crucial.

However, the aforementioned salient features of OFDMA and cooperative relaying techniques also hinge on the availability of Channel State Information (CSI) accuracy, which is a practical limitation and needs to be considered seriously when planning new resource allocation schemes. Schemes that are proposed based on the assumption that CSI is perfectly available at the BS without the feedback delay and/or the estimation fail in practical wireless networks.However, due to the inaccuracy of the channel estimator at the receiver side and the feedback delay/error, which are normal for large scale networks, CSI cannot be obtained perfectly in practice. Therefore, the development of practical resource allocation schemes requires accounting for the inaccuracy of CSI. To sum up, with the objective to maximize the spectrum efficiency, adding fixed relays into a cellular network brings new considerations to the research, namely:

– which relay(s) should be selected to serve a user;
– how the subcarriers and power can be allocated for the hops according to the relay(s) selection;
– how the radio resource allocation problem can be addressed when two-hop asymmetry is considered;
– how the radio resource allocation problem can be addressed in presence of imperfect channel state information;

Traditionally, mobile relay means that the device only has the data relaying function and the only difference from a fixed relay is that it is movable. However, the capabilities of users themselves to act as relays have been investigated recently. Selected users would not only receive the required data from BS but would also be able to forward it to other users. Through user collaboration of this kind, potential gain in energy efficiency and spectrum efficiency can be obtained [12] [14] [15]. Therefore, in the role of mobile relay research, the following research questions are taken into consideration,

– what are the expected energy efficiency gains when considering collaborative mobile cloud environment;
– what kind of transmission strategies can be utilized for user cooperation;
– which user(s) should be chosen to relaying data to other users;

The major objective of this research is to develop practical spectrum and energy efficient algorithms for various transmission technologies employed by OFDMA collaborative networks. The schemes developed address practical issues such as, inaccuracy of CSI, limited computational power, link asymmetry and the support of multiple services with diverse QoS requirements in OFDMA collaborative networks.

1.3 Research Contributions

1.3.1 Achieved results

The research objective was reached over several stages. In the first stage, a novel RRA approach to general OFDMA multi-relay was proposed and analyzed in

[PI]. A general system model was considered such that insights on the effect of RRA in OFDMA networks employing multiple fixed relays can be obtained. Later on, with the consideration of two-hop asymmetry, related RRA was proposed to efficiently select relay for transmission and allocate subcarriers and transmit power jointly [PV][PVII].

In the second stage, the CSI inaccuracy effect on the performance of OFDMA networks as a function of estimation error statistics was quantified in terms of the channel capacity. With the knowledge of error statistics and based on the developed approach, relay, subcarriers and power can be allocated to achieve a performance that is close to the one when accurate CSI is available [PII].

In the third stage, the RRA scheme with imperfect CSI was developed to allocate subcarriers, power and relays to users. Moreover, the link asymmetry was also taken into consideration in the context of CSI imperfection as show in [PVIII], [PXII].

In the fourth stage, by utilizing the mobile relay concepts, a novel user cooperation scheme was proposed. The introduced model, namely Collaborative Mobile Cloud (CMC) is foreseen as an energy efficient infrastructure for the future OFDMA networks to offer high data rate services [PIV].

In the fifth stage, the energy efficiency performance of different transmission strategies were examined in the context of CMC, in [PVI] and [PXI]. Various approaches that can improve the energy efficiency for CMC were proposed and evaluated in [PVIII] and [PX].

1.3.2 Author's Role in Included Articles

The author of this thesis was the main author of articles [PI] [PII] [PV] [PVII] [PVIII] and [PXII] in which he participated in the algorithm design, performance evaluation and in writing the articles. In article [PIII] [PIV] [PVI] [PIX] [PX] [PXI] and [PXII], he contributed in system investigation, performance analysis and algorithm proposal as well as in writing.

1.3.3 Other Publications

In addition to the included articles, the author of this thesis has the following articles published during the doctoral study:

1. Zheng Chang, Natalia Ermolova, Olav Tirkkonen and Tapani Ristaniemi, "OFDM Interference Analysis with Dirty RF", *Proc. of International Conference in Pervasive and Embedded Computing and Communication Systems(PECCS)*, Vilamoura, Portugal. March 2011.
2. Eng Hwee Ong, Jarkko Kneckt, Olli Alanen, Zheng Chang, Toni Huovinen and Timo Nihtilä, "IEEE 802.11ac: Enhancements for Very High Throughput WLANs", *Proc. of IEEE 22nd Symposium on Personal, Indoor, Mobile and Radio Communications (PIMRC'11)*, Toronto, Canada, Sep. 2011.
3. Zheng Chang, Olli Alanen, Toni Huovinen, Timo Nihtilä, Eng Hwee Ong, and Jarkko Kneckt, "Performance Analysis of 802.11ac DCF with Hidden

Nodes", *Proc. of IEEE 75th Vehicular Technology Conference (VTC'12-spring)*, Yokohama, Japan, May 2012.

4. Zheng Chang, Olli Alanen, Eng Hwee Ong and Jarkko Kneckt, "Enhanced Channel Scanning Schemes for Next Generation WLAN system", *Proc. of IEEE 1st International Conference on Communication in China (ICCC'12)*, Beijing, China, Aug. 2012.

1.4 Organization of this Thesis

The foremost objective of this thesis is to enhance the spectrum efficiency and energy efficiency of OFDMA cooperative networks. It is structured as follows:

Chapter 2 : This chapter provides the relevant preliminary knowledge for what follows. Basic models for OFDMA systems together with relevant background information are presented. In addition, general concepts of relays are introduced.

Chapter 3 : The related work on the area of spectrum efficient radio resource allocation algorithms are widely surveyed. Conventional schemes as well as state-of-the-art algorithms are presented to explore the direction of the research in the OFDMA relay networks. In addition, shortcomings of the previous work are treated as challenges. Moreover, a comprehensive literature review of the user cooperation schemes in general OFDMA platforms are listed.

Chapter 4 : Our proposed novel research algorithms as well as performance evaluations are presented in this chapter. The research results on the research challenges discussed previously are categorized into two groups: our proposed novel practical RRA scheme for the OFDMA collaborative relay networks to enhance the spectrum efficiency and the energy efficiency of novel collaborative mobile cloud platform. Some examples of simulation results of the research work are included well.

Chapter 5 : The thesis is concluded and suggestions for future studies are made available.

2 PRELIMINARIES

In this chapter, we briefly overview the concepts that are related to this thesis. In particular, basic concepts of OFDMA and knowledge of relay networks are presented to help understanding this thesis. Both the advantages and challenges of OFDMA and relay networks are discussed. First in Section 2.1, the concepts of OFDMA are introduced. Then in Section 2.2, properties of different types of relays are presented. Section 2.3 summaries the chapter.

2.1 Principles of OFDMA

Orthogonal Frequency Division Multiple Access (OFDMA) is a multi-access version of the Orthogonal Frequency Division Multiplexing (OFDM). The principle of an OFDM system is to use narrow, mutually orthogonal subcarriers on certain frequency to carry data, and OFDMA is achieved by assigning different subcarriers to carry data from/to different users. It means that the total channel bandwidth is divided into subchannels with subcarriers and each subcarrier is modulated with a lower data rate. Then these lower data rate streams are transmitted simultaneously through the subcarriers, which results in achieving high-speed data transmission [19].

OFDM can be viewed as a form of frequency division multiplexing. In the OFDM system, all subcarriers are orthogonal to each other. OFDM allows the spectrum of each subcarrier to overlap, and by selecting a special set of orthogonal carrier frequencies, high spectral efficiency can be achieved because the mutual influence among the orthogonal subcarriers can be avoided. The orthogonality also greatly simplifies the design of both the transmitter and the receiver. A receiver can detect every subcarrier data, which commonly is done via fast Fourier transform (FFT). Therefore a separate filter for each subchannel is not required.

Fig. 2 depicts five orthogonal carriers in the time domain. In this example, all the subcarriers have the same amplitude and same initial phase. However, in practice, the subcarriers are modulated at different amplitude and phase. It can be seen from the figure, that the orthogonality in the time domain means that within an OFDM symbol period, all the subcarriers have integer cycles and the number of cycles between the channels differ by integer numbers.

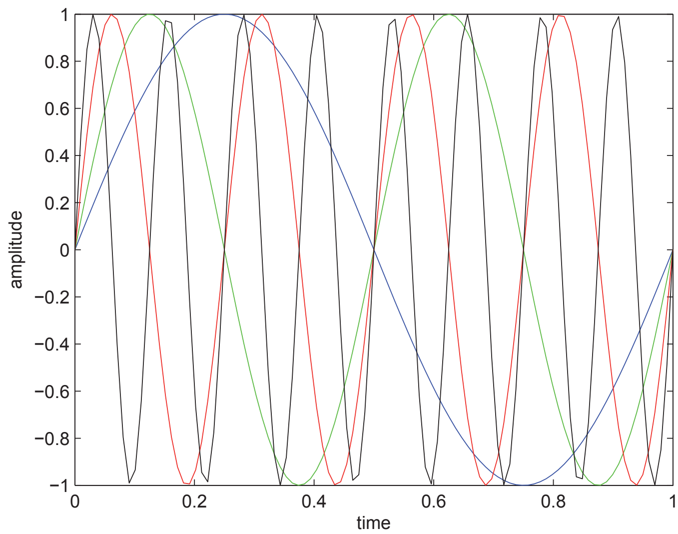


FIGURE 2 Orthogonal subcarriers in time domain

Fig 3 describes the frequency and time domain relations. In the frequency domain, the orthogonality of the subcarriers can also be viewed as subcarriers at integer multiple copies of a single subcarrier.

OFDMA can utilize the advantages of OFDM to enable multipath mitigation and interference cancelation and combat against channel fading effect. However, in OFDMA based networks, narrowband transmission on different orthogonal subcarriers is used which means that there will be a large number of subcarriers which need to be carefully assigned and scheduled during transmission. This calls for the design of flexible subcarrier allocation where OFDMA can select certain subcarriers for dedicated transmission according to channel conditions or users' demands so that dynamic frequency allocation can be achieved. A good resource allocation scheme can also fully make use of diversity gain to get optimal system performance [21].

2.2 Relay Networks

The requirements for high data rate, high spectral and energy efficiency indicate that the conventional cellular network architecture is not feasible for the future system due to several reasons, e.g.,

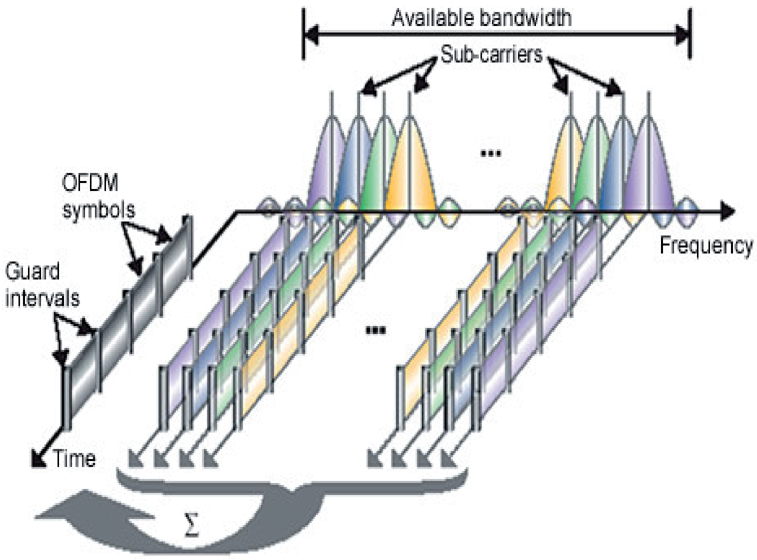


FIGURE 3 Orthogonal subcarriers in frequency domain [20]

– since the required transmission rate will be much higher to support applications, higher transmit power is needed at BS to provide qualified QoS.
– in order to provide the same data rate to the edge users or to extend the coverage of the cell, BS has to use more resource for the dedicated users. However, due to NLOS condition on high central frequency, both spectrum and energy efficiency will not be sufficiently utilized.

To overcome the aforementioned problems, some fundamental new technologies should be employed to satisfy the future network requirements for throughput and coverage. This calls for the modification of current point-to-multipoint wireless network architecture as well as investigation into advanced transmission techniques. As mentioned, increasing the density of BSs or adding small cell BSs would be a potential solution for these problems, but it would seriously increase deployment costs. Deploying RNs has received much attention [22]: adding RN in a cellular system can bring many benefits, such as extending cell coverage, overcoming multi-path fading and increasing system capacity [24]. Now relay-assisted network is considered to be one promising architecture for providing high spectrum and energy efficiency as well as extending the cell coverage for future systems [23].

In this section, we present the basic concept of RNs, its categories and its usage.

2.2.1 Concept of Relay

Relays, which can be either network elements or user equipments/terminals, are more intelligent than conventional repeaters and are capable of decoding, storing and forwarding data, making scheduling and routing decisions, and supporting radio resource management [22]. The cost of deploying RNs is much lower compared to that of just adding more BSs because RNs have more limited functionality, such as low transmit power limits, small antenna elements, etc. Compared with single-hop networks, in which data is exchanged directly between BS and MT, in relay assisted networks, information can be routed from source to destination via different RNs.

2.2.2 Classification of Relays

2.2.2.1 AF Relay and DF Relay

According to its way of processing the received data from source, RNs can be classified into Amplify-and-Forwarding (AF) relay and Decode-and-Forwarding (DF) relay.

AF relay : An AF relay only amplifies the received signal and retransmits/forwards it to the destination. The received signal consists of useful signals from the transmitter and the interference plus noise. The receiver can decide whether to receive the original signal from BS or the amplified signal from RN, or even whether to combine both. As one may notice, interference and noise can be amplified by RN, which is considered as a drawback of the AF relay. Nevertheless, the system performance can still be improved by the AF relay using some advanced technologies, such as selective receiving or combined receiving [23].

DF relay : Unlike the AF relay, a DF relay is able to decode the received data and regenerate the received signal. Thus, neither interference nor noise is retransmitted. Although the system time delay may be longer, the received Signal-to-Noise Ratio (SNR) can be enhanced [23].

There are some other relay types, such as Compress-and-Forwarding (CF) relay that compresses and forwards the received data [23]. However, AF and DF relays are the most common types . In this thesis only DF relay is used so that other types will not be considered further.

2.2.2.2 Half-Duplex Relay and Full-Duplex Relay

According to the time of receiving and transmitting data, relays can be categorized as Half-Duplex (HD) relay and Full-Duplex (FD) relay.

HD relay : HD relay systems operate in a half-duplex manner, where the source-relay and the relay-destination links are kept orthogonal by either frequency division or time division multiplexing. Therefore, in one time slot, either transmitting or receiving is executed on HD relay.

FD relay : In FD relay systems, the source and RN can share a common time-frequency signal space, so that the relay can transmit and receive simultaneously over the same frequency channel.

Technically, HD relay causes loss of spectral efficiency since the data rate achieved in the full-duplex mode can be twice as that of the half-duplex mode due to the simultaneous transmission. However, in practice full-duplex operation is difficult to implement, because of the large amount of self-interference observed at the receiving antenna to the signal from the transmitting antenna of the same RN. Hence, use of FD relay calls for advanced relay design, where transmit and receive antennas are spatially separated in order to mitigate the self-interference. As we do not take the design of RN into consideration, only HD relay is considered in this thesis.

2.2.2.3 Fixed Relay and Mobile Relay

Relay can also be classified into fixed RN and mobile RN according to it deployment and mobility properties.

Fixed Relay : The position of a fixed RN is pre-determined by a network planning scheme and it cannot be changed to another position. Fixed RNs can be used to give uniform data rate coverage for all the users within the cell area as well as extending the cell coverage with high data rates. Major investigation in previous/current research and standardization work usually focused on fixed RN scenarios. Some of the relevant research results on fixed RN can be extended, with some extra complexity, to mobile RN scenarios. In this thesis, relay selection and resource allocation algorithms are proposed for fixed RN scenarios targeted for cell extension.

Mobile Relay : Unlike fixed RN, mobile RN is movable, and the topology of mobile RN based wireless networks is therefore reconfigurable. Mobile RN can be either a network element (e.g., traditional relay) or a mobile user serving as a relay for other users. A recent trend in mobile relay research is that of using MT as relay. A selected MT can act as a relay, and it has the capability of forwarding data to other MTs.

The key research points of relevant research work and standardization also focus on fixed RN scenarios [5]. However, as mobile RN is an emerging technique, invoking mobile RN through user cooperation has recently begun to draw much attention. Therefore, in this thesis, we will also focus on the new research framework to improve the energy efficiency of mobile RN and provide new thoughts on the usage of mobile RNs through user cooperation and coalition.

2.2.3 Usage of Relays

Relays can be used for different perspectives [25]. Fig. 4 illustrates some of the cases that appear in this usage model:

- deployment of RNs to provide coverage extension at the edge of the cell;
- coverage for indoor locations;
- coverage for users in a coverage "hole" due to shadowing and in areas between buildings;

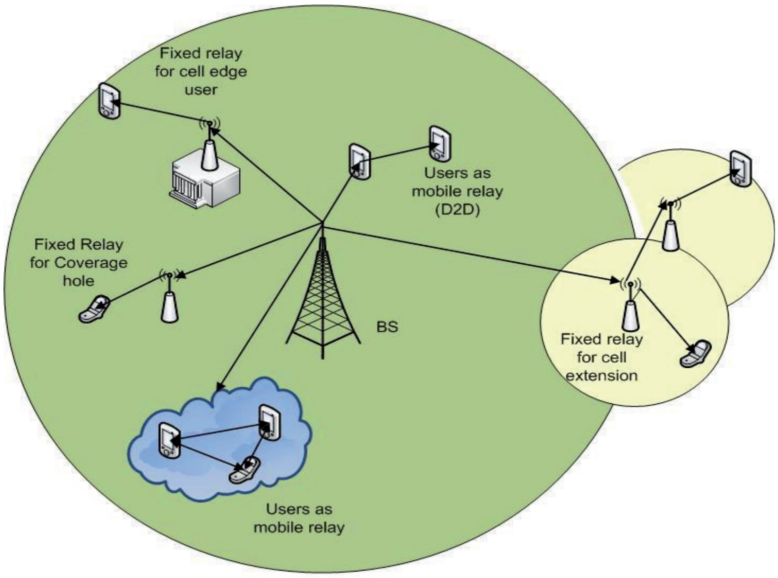


FIGURE 4 Use cases of relays

Usually, fixed RN can be deployed in a relatively high place, for example inside or outside buildings, to provide better data rate coverage. It can also be used for offering higher throughput inside some closed places, such as shopping malls or some other areas which the signal of BS cannot reach. However, there are some important factors that affect fixed-relay systems' performance, e.g., the distance between the BS and RNs, the number of selected relays, number of hops, etc. A two-hop relay network is well-known for its simplicity with respect to RRA and the routing scheme design. In addition, the two-hop scheme can provide a good tradeoff between diversity gain and repetition coding [24]. In this thesis, the proposed schemes only concern a two-hop structure.

For mobile RNs, use cases are broader. Traditionally, a fixed RN can be attached on a vehicle to move within the cell to enhance the data rate of stationary users wherever needed. Another example is that of a RN that can be located on a mobile vehicle, such as a ferry, ship, bus or train, and will provide service directly to a number of MTs that are moving together in those vehicles. In this case, although RNs are fixed relative to MTs, they are actually mobile in the sense that they are in a moving vehicle. RNs deployed in this usage model are expected to be complex, being able to enter and exit the network when the vehicle enters or exits the coverage area of the network. In this model, topologies may exceed that of a two-hop network since other RNs may be involved in the transmission [25].

Another type of mobile RN is using MT as a relay, providing us with new research directions. One trend, referred to as Device-to-Device (D2D) communications, is to use an idle MT to act as a relay for forwarding data from the BS to the requested MTs [12] [16]. Another trend utilizes mobile relay and D2D concepts:

a number of users can form a cluster/group within which users can receive and share the requested data together [17]. Through this system model, energy efficiency can be achieved. That system, which we call Collaborative Mobile Cloud (CMC) hereafter, is another main research direction in this thesis.

As one may notice, RNs do not have the full functionality of BS or MT, thus, RNs cannot orient a transmission by themselves. Therefore, the usage of RNs requires a relay selection scheme where they can participate by assisting transmission from source to destination. The relay selection scheme can directly and seriously affect the quality of its assisted transmission.

The incorporation of OFDMA and cooperative relays is an emerging framework for providing uniform data services to users. A relay-assisted OFDMA network calls for a cautious sign of RRA schemes including relay selection, subcarrier allocation and power allocation design since the network infrastructure is more complicated than before.

2.3 Summary

This chapter introduced the relevant concepts in OFDMA relay networks, including concepts of relay, the classification of relay and the usage of relays. Also, the basic concept of OFDMA was introduced and the network configuration in relay-assisted OFDMA networks was discussed.

3 RELATED WORK

In this chapter, a comprehensive literature review will be provided. We categorize the related work into two groups, which are the work considering general RRA problem in fixed RN network and the work about mobile relay research through user cooperation concept.

3.1 Related Work on RRA for OFDMA Wireless Networks

3.1.1 RRA for Conventional OFDMA Networks

Without considering relay-assisted transmission, RRA for conventional OFDMA networks was usually concerned with the subcarrier and power allocation algorithm design [26]–[38]. In [26], the overview of research developments in cross-layer optimization-based approaches for resource allocation problems in wireless systems was given. This tutorial started from the channel aware scheduling algorithm overview for single-hop networks and then extended the work to multi-hop networks. It was shown that in Medium Access Control (MAC) layer, the optimal scheduling scheme is very complex and thus, simpler sub-optimal method investigation is needed. A general survey about convex optimization applied in communication system and signal processing was presented in [27]. Specially, authors gave interpretation of how to use lagrangian duality in the multicarrier system. In [28], a theoretical framework for cross-layer optimization for OFDM system was provided. An utility function was used to bridge the Physical (PHY) layer and MAC layer and balance the spectrum efficiency and fairness of subcarrier and power allocation. Necessary and sufficient conditions for optimal subcarrier assignment and power allocation as well as the convergence of algorithms were discussed. In addition, authors also presented some effective and practical (suboptimal) algorithms for resource allocation in OFDM wireless networks in [29]. The proposed schemes included sorting-search dynamic subcarrier assignment, greedy bit loading, and power allocation, as well as objective aggregation algorithms. Simulations showed that the performance gains which come from multiuser diversity, frequency diversity, as well as time diversity can be significantly improved by using utility based cross-layer optimization schemes. The authors of [30] investigated subcarrier allocation and power allocation in a multiuser OFDM system. The objective was to maximize the overall rate while achieving proportional fairness among users with a total power constraint consideration. Weighted Sum Rate maximization (WSRmax) as well as weighted sum power minimization (WSPmin) problems were considered for a multiuser OFDMA networks in [31]. It was also shown in [31] that, when using dual decomposition algorithm to solve the resource allocation problems, with practical number of tones, the duality gap is virtually zero and the optimal solutions can be efficiently obtained. Based on branch-and-bound approach, a fast optimal solution for solving RRA problems in OFDMA wireless networks was proposed [32]. The computation complexity can be reduced by the proposed scheme while same throughput as other algorithms can be guaranteed.

Unlike the previous works, the aim of [33] was to minimize the total transmitted power of the whole system while satisfying the data rate requirements of each user in multiuser OFDM networks. To achieve such an objective, this paper presented a subcarriers assignment and bits allocation algorithm in the presence of co-channel interference and Rayleigh fading channel. Similarly, in [34], a subcarrier and power allocation scheme was proposed for QoS support in OFDMA systems. The key QoS factors were interpreted as bit rate and bit error rate (BER), which were then used to determine the each users' traffic demands. To address a OFDMA downlink packet scheduling problem for proportional fairness, efficient subcarrier and power allocation algorithms were proposed in [35]. Necessary conditions for optimality were also derived. A good trade-off between throughput and fairness was demonstrated by the simulation results. In [36], a centralized RRA scheme was proposed for the OFDMA multi-cell system, which allows to highly outperform iterative decentralized allocation strategies based on local optimization criteria. The RRA problem in [37] involved assignment of BS and subcarriers, bit loading, as well as power allocation for various users. A three-phrase and low-complexity algorithm was proposed to distribute radio resources among multiple users according to individual QoS requirements. A joint packet scheduling and subchannel allocation scheme applicable for the IEEE 802.16e OFDMA was presented in [38]. As a multiuser, multi-service and multi-channel packet-switched system was assumed, a distinct scheduling priority for each packet on each subchannel that integrates QoS requirements, service type and CSI was defined. Based on the scheduling priorities efficient QoS guaranteed RRA could be achieved in the presented scheme.

3.1.2 RRA for Relay-assisted OFDMA Networks

As we can see the algorithms for the RRA scheme for a conventional OFDMA wireless networks have been developed over the last decades and the achievements can provide us the fundamentals for the same subject for a relay-aided OFDMA system as well. [39] proposed a centralized utility maximization framework for network with cooperative relays. The scenario was considered under the assumption that the users in this system may require relay support due to their channel conditions. For the relay-aided system, the RRA design should concern about frequency-selective slow-fading environment, the choices of relay node, relay strategy, and the allocation of power and subcarriers for each user. The design challenge was compounded further by the need to take user traffic demands into consideration. The proposed scheme in [39] incorporated both user traffic demands and the CSI in a cross-layer design that not only allocated power and subcarriers optimally for each user, but also selected one best relay node for each transmission pair. Two resource allocation algorithms which improved the overall throughput and coverage were proposed in [40]. The algorithm has the advantage of minimizing the complexity and the required amount of CSI, which were suitable for practical use. In [41], a joint relay selection and subcarrier allocation in the OFDMA relay system with considerations of QoS and service support was investigated. By introducing QoS price, a dual based QoS-aware scheduling algorithm was proposed to tackle the problem. In the context of multiple source and multiple relays, [42] studied the resource allocation for OFDMA relay network. The optimal source, relay and subcarrier allocation problem with fairness consideration on relays was formulated as a binary integer programming problem. Using a graph theoretical approach the formulated problem was then tackled by transforming it into a linear optimal distribution problem. WSRmax problem for OFDMA networks constrained on the overall system power was investigated in [43]. In this work, multiple relays may cooperate with the source for relaying. [44] focused on the problem of maximizing the total data rate under the constraints of joint total power and subchannels occupation, while maintaining the maximum fairness among multiple RNs in the OFDMA DF relay network. In [45], an algorithm which addressed the joint routing, subchannel and power allocation problem in OFDMA relay networks was proposed. Optimization problem was decomposed into two subproblems including i) subchannel allocation problem; ii) routing and power allocation problem, and they were solved by iterative two-step approach. A cross-layer optimization problem was formulated to maximize the balanced end-to-end throughput under the routing and the PHY/MAC constraints in [46]. A cooperative relaying technique was incorporated into the framework by introducing virtual links and nodes. In [47], joint allocation of RNs, subcarriers and power problem in multi-relay assisted OFDM systems was studied. AF relay was used to assist the transmission from the source to destination simultaneously. A subcarrier-pair based resource allocation problem was formulated in a way that the joint optimization of subcarrier pairing, subcarrier-pair-to-relay assignment, and power allocation was the objective. The dual-based method was also applied to address the problem.

In the context of fairness consideration, [48] investigated RRA issue in OFDMA-based DF cooperative networks and proposed joint subcarrier and power allocation schemes. Two-phase suboptimal method was introduced to solve the considered problem. The first step was to distribute subcarriers to relays under the assumption of equal power distribution. Proportional allocation strategy with Threshold was then proposed to achieve tradeoff between total throughput and fairness. [49] introduced an adaptive relay selection scheme for the OFDMA relay network with fairness constraints. The proposed scheme was able to select one set of best relays out of all potential relays to maximize the system capacity. Among these selected relays, fairness constraints were satisfied by subcarriers reallocation. In addition, as the number of potential relays increases with proposed scheme, multiuser diversity can be obtained. [50] presented a number of distributed RRA schemes for OFDMA relay networks. By applying cognitive radio technique at the RN, the spectrum efficiency and user fairness can be obtained. Iterative waterfilling as well as iterative multilevel waterfilling were exploited in the power allocation, and results showed that optimal power allocation was achieved. Further, an iterative barrier constrained waterfilling algorithm was then presented to address the throughput limitations imposed by poor BS-RN links. It was shown by simulations that the proposed algorithm can research fast convergence, and complexity was seriously reduced by the distributed implementation. A fairness-aware adaptive RRA method for multihop OFDMA systems was investigated for downlink [51]. Assuming that perfect CSI was known at BS, an optimization problem for an adaptive subchannel, route and power allocation scheme that maximizes system throughput while guaranteeing minimum resources for each user was formulated. In order to perform the optimization in real time, an efficient heuristic algorithm was proposed.

By relaxing the constraint on the symmetry of two hops, in [52], an asymmetric resource allocation scheme for the multi-user OFDMA single relay systems was introduced. Unlike the previous work, the transmission durations at the BS and the RN were designed to be asymmetric, which enhanced the degree of freedom for transmission. A higher system throughput can be obtained by link asymmetry, and it was also proven to be optimal in [52]. Similarly, [53] proposed a novel asymmetric RRA scheme for the OFDMA DF multi-relay system. An optimal RRA algorithm to maximize the data rate, with joint asymmetric time allocation, power allocation, and subcarrier selection/allocation was discussed with simulation results. Authors of [54] considered the wireless communication of common information between several MTs with the help of one RN. The assumption was that there was no direct link between the MTs, and the time and rates allocation in all directions can be asymmetric. A closed form expression of the optimal time allocation was derived under various constraints. Further a closed form expression of the optimal rate ratio can be achieved such that the sum-rate of all transmissions is maximized under the assumption that the time allocation was optimally chosen.

3.1.3 RRA with Imperfect CSI

All aforementioned works concerned with RRA were under the constraint that allocation unit has the perfect knowledge of CSI. However, in practise, CSI perfectness cannot be easily obtained. Thus, research work about RRA with imperfect CSI has drawn much attentions. In [55], a theoretical analysis on the channel capacity with imperfect CSI was presented, which provided the baseline of the related research. In the conventional OFDMA networks without RN deployment, the objective of [56] was to maximize the expected WSR while satisfying individual user's minimum data rate and system fairness requirements under total power constraint. The dual method was also used to address such a problem. In [57], optimal subcarrier and power allocation algorithms for the OFDMA downlink were developed assuming the availability of imperfect CSI. Both continuous and discrete Weighed Sum Rate (WSR) maximization were considered subject to total power constraints, and average BER constraints for the discrete rate case. A joint scheduling and RRA problem in the downlink of OFDMA wireless network when the per-user SNR was known only in distribution was considered in [58]. The main objective of this work was to maximize sum-utility over user schedules, powers, and code rates subject to an instantaneous sum-power constraint. The rate-power allocation algorithms were developed in [59] and two channel uncertainty models were studied.

With the consideration of deploying cooperative RNs, [60] aimed to maximize expected throughput by proper design of the data rates, cooperation architecture and beamforming vectors from the RNs. [61] considered the RRA algorithm for conventional OFDMA networks without relays. A recent work in this line [62] investigated the issue of joint RRA and relay selection with imperfect CSI. The authors, however, focused on power minimization and mean rate to characterize the CSI uncertainty, which resulted in different interpretations for system optimization. Another recent work about RRA for OFDMA relay networks with imperfect CSI was introduced in [63], where only one relay was selected for assisting the transmission.

3.2 Related Work on Collaborative Mobile Cloud Platform

Obtaining energy efficiency for both BS and MT through mobile relay concept is one recent promising research direction. Some key research ideas to obtain energy efficiency is about to reduce the receive time [64] as well as to share the computing task among number of MTs [65] [66], etc. As stated before, mobile relay can be implemented by user cooperation and thus, the energy efficiency can be achieved by reducing terminal energy cost [67][68].

To shape the research area and wrap up relevant research work, an energy efficient platform called Collaborative Mobile Cloud was proposed in [17]. In [17], authors utilized the concept of mobile relays and D2D communications, presented the CMC structure and introduced its potential in content sharing and social networks. In [69]–[72], a series works have been presented to address the problem about how to form a content sharing cluster and how to achieve the energy saving. In particular, authors in [73] presented a literature survey of recent trends in this area and also gave comments on the implementation issues. The idea of incorporation of network coding and CMC were given in [74] [75], and performance analysis on energy savings was presented. Energy efficiency study of data delivery for CMC was also introduced in [76]. Without refereing to the CMC frame, [77] brought into consideration a social grouping method in which objective was to form a group for social networks. In [79], a hybrid broadcast/unicast transmission scheme to improve the energy efficiency of content distribution for wireless networks with multi-rate support was proposed. To explore the short range transmission benefits, [78] proposed a novel energy saving approach that exploits the multi-radio feature of recent mobile devices equipped with WLAN and Bluetooth interfaces was presented.

As one can observe, regarding the transmission within a CMC, multicast or broadcasting is more energy efficient than unicast. For example, in [80], MTs pulled a video description on the Long Range (LR) transmission and distributed it on the Short Range (SR) transmission via multicast. Therefore, the design of transmission strategy calls for attention. There are several improved multicast scheme that can be applied in this area. Multicast is known as an efficient transmission strategy to deliver the same data to different users. Some recent work tried to improve its efficiency by proper protocol design [82]–[88]. To obtain BS energy saving [83] presented a user selection algorithm in order to select users as relay to forward the data. In a similar scenario, [84] proposed clustering algorithm where a cluster of users could be selected for relaying. Two proportional fair multicast scheduling algorithms named Inter-group Proportional Fairness and Multicast Proportional Fairness that can adapt to dynamic channel states were introduced in [85]. The algorithms were targeted to achieve trade-off between throughput and fairness. Through utility theory and clustering method, an energy efficient multicast grouping scheme was proposed in [86]. To utilize the advantages of unicast transmission, [87] presented an adaptive transmission scheme for mixed multicast and unicast traffic. Similarly, [88] also used unicast to mitigate inherent drawbacks of multicast, where unicast was invoked and dedicated to the users who cannot obtain satisfied QoS through multicast only.

RRA for multicast OFDMA networks is also a crucial issue [89]. However, unless unicast transmission, power minimization is the main concern when allocating resource in multicast OFDMA networks [90] [91] [92]. For instance, in [90], at first users were selected as relays and a power optimization scheme was proposed for both BS and selected users in order to minimize the energy consumption. Moreover, RRA scheme for a mixed network consisting of multicast and unicast was also under investigation [94]. For example, [93] focused on the resource allocation for mixed multicast and unicast traffic in wireless OFDMA networks, where the objective was is to maximize the network total throughput with a total power constraint while guaranteeing the minimum rate requirements of both traffics.

As we can see, the design of green CMC platform for energy efficient transmission, content sharing is a new trend in the wireless communications and there are many open issues on this research direction.

3.3 Summary

The related work on the area of spectrum efficient radio resource allocation was widely surveyed in this chapter. Conventional schemes as well as state-of-the-art algorithms were presented to explore the direction of the research in OFDMA relay networks. In addition, challenges were found from shortcomings of the previous work. Moreover, a comprehensive literature review on the user cooperation/content sharing/mobile cloud in general OFDMA platforms was presented as well.

4 RESEARCH RESULTS

The major contributions in this thesis can be categorized into two groups: spectrum efficiency enhancements and energy efficiency enhancements in OFDMA collaborative wireless networks.

4.1 Spectrum Efficiency Enhancement through RRA Algorithms

4.1.1 RRA scheme for General OFDMA Cooperative Networks

Reference paper:

– [PI] Z. Chang and T. Ristaniemi, "Radio Resource Allocation for Relay-assisted OFDMA Wireless Networks" *Proc. of 3rd IEEE International Workshop on Cross-layer Design (IWCLD)*, Rennes, France, 2011.

In this work, we investigated the problem of RRA in a cooperative relay OFDMA network for spectrum efficiency enhancement. We considered our system as a two-hop time-division duplex downlink relay system. The whole system consisted of a source, e.g., BS, a destination node, e.g., MT and several RNs. In this work, relays were deployed for extending cell coverage, so we did not consider a direct link from source to destination. The first hop was the so called broadcast phase, where BS broadcasted information data to a cluster of DF relays. In the second hop, RNs cooperated to transmit the information data to the MT, so the spatial diversity gain can be achieved (relays are assumed to be far enough from each other).

In this work, we also assumed that the transmission durations of two hops are symmetric and that the CSI can be obtained perfectly at BS. The presented relay-assisted collaborative OFDMA network is shown in Fig. 5 where two relays are assisting the transmission.

The main objective of this study was to maximize the BS-MT (end-to-end) throughput through RRA schemes, including relay selection, subcarrier assignment and power allocation. Since the first hop was a broadcast phase and second

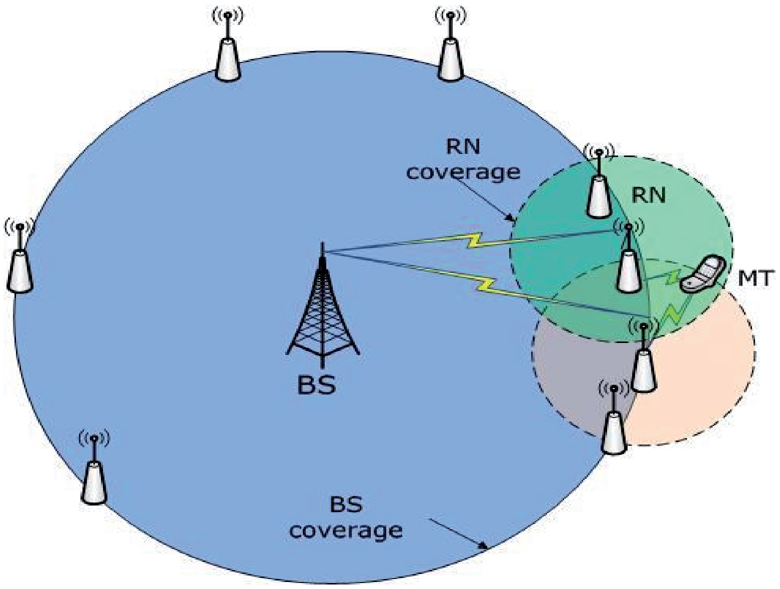


FIGURE 5 Considered system model for RRA design

hop was a virtual MISO transmission, the trade-off between relay and subcarrier allocation can be reached when the relay selection was performed. It should be noticed that our formulated resource allocation problem is combinatorial in nature with nonconvex structure. However, it can be solved by convex optimization theory [97] [98] as the number of subcarriers becomes sufficient large, as the dual gap then tends to zero [39]. Therefore, the problem was solvable in dual domain.

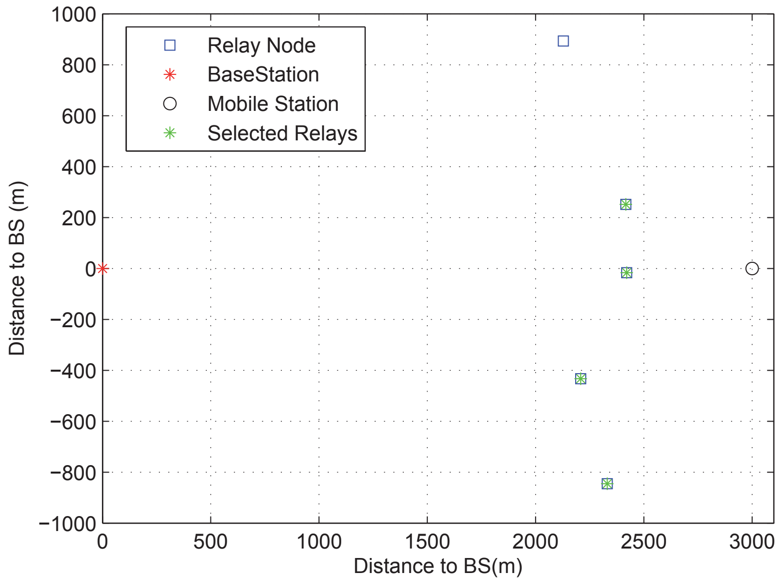


FIGURE 6 Relay node distribution and 4 relays are selected

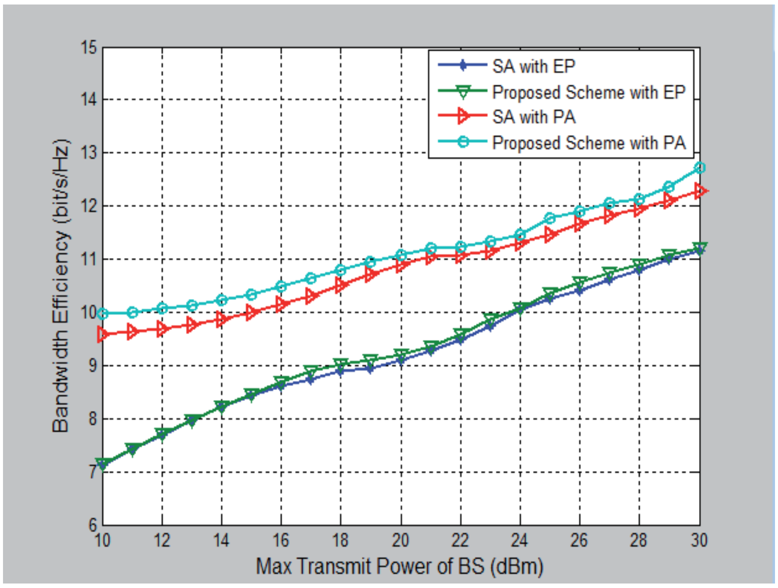


FIGURE 7 Impact of BS maximum transmit power on system bandwidth efficiency, general problem

One example of relay selection process is shown in Fig. 6 where four relays are selected. Fig. 7 shows an example of the performance of our proposed algorithm in [PI] by comparing it with other schemes. The "Proposed scheme with PA" denotes the case that combines with proposed relay selection and subcarrier allocation schemes with equal power allocation and the "Proposed scheme with EP" means that combining the proposed relay selection and subcarrier allocation schemes with the proposed power allocation. "SA" is the scheme proposed in [49]. In Fig. 7, we can see that our proposed "Proposed scheme with PA" has better performance over others. Fig. 8 presents the convergence performance of the proposed schemes compared with the "Fairness SA" proposed in [48]. These simulation results show that the achieved system performance of the proposed schemes is better than that of other existing schemes.

4.1.2 RRA for OFDMA Cooperative Wireless Networks with Imperfect CSI

Reference paper:

– [PII] Z. Chang and T. Ristaniemi, "Resource Allocation for Cooperative Relay-assisted OFDMA Networks with Imperfect CSI, " *Proc. of IEEE Military Communication Conference (MILCOM'12)*, Orlando, FL, 2012.

In this work, the system model was the same as in previous work. However, the proposed RRA scheme addressed a practical implementation issue of resource allocation in OFDMA networks: the inaccuracy of CSI available at the source. Instead, the source only knew the estimated channel status and distributions of related estimation errors. The estimated CSI was assumed to be known at the

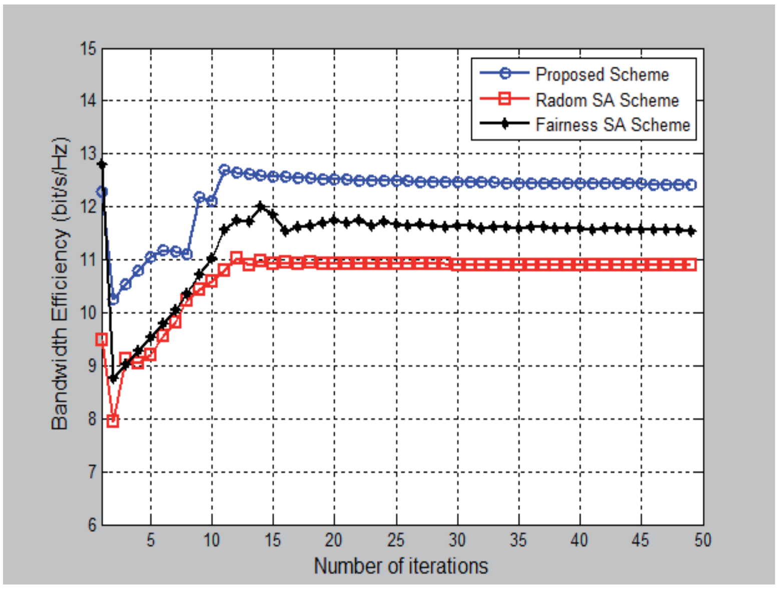


FIGURE 8 Convergence performance comparison, general problem

receiver by using the estimator and fed back from the receiver to the transmitter perfectly. We also assumed that channel estimation error pertains to the amplitude of the correct channel gain, while the phase of the channel gain can be perfectly obtained. As a result, information about the channel gain with an estimation error was available to both the transmitter and the receiver. The BS acted as a central controller to carry out all operations related to resource allocation based on the imperfect CSI.

It was known that the actual capacity is hard to obtain when only imperfect CSI is available. Thus, we used conditional expectation of achievable throughput instead. The estimation error also had impact on the conditional expectation of achievable throughput which was shown in the equations in [PII]. By using mathematical tools in [100] and [99], the closed-form solutions for relay selection, subcarrier and power allocations were obtained.

One example is shown in Fig. 9 where different values of CSI error variance are considered. We can see that when the estimation error is relatively small, the power allocation in the presence of imperfect CSI is very close to that of perfect CSI is assumed at the BS. The system bandwidth efficiency performance is shown in Fig. 10 by comparing the proposed scheme with "Fairness SA" proposed in [48]. The "Waterfilling" scheme in Fig. 10 denotes the traditional waterfilling power allocation scheme combing with the proposed relay selection and subcarrier allocation schemes. It is shown that by designing RRA scheme with imperfect CSI for different hops, it is possible to reach a noticeable gain in the cell-edge throughput.

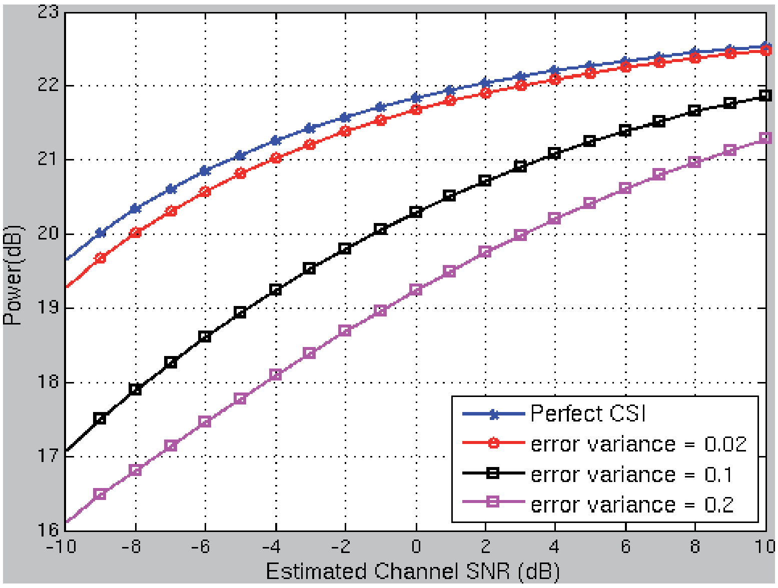


FIGURE 9 Impact of imperfect CSI on power allocation

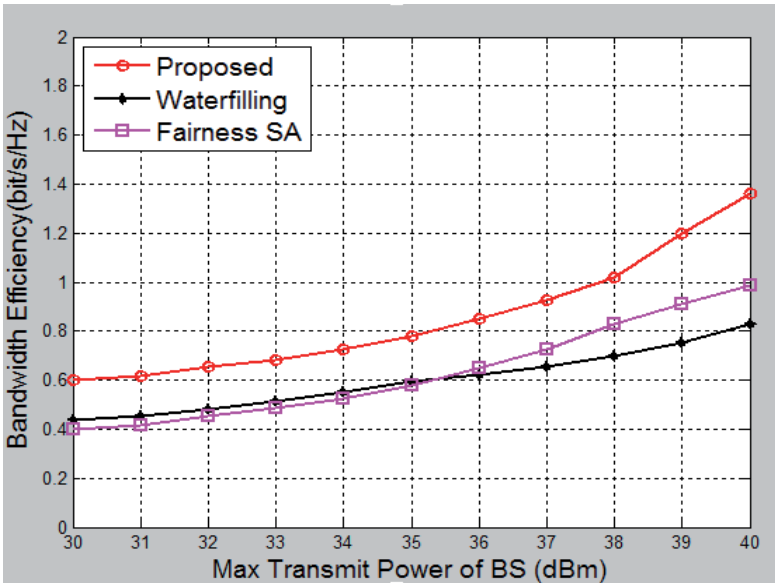


FIGURE 10 Impact of BS maximum transmit power on system bandwidth efficiency, when imperfect CSI is available

4.1.3 RRA for Asymmetric OFDMA Cooperative Wireless Networks

Reference papers:

– [PV] Z. Chang and T. Ristaniemi, "Asymmetric Resource Allocation for OFDMA Networks with Collaborative Relays," *Proc. of 10th IEEE Consumer Commu-*

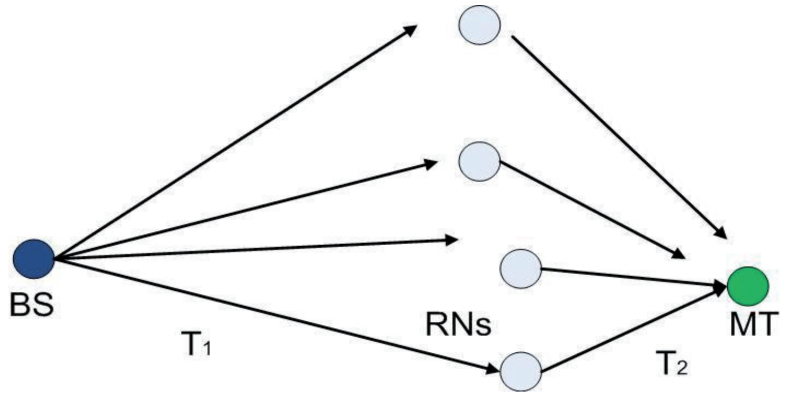


FIGURE 11 Considered OFDMA relay networks with link asymmetry

nication and Networking Conference(CCNC'13), Las Vegas, NV, Jan. 2013.
- [PVII] Z. Chang and T. Ristaniemi, "Asymmetric Radio Resource Allocation Scheme for OFDMA Wireless Networks with Collaborative Relays," *Springer/ACM Wireless Networks*, Vol. 19, No. 5, pp. 619-627, 2013.

In this work, unlike in the previous ones, we released the symmetry of two hops and assumed the network to be asymmetric. The example of asymmetric relay network is shown in Fig. 11, where the transmission time durations for the first hop and second hop are assumed to be T_1 and T_2, respectively. Since we considered our system as a two-hop time-division duplex downlink relay system, link asymmetry consideration results in a different form of system throughput. In particular, we considered optimization of the set of cooperative relays and link asymmetries together with subcarrier and power allocation. We derived theoretical expressions for the solutions and illustrated them through simulations.

An example of system performance can be found in Fig. 12, where the throughput performance is presented. The "ARA" scheme was presented in [52]. It is shown that by designing asymmetric time slots for different hops, it is possible to reach a noticeable gain in the cell-edge throughput. Our proposed scheme also has the superior performance over other schemes.

4.1.4 RRA for Asymmetric OFDMA Cooperative Wireless Networks with Imperfect CSI

Reference papers:

- [PIX] Z. Chang, T. Ristaniemi and Z. Niu, "Asymmetric Resource Allocation for Collaborative Relay OFDMA Networks with Imperfect CSI" *Proc. of 2nd IEEE/CIC International Conference on Communications in China (ICCC'13)* , Xi'an, China, 2013.
- [PXII] Z. Chang, T. Ristaniemi and Z. Niu, "Asymmetric Relay Selection and Resource Allocation for OFDMA multi-Relay Networks with Imperfect CSI," *submitted to IEEE/CIC China Communications*, 2013

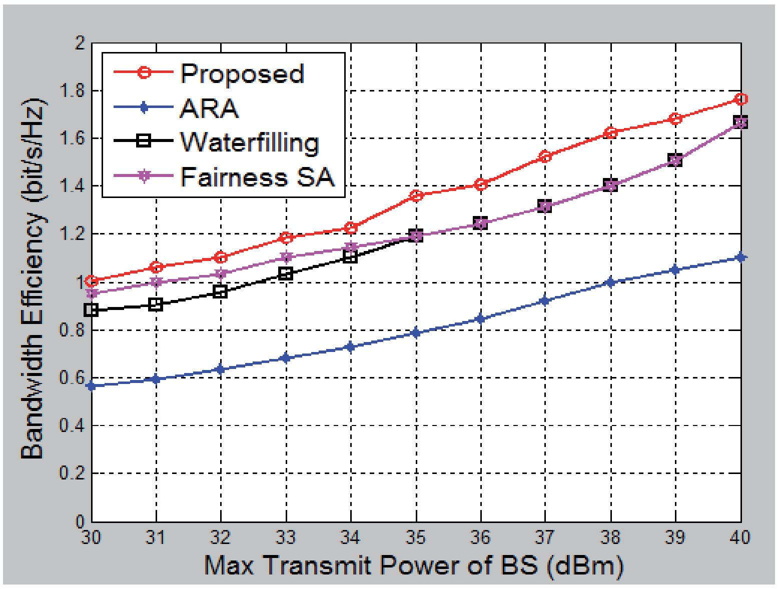


FIGURE 12 Impact of maximum transmit power $P_{s,max}$ on the system bandwidth efficiency, when link asymmetry is assumed

In these works, we considered the RRA problem for asymmetric OFDMA cooperative wireless networks with imperfect CSI, which is a rather practical case for the future networks. Following mathematical derivation process through mathematical tools in [97]–[99], we obtained the solutions for relay selection, subcarrier and power allocation for the considered system.

One example of impact of CSI error variance to the system spectral efficiency is depicted in Fig. 13. We cannotice that the accuracy of the estimator can lead to up to 20% difference on the spectral efficiency when the estimated channel SNR is 20 dB. Fig. 14 demonstrates the impact of maximum transmit power of BS on the system spectral efficiency. "ES" stands for the exhaustive search of relay and subcarrier assignments, which presents the optimal performance. The "Proposed ARRA" denotes the proposed asymmetric RRA scheme in these works and the "Proposed RRA" is the scheme presented in [PII]. The other schemes are the ones used also in Sections 4.1.2 and 4.1.3. Fig 15 presents the impact of the distance between BS and RN on the system bandwidth efficiency when compared with various schemes. The results manifest that by designing a proper asymmetric resource allocation scheme with imperfect CSI for different hops, it is possible to achieve a noticeable gain in the cell-edge throughput.

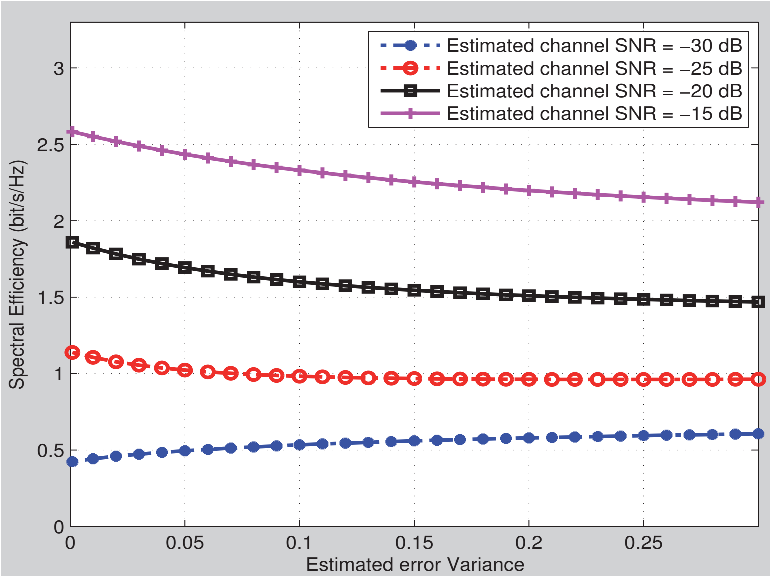


FIGURE 13 One example of impact of estimated error on the system bandwidth Efficiency, when link asymmetry and imperfect CSI are considered

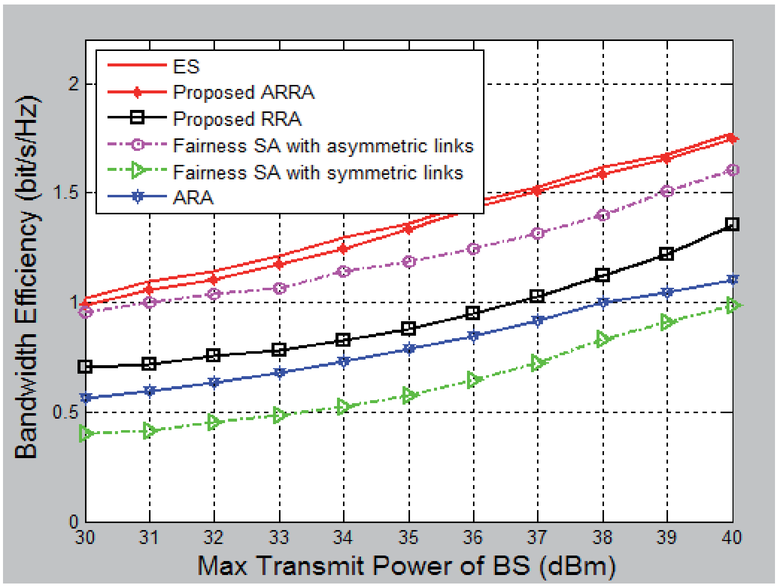


FIGURE 14 The impact of BS maximum transmit power on the system bandwidth efficiency, with link asymmetry and imperfect CSI

4.2 Energy Efficiency Enhancement through Mobile Cloud

4.2.1 Energy Efficient Collaborative Mobile Cloud Platform

Reference papers:

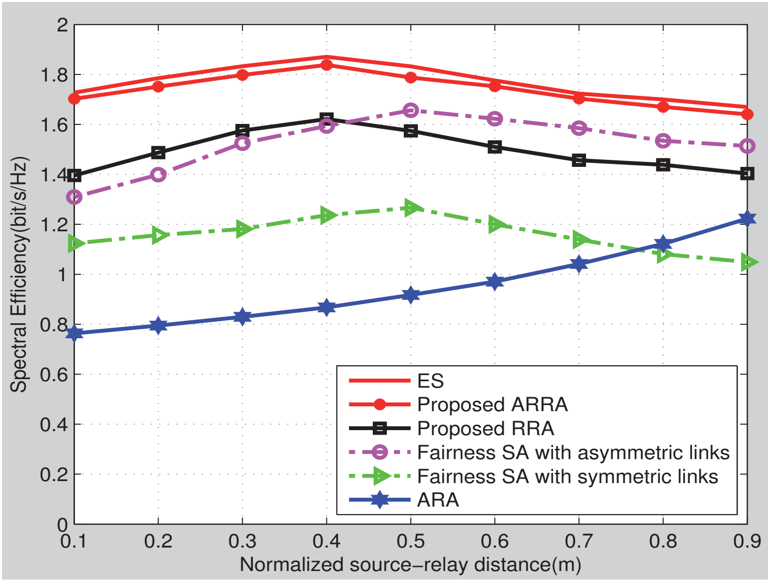


FIGURE 15 The impact of the distance between BS and RN on the system bandwidth efficiency, with link asymmetry and imperfect CSI

– [PIII] Z. Chang and T. Ristaniemi, "Reducing Energy Consumption via Cooperative OFDMA Mobile Cluster," *Proc. of 17th IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD'12)*, Barcelona, Spain, 2012.
– [PIV] Z. Chang and T. Ristaniemi, "Energy Efficiency of Collaborative OFDMA Mobile Cluster," *Proc. of 10th IEEE Consumer Communication and Networking Conference(CCNC'13)*, Las Vegas, NV, 2013.

In [PIII], we briefly presented the concept of Collaborative Mobile Cloud Platform. As shown in Fig. 16, a CMC is formed by a cluster of resource-constrained users that are interested in downloading the same content from BS. Borrowing the concept of mobile relays, all users inside CMC carry out receiving and decoding cooperatively and distributively [16] [17], and then exchange the received data with others through device-to-device (D2D) links. By exploiting the benefits of CMC, we are able to obtain the reduction in receiver energy consumption. Such model can potentially offer several advantages over traditional BS-to-MT (or Point-to-Point, P2P) networks, including reduction of energy and resource consumption per node. It was shown in [PIV], in a detailed manner, that the proposed CMC model can significantly reduce the energy consumption of mobile users.

In Fig. 17, energy saving by using CMC is illustrated. The energy saving ratio is obtained through comparing with the traditional P2P networks. Unicast is used here as the transmission strategy within CMC. ρ is defined as the data rate ratio between unicast within CMC and traditional P2P, i.e., $\rho = R_{CMC}/R_{P2P}$. From Fig. 17, one can see that as the number of MTs increases, the energy sav-

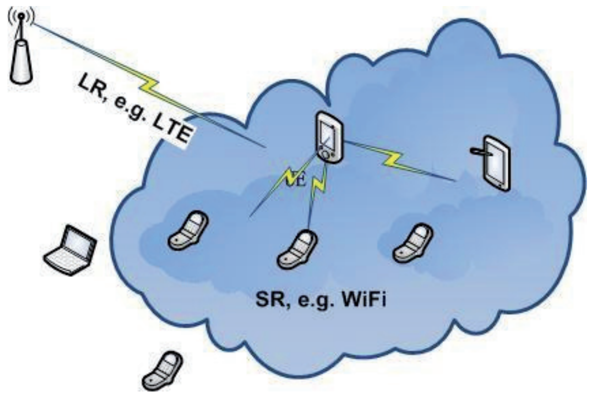


FIGURE 16 Collaborative Mobile Cloud model

ing gain obtained by using CMC arises as well. In general, CMC shows a great potential for reducing the energy consumption of MT during receiving process.

4.2.2 Energy Efficiency Investigation for Collaborative Mobile Cloud

Reference papers:

- [PVI] Z. Chang and T. Ristaniemi, "Efficient Use of Multicast and Unicast in Collaborative OFDMA Mobile Cluster," *Proc. of 77th IEEE Vehicular Technology Conference(VTC'13-spring)*, Dresden, Germany, 2013.
- [PXI] Z. Chang and T. Ristaniemi, "Collaborative Mobile Clusters: An Energy-Efficient Emerging Paradigm," *in book "Broadband Wireless Access Networks for 4G: Theory, Application, and Experimentation"*, IGI Global, in press.

To extend the research on CMC, energy efficiency analysis of using multicast as the transmission strategy within CMC was presented in [PVI] [PXI]. Compared with use unicast transmission inside CMC in [PIV], it was shown and observed that by using multicast transmission, energy efficiency performance of CMC was greatly improved.

For example, in Fig. 18, the energy saving is compared between multicast and unicast is shown. In general, we can conclude that the performance of multicast is generally better than that of unicast when the same scenario is assumed.

4.2.3 Energy Efficiency Optimization for Collaborative Mobile Cloud

Reference papers:

- [PVIII] Z. Chang and T. Ristaniemi, "Energy Efficiency of Unicast Support Multicast with QoS Guarantee," *Proc. of 2nd IEEE/CIC International Conference on Communications in China (ICCC'13)*, Xi'an, China, 2013.
- [PX] Z. Chang and T. Ristaniemi, " Power Efficient Multicast Transmission Framework with QoS Awareness," *Proc. of 2013 International Conference on*

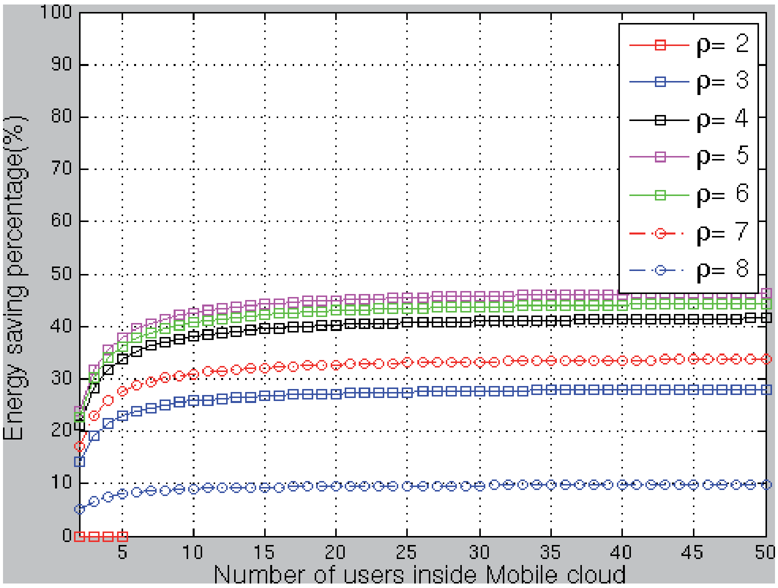


FIGURE 17 Energy saving of CMC using unicast

Wireless Communications and Signal Processing (WCSP'13), Hangzhou, China, 2013.

It is known that although the multicast scheme is an efficient scheme for delivering data, energy consumption can seriously increase if there is a user with a much worse channel condition than those of others. Thus, we presented a different and novel Unicast Supported Multicast (USM) scheme in [PVIII] to optimize the energy performance of multicast in CMC. The USM scheme can invoke unicast as an additional support to multicast to improve energy-efficiency performance while meeting the system QoS requirement. The essence of the USM scheme is to allocate unicast channel to the specified MTs that cannot obtain satisfied data rate as others when a fixed transmit power for multicast is used. The energy saving performance is shown in Fig 19 where the channel quality indicator is used for present the channel quality difference between the worst channel user and other users. One can observe that with USM, we can obtain range extension for CMC with the same energy saving percentage. In other words, CMC is able to host MTs that are further away from others without loss of energy saving gain. With same channel quality, the USM can save more energy (e.g. 20% as shown in the figure) than multicast. Therefore, the energy efficiency of USM over multicast for CMC can be easily found.

The proposed scheme in [PX] also tried to improve the energy efficiency performance of multicast when serving users with bad channel conditions. The objective of [PX] was to propose an energy efficient framework called Multicast Support Multicast (MSM) and examined its energy saving performance. The proposed MSM can dynamically use an extra channel as an additional support for traditional multicast transmission, by which power consumption of transmitter

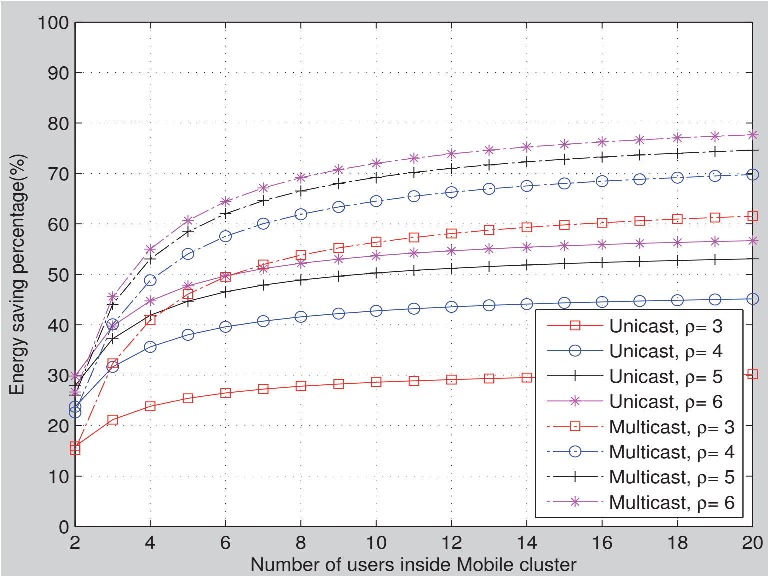


FIGURE 18 Energy saving of CMC using multicast and unicast

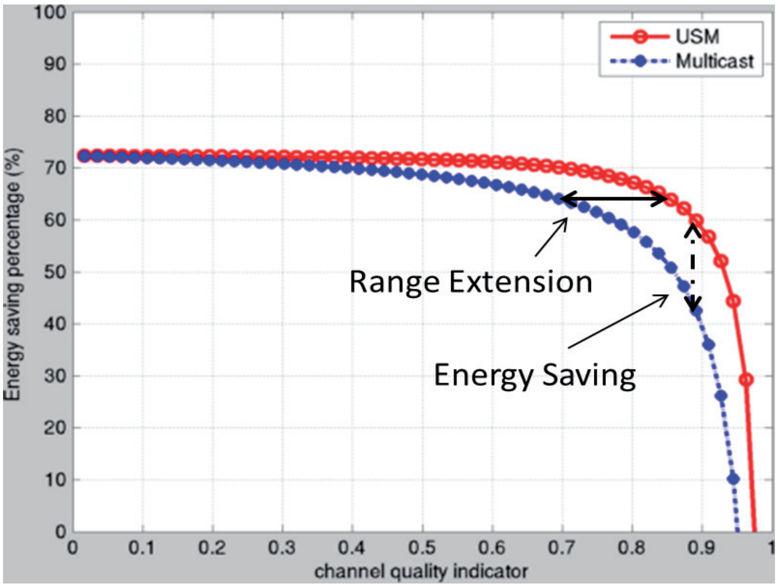


FIGURE 19 Energy saving of CMC using USM

can be reduced. Since the optimal solution of the proposed scheme incurred a high computational cost, suboptimal algorithm was also presented. It is shown in Fig. 20 using our proposed schemes that significant power saving can be achieved especially when QoS for multicast users is high. It can be observed that suboptimal algorithm can obtain almost the same performance as the optimal one.

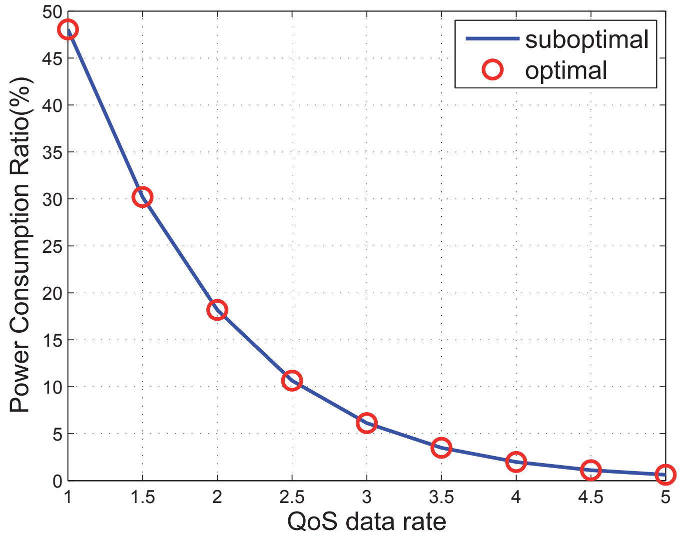


FIGURE 20 Energy saving of CMC using MSM

4.3 Summary

In this chapter, we briefly introduced the research contributions and results related to the publications. System models as well as proposed schemes were overviewed to make the refereed articles easier to understand.

5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusion

Focusing on enhancements in spectrum efficiency and energy efficiency, this thesis discussed various novel schemes in the context of OFDMA collaborative networks. In particular, different radio resource allocation schemes were developed to obtain improvements in spectrum efficiency. Moreover, with the help of the concept of mobile relay, we presented an improvement in energy efficiency through collaborative mobile cloud.

The overall conclusion is that spectrum efficiency can be enhanced by proper relay selection and by the design of subcarrier and power allocation schemes. Also, energy savings can be significantly improved by using CMC for a group of users who require the same content from BS. The specific outcomes that resulted from the related articles and were presented in this thesis are:

- For OFDMA multi-relay networks, a RRA algorithm including relay selection, subcarrier and power allocation was proposed to improve the spectrum efficiency.
- With the assumption of two-hop asymmetry, joint relay selection and resource allocation scheme was presented.
- With the practical consideration of imperfect CSI available at BS, RRA was proposed for both symmetric and asymmetric OFDMA multi-relay networks to improve the system performance.
- The energy efficiency of CMC was examined in terms of using unicast and multicast as its transmission strategies.
- To improve the energy efficiency performance of CMC, various schemes were proposed to overcome the inherent drawback of multicast.

5.2 Future Work

In this thesis, one aspect of focus was the RRA design for fixed-relay based OFDMA networks and the other one was the presentation of appropriate techniques that can significantly reduce users' energy consumption while maintaining acceptable performance for them. Future work can be done to extend this work in the following aspects:

– RRA design for heterogenous QoS service categories can be considered.
– As the use of mobile relays becomes the trend in wireless communications, proper design of RRA for CMC will be emphasized.
– the study of trade-off in spectrum and energy efficiency is important.
– Investigation on how to create the CMC will be an essential part of future research.

In particular, as energy saving and environmental protection are becoming a global issue and an inevitable trend, the research focus will shift to design that is oriented towards energy efficiency, towards green communications, as it is called. Therefore, energy efficiency design will be one of the main goals of the future research.

YHTEENVETO (FINNISH SUMMARY)

OFDMA-teknologia sekä kehittyneet toistinratkaisut nähdään yhdeksi varteenotettavaksi vaihtoehdoksi tulevaisuuden langattomissa järjestelmissä. Tässä väitöskirjassa keskitytään spektritehokkuuden ja energiatehokkuuden parantamiseen langattomissa OFDMA-verkoissa, joissa toistimet toimivat keskenään yhteistyössä. Aluksi työssä ehdotetaan ja analysoidaan radioresurssien allokointimenetelmiä, joiden tavoitteena on maksimoida tiedonsiirtokapasiteetti valitsemalla tietty osajoukko toistimia aktiivisiksi sekä allokoida näille toistimille käytettävät kantoaallot ja lähetystehot. Ehdotetut menetelmät ottavat huomioon erityisesti kanavaestimaatin epätäydellisyyden sekä toistinten ylä- ja alalinkkien epäsymmetrisyyden. Työn toinen keskeinen teema on mobiilipäätelaitteiden muodostaman yhteistyöverkoston, nk. mobiilipilven, analysointi energiatehokkuuden parantamiseksi. Mobiilipilvessä kukin päätelaite vastaanottaa ja purkaa ryhmälle tarkoitetusta viestistä vain osan ja jakaa sen ryhmän toisille päätelaitteille jonkin lyhyenkantaman radioteknologioiden (esim. wifi) avulla. Työssä ehdotetaan erilaisia tapoja viestien edelleenlähettämiseen mobiilipilven päätelaitteiden kesken ja analysoidaan niistä saatavia energiatehokkuushyötyjä.

REFERENCES

[1] E. Dahlman, S. Parkvall, J. Sköld and P. Beming , *3G Evolution HSPA and LTE for Mobile Broadband*. Elsevier, San Diego, CA, 2007.

[2] ITU-R, *Requirements related to technical performance for IMT-advanced radio interface(s)*, 2008.

[3] S. Sadr, A. Anpalagan and K. Raahemifar, "Radio Resource Allocation Algorithms for the Downlink of Multiuser OFDM Communication Systems," *IEEE Communication Surveys & Tutorials*, Vol. 11, No. 3, pp.92-106, 2009.

[4] *Wireless LAN Medium Access Control and Physical Layer Specifications: High-speed Physical Layer in the 5 GHz Band*, IEEE 802.11 standard, Sep. 1999.

[5] *3rd Generation Partnership Project Specifications Home Pages.* [Online]. available: http://www.3gpp.org/specs/specs.htm

[6] *IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface*, IEEE std. 802.16-2011, Jun.1998

[7] K. Johansson, A. Furuskar, P. Karlsson, and J. Zander, "Relation between base station characteristics and cost structure in cellular systems," *in Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Barcelona, Spain, Sep. 2004.

[8] N. Esseling, B. Walke, and R. Pabst, "Fixed relays for next generation wireless systems," *Emerging Location Aware Broadband Wireless Ad Hoc Networks*, R. Ganesh, S. L. Kota, K. Pahlavan, and R. Agusti, Eds. Springer US, 2005.

[9] C. Wijting, K. Doppler, K. KallioJarvi, T. Svensson, M. Sternad, G. Auer, N. Johansson, J. Nystrom, M. Olsson, A. Osseiran, M. Dottling, J. Luo, T. Lestable, and S. Pfletschinger, "Key technologies for IMT-advanced mobile communication systems," *IEEE Transactions on Wireless Communications*, Vol. 16, No. 3, pp. 76-85, Jun. 2009.

[10] R. Pabst, B. Walke, D. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. Falconer, and G. Fettweis, "Relay-based deployment concepts for wireless and mobile broadband radio," *IEEE Communications Magazine*, Vol. 42, No. 9, pp. 80-89, 2004.

[11] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Transactions on Information Theory,* Vol. 50, pp. 3062-3080, December 2004.

[12] Chia-Hao Yu, Klaus Doppler, Cassio Ribeiro, and Olav Tirkkonen, "Resource Sharing Optimization for Device-to-Device Communication Underlaying Cellular Networks," *IEEE Transactions on Wireless Communications*, Vol. 10, No. 8, pp. 2752-2763, August 2011.

[13] Y. Chen, S. Zhang, and S. Xu, "Fundamental Trade-offs on Green Wireless Networks," *IEEE Communications Magazine*, Vol 49 , No. 6, pp. 30-37, June 2011.

[14] J. Lee, Y.-M. Lim, K. Kim, S.-G. Choi and J.-K. Choi, "Energy Efficient Cooperative Multicast Scheme Based on Selective Relay," *IEEE Communications Letters*, Vol. 16, No. 3, pp. 386-388, March 2012.

[15] S. Haloka, T. Chen, J. lehtomaki and T. Koskela, "Device-to-Device(D2D) Communication in Cellular Network- Performance Analysis of Optimal and Practical Communication Mode Selection," *in Proc. of IEEE Wireless Communications and Networking Conference*, Sydney, Australia, April 2010.

[16] M. Hoyhtya, M. Palola, M. Matinmikko, and M. Katz, "Cognitive engine: design aspects for mobile clouds, " *in Proc. of International Conference on Cognitive Radio and Advanced Spectrum Management*, Barcelona, Spain, 26-29 October, 2011.

[17] M. V. Pederson and F. H. P. Fitzek, "Mobile Clouds: The New Content Sharing Platform," *Proceeding of IEEE*, Vol. 100, pp. 1400-1403, 2012.

[18] H. Yin and S. Alamouti. "OFDMA: A Broadband Wireless Access Technology," *in Proc. of IEEE Sarnoff Symposium*, Princeton, NJ, 2006.

[19] H. Schulze and C. Lueders, Theory and Applications of OFDM and CDMA Wideband Wireless Communications. John Wiley, 2005

[20] Renesas, [Online], available: http://www.renesas.com/media/edge_ol/technology/03/img_ 01.jpg

[21] H. Liu and G. Li, OFDM-Based Broadband Wireless Networks: Design and Optimization. Hobken, New Jersey: Wiley-Interscience, 2005.

[22] X. J. Li, B. C. Seet and P. H. J. Chong, "Multihop Cellular Networks: Technology and Economics," *Computer Networks*, Vol. 5, No. 9, 1825-1837, 2008.

[23] K. J. Ray Liu, A. K.Sadek, W. Su and A. Kwasinski. Cooperative communications and networking. Cambridge: Cambridge University Press, 2009, pp. 122-126.

[24] L. Long; E. Hossain, "Multihop Cellular Networks: Potential Gains, Research Challenges, and a Resource Allocation Framework," *IEEE Communications Magazine*, Vol. 45, No. 9, pp. 66-73, Sep. 2007.

[25] J. Sydir, "IEEE 802.16j-06/015: Harmonized Contribution on 802.16j (Mobile Multihop Relay) Usage Models," Sep. 2006.

[26] X. Lin, N. B. Shroff and R. Srikant, "A Tutorial on Cross-layer Optimization in Wireless Networks," *IEEE Journal on Selected Areas of Communications*, Vol. 24, No.8, 1452-1463, August 2006.

[27] Z. Q. Luo and W. Yu, "An introduction to convex optimization for communications and signal processing," *IEEE Journal on Selected Areas of Communications*, Vol. 24, No.8, pp. 1426-1438, August 2006.

[28] G. Song and Y. Li, "Cross-layer Optimization for OFDM Wireless Networks-Part I: Theoretical Framework," *IEEE Transaction on Wireless Communications*, Vol. 4, No. 2, pp. 614-624, March 2005.

[29] G. Song and Y. G. Li, "Cross-layer optimization for OFDM wireless network part II: Algorithm development," *IEEE Transactions on Wireless Commuications*., Vol. 4, No. 3, pp. 625-634, March 2005.

[30] C. Mohanram and S. Bhashyam, "A sub-optimal joint subcarrier and power allocation algorithm for multiuser OFDM," *IEEE Communications Letters*, Vol. 9, No. 8, pp. 685-687, August 2005.

[31] K. Seong, M. Mohseni and M. Cioffi, "Optimal resource allocation for OFDMA downlink systems," *in Proc. of IEEE International Symposium on Information Theory*, Seattle, USA, 2006.

[32] Z. Mao and X. Wang, "Efficient optimal and suboptimal radio resource allocation in OFDMA system", *IEEE Transactions on Wireless Communications*, Vol. 7, No. 2, pp. 440-445, February 2008.

[33] G. Kulkarni, S. Adlakha and M. Srivastava, "Subcarrier allocation and bit loading algorithms for OFDMA-based wireless networks," *IEEE Transactions on Mobile Computing* Vol. 4, No. 6 pp. 652-662, 2005.

[34] S. Pietrzyk and G.J.M Janssen, "Multiuser subcarrier allocation for QoS provision in the OFDMA systems," *in Proc. of IEEE Vehicular Technology Conference*, Bacelona, Spain, 2002.

[35] T.-D. Nguyen ; Y. Han, "A Proportional Fairness Algorithm with QoS Provision in Downlink OFDMA Systems." *IEEE Communications Letters*, Vol. 10, No. 11, pp. 760-762 , November 2006.

[36] A. Abrardo, A. Alessio, P. Detti, M. Moretti, "Centralized Radio Resource Allocation for OFDMA Cellular Systems," *in Proc. of IEEE International Conference on Communications*, Glasgow, UK, June 2007.

[37] S. Pietrzyk and G. J. M Janssen, "Radio resource allocation for cellular networks based on OFDMA with QoS guarantees," *in Proc. of IEEE Global Telecommunications Conference*, Dallas, TX, December 2004.

[38] L. Wan, W. Ma and Z. Guo, "A Cross-layer Packet Scheduling and Subchannel Allocation Scheme in 802.16e OFDMA System," *in Proc. of IEEE Wireless Communications and Networking Conference*, Hong Kong, China, March 2007.

[39] T.C-Y. Ng and W. Yu, "Joint Optimization of Relay Strategies and Resource Allocation in Cooperative Cellular Networks," *IEEE Journal on Selective Area in Communications*, Vol.25, No.2, pp.328-339, February 2007.

[40] M. Kaneko and P. Popovski, "Radio Resource Allocation Algorithm for Relay-Aided Cellular OFDMA System," *in Proc. of IEEE International Conference on Communications*, Glasgow, UK, June 2007.

[41] D. Zhang, Y. Wang and J. Lu, "QoS aware relay selection and subcarrier allocation in cooperative OFDMA systems," *IEEE Communications Letters*, Vol. 14 No. 4 pp. 294-296 , Apr. 2010.

[42] G. Li and H. Liu, "Resource Allocation for OFDMA Relay Networks With Fairness Constraints," *IEEE Journal on Selected Areas in Communications*, Vol. 24, No.11, pp.2061-2069, Nov. 2006.

[43] T. Wang and L. Vandendorpe, "WSR Maximized Resource Allocation in Multiple DF Relays Aided OFDMA Downlink Transmission," , *IEEE Transactions on Signal Processing*, Vol. 59, No. 8, pp. 3964-3976, Aug. 2011.

[44] H. Li, H. Yu, H. Luo, J. Guo and C. Li, "Dynamic Subchannel and Power Allocation in OFDMA-Based DF Cooperative Relay Networks," *in Proc. of IEEE Global Telecommunications Conference*, New Orleans, LA, 2008.

[45] C. Jeong and H-M. Kim, "Radio Resource Allocation in OFDMA Multihop Cellular Cooperative Networks," *in Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Cannes, France, Sep. 2008.

[46] S.-K. Kim, X. Wang, and M. Madihian, "Optimal Resource Allocation in Multi-hop OFDMA Wireless Networks with Cooperative Relay," *IEEE Transaction on Wireless Communications*, Vol. 7, No. 5, pp.1833-1838, May 2008.

[47] W. Dang, M. Tao, H. Mu and J. Huang, "Subcarrier-Pair Based Resource Allocation for Cooperative Multi-Relay OFDM systems," *IEEE Transactions on Wireless Communications*, Vol. 9, No. 5, pp. 1640-1649, May 2010.

[48] M. Tang, X. Wang, Y. Wang and J. Liao, "Dynamic Resource Allocation with Threshold in OFDMA-based Relay Networks," *in Proc. of IEEE Vehicular Technology Conference*, Taipei, Taiwan, May 2010.

[49] H. Jeong and J. H. Lee, "Adaptive Relay Selection for Regenerative OFDMA Relay Networks with Fairness Constraints," *in Proc. of IEEE Vehicular Technology Conference*, Calgary, Canada, September 2008.

[50] Y. Pan, A. Nix, and M. Beach, "Distributed Resource Allocation for OFDMA-Based Relay Networks," *IEEE Transactions on Vehicular Technology*, Vol.60, No. 3, pp. 919-931, March 2011.

[51] C. Bae, and D.-H. Cho, "Fairness-Aware Adaptive Resource Allocation Scheme in Multihop OFDMA Systems," *IEEE Communications Letters*, Vol. 11, No. 2, pp. 134-136, February 2007.

[52] N. Zhou, X. Zhu and Y. Huang, "Optimal Asymmetric Resource Allocation and Analysis for OFDM-Based Multidestination Relay Systems in the Downlink," *IEEE Transaction on Vehicular Technology*, Vol. 60, No. 3, pp. 1307-1312, March 2011.

[53] L. Dong, X. Zhu and Y. Huang, "Optimal Asymmetric Resource Allocation for Multi-Relay Based LTE-Advanced Systems," *in Proc. of IEEE Global Telecommunications Conference*, Houston, TX, December 2012.

[54] C. Hausl, O. Iscan and F. Rossetto, "Resource Allocation for Asymmetric Multi-Way Relay Communication over Orthogonal Channels," *EURASIP Journal on Wireless Communications and Networking*, 2012:20 doi:10.1186/1687-1499-2012-20.

[55] M. Medard, "The Effect Upon Channel Capacity in Wireless Communications of Perfect and Impefect Knowladge of the Channel," *IEEE Transaction on Information Theory*, Vol. 46, No. 3, pp. 933-946, May 2000.

[56] F. Brah, L. Vandendorpe, and J. Louveaux, "Constrained resource allocation in OFDMA downlink systems with partial CSIT," *in Proc. of IEEE International Conference on Communications*, Beijing, China, May 2008.

[57] I.C. Wong and B.L. Evans, "Optimal resource allocation in the OFDMA downlink with imperfect channel knowledge," IEEE Transactions on Communications, Vol. 57, No. 1, pp.232-241, Jan. 2009.

[58] R. Aggarwal, M. Assaad, C. E. Koksal, and P. Schniter, "Optimal Resource Allocation in OFDMA Downlink Systems with Imperfect CSI," *in Proc. of IEEE Workshop on Signal Processing Advances in Wireless Communications*, San Francisco, CA, June 2011.

[59] Y. Yao and G. B. Giannakis, "Rate-Maximizing Power Allocation in OFDM Based on Partial Channel Knowledge," *IEEE Transactions on Wireless Communications*, Vol. 4, No. 3, 1073-1083, Mar. 2005.

[60] G. Atia and A. F. Molisch, "Cooperative Relaying with Imperfect Channel State Information," *in Proc. of IEEE Global Telecommunications Conference*, New Orleans, LA, Dec. 2008.

[61] M. K. Awad, V. Mahinthan, M. Mehrjoo, X. Shen and J. W. Mark, "A Dual-Decomposition-Based Resource Allocation OFDMA Networks with Impefect CSI," *IEEE Transactions on Vehicular Technology*, Vol.59, No.5, pp. 2394-2403, May 2010.

[62] M. Ahmad and M. Assaad, "Joint Resource Optimization and Relay Selection for cooperative Cellular Networks with Imperfect Channel Knowledge," *in Proc. of IEEE Workshop on Signal Processing Advances in Wireless Communications*, Marrakech, Morocco, June 2010.

[63] J-H. Wang, Y-B. Lin, and Y. T. Su, "Resource Allocation and Relay Selection for cooperative OFDMA Networks with Imperfect Channel Information," *in Proc. of IEEE Workshop on Signal Processing Advances in Wireless Communications*, San Francisco, CA, June 2011.

[64] F-S. Chu, K-C. Chen, and G. Fettweis, "Green Resource Allocation to Minimize Receiving Energy in OFDMA Cellular Systems," *IEEE Communications Letters*, Vol.16, No. 30, pp.372-375, March 2012.

[65] D. Datla, X. Chen, T. R. Newman, J. H. Reed, and T. Bose, "Power Efficiency in Wireless Network Distributed Computing," *IEEE Vehicular Technology Conference*, Bacelona, Spain, April 2009.

[66] D. Datla, H. I. Volos, S. M. Hasan, J. H. Reed and T. Bose, "Wireless Distributed Computing in cognitive radio networks," *Ad Hoc Networks*, 10(2012), pp. 845-857, April 2012.

[67] C. Bontu and E.Illidge, "DRX mechanism for power saving in LTE," *IEEE Communication Magazine*, Vol. 47, No. 6, pp. 48-55, June 2009.

[68] A. Radwan and J. Rodriguez, "Energy Saving in Multi-standard Mobile Terminals through Short-range Cooperation," *EURASIP Journal on Wireless Communications and Networking*, 2012:159, doi:10.1186/1687-1499-2012-159.

[69] Lina Al-Kanj and Z. Dawy, "Optimized Energy-Aware Multicasting over Wireless Cellular Networks with Multihop Cooperation," *in Proc. of IEEE Internation Conference on Communications*, Ottawa, Canada, June 2012.

[70] Lina Al-Kanj, Michael Abdallah and Z. Dawy,, "On Optimal Mobile Terminal Grouping in Energy Aware Cooperative Content Distribution Networks," *in Proc. of IEEE Wireless Communications and Networking Conference*, Paris, France, 2012.

[71] E. Yaacoub, L. Al-Kanj, Z. Dawy, S. Sharafeddine, F. Filali and A. Abu-Dayya, "A Utility Minimization Approach for Energy-aware Cooperative Content Distribution with Fairness Constraints,"*Transactions on Emerging Telecommunications Technologies*, 23:378-392, 2012;

[72] Lina Al-Kanj, Z. Dawy, W. Saad and E. Kutanoglu, "Energy-Aware Cooperative Content Distribution over Wireless Networks: Optimized and Distributed Approaches", *IEEE Transaction on Vehicular Technology*, to appear, 2013.

[73] Lina Al-Kanj, Z. Dawy and Elias Yaacoub, "Energy-Aware Cooperative Content Distribution over Wireless Networks: Design Alternatives and Implementation Aspects," *IEEE Communications Surveys & Tutorials*, to appear, 2013.

[74] Janus Heide, F. H. P. Fitzek, M. V.Pedersen and Marcos Katz, "Green Mobile Clouds: Network Coding and User Cooperation for Improved Energy Efficiency," *in Proc. of IEEE International Conference on Cloud Networking*, Paris, France, 2012.

[75] F. H. P. Fitzik, J. Heide, M. V. Pedersen and M. Katz, "Implementation of Network Coding for Social Mobile Clouds", *IEEE Signal Processing Magazine*, Vol. 30, No. 1, pp. 159-164, Jan. 2013

[76] P. Karunakaran, Hamidreza Bagheri, Marcos Katz, "Energy Efficient Multicast Data Delivery using Cooperative Mobile Clouds," *in Proc. of European Wireless*, Poznan, Poland, April 2012.

[77] J. B. Seo, T. Kwon, V. C. M. Leung, "Social Groupcasting Algorithm for Wireless Cellular Multicast Service," *IEEE Communications Letters*, Vol. 17, No. 1, pp. 47-50, January 2013.

[78] J.-W. Yoo and K.H. Park, "A Cooperative Clustering Protocol for Energy Saving of Mobile Devices With Wlan and Bluetooth Interfaces," *IEEE Transactions on Mobile Computing*, Vol. 10, No. 5, pp. 491-504, April 2011.

[79] E.M. Lo, J. Zhang and Q. Zhang, "Cooperative content distribution in multirate wireless networks," *in Proc. of IEEE Global Communications Conference*, Honolulu, HI, December 2009.

[80] M. F. Leung and S.H. Chan, "Broadcast-based Peer-to-Peer Collaborative Video Streaming Among Mobiles," *IEEE Transactions on Broadcasting*, Vol. 53, No. 1, pp. 50-61, March 2007.

[81] C. Diot, W. Dabbous, and J. Crowcroft, "Multipoint Communication: A Survey of Protocols, Functions, and Mechanisms," *IEEE Journal on Selected Areas in Communications*, Vol. 15, No. 3, pp. 277-290, April 1997.

[82] Q. Zhang and F. Fitzek, "Cooperative Retransmission for reliable wireless Multicast Service," *Coginitive Wireless Networks*, Cambrige University Press, pp. 485–498, 2007.

[83] Tao Han and Nirwan Ansari, "Energy Efficient Wireless Multicasting," *IEEE Communications Letters*, Vol. 15, No. 6, pp. 620-622, June 2011.

[84] N. Guan, Y. Zhou, H. Liu, L. Tian and J. Shi "An Energy Efficient Cooperative Multicast Scheme with Power Control," *in Proc. of IEEE Global Communication Conference*, Houston, TX, 2011.

[85] H. Won, H. Cai, D. Y. Eun, K. Guo, A. Netravali, I. Rhee, and K. Sabnani, "Multicast Scheduling in Cellular Data Networks," *IEEE Transactions on Wireless Communications*, Vol. 8, No. 9, pp. 4540-4549, Sep. 2009.

[86] J. Liu, W. Chen, Y. Zhang and Z. Cao, "A Utility Maximization Framework for Fair and Efficient Multicasting in Multicarrier Wireless Cellular Networks," *IEEE/ACM Transaction on Networking*, Vol. 21, No. 1, pp.110-120, Feb. 2013

[87] S. Y. Baek, Y.-J. Hong, D. K. Sung, "Adaptive Transmission Scheme for Mixed Multicast and unicast Traffic in Cellular Systems," *IEEE Transaction on Vehicular Technology*, Vol. 58, No. 6, pp. 2899-2907, July 2009.

[88] S. J. Lee, Y. Tcha, S.-Y. Seo, and S.-C. Lee "Efficient Use of Multicast and Unicast Channels for Multicast Services Transmission," *IEEE Transaction on Communications*, Vol. 59, No. 5, pp. 1264-1267, May 2011.

[89] R. O. Afolabi, A. Dadlani, K. Kim, "Multicast Scheduling and Resource Allocation Algorithms for OFDMA-Based Systems: A Survey," *IEEE Communications Surveys & Tutorials*, Vol. 15, No. 1, pp. 240-254, 2013.

[90] H.V. Zhao and W. Su, "Cooperative Wireless Multicast: Performance Analysis and Power/Location Optimization," *IEEE Transactions Wireless Communications*, Vol. 9, No. 6, pp. 2088-2100, Jun. 2010.

[91] J. Kim, T. Kwon, D. Cho, "Resource Allocation Scheme for Minimizing Power Consumption in OFDM Multicast Systems," *IEEE Communications Letters*, Vol. 11, No. 6, pp. 486-488, June 2007.

[92] H. Kwon and B.-G. Lee, "Cooperative Power Allocation For Broadcast/Multicast Services in Cellular OFDM System," *IEEE Transactions on Communications*, Vol. 57, No. 10, pp. 3092-3102, Oct. 2009.

[93] H. Deng, X. Tao, J. Lu, "Qos-Aware Resource Allocation for Mixed Multicast and Unicast Traffic in OFDMA Networks," *EURASIP Journal on Wireless Communications and Networking*, 2012:195, doi:10.1186/1687-1499-2012-195.

[94] D. Kim, Takeo Fujii, K. Lee, "A resource allocation algorithm for OFDM-based cellular system serving unicast and multicast services," *EURASIP Journal on Wireless Communications and Networking*, 2013:41 doi:10.1186/1687-1499-2013-41, Feb. 2013.

[95] John G. Proakis and M. Salehi, *Digital Communications*,5th edition, McGraw-Hill Science, 2007.

[96] D. Tse and P. Viswanath. *Fundamentals of Wireless Communications*, Cambridge UK: Cambridge University Press, 2005.

[97] S. Boyd, and L. Vandenberghe, *Convex Optimization* , Cambridge UK: Cambridge University Press, 2004.

[98] S. Boyd, and A. Mutapcic, *Lecture Notes for EE364b* , Standford University , 2006–2007.

[99] I. Gradshtein, I. Ryzhik, D. Zwillinger and A. Jeffrey, *Table of Intergrals, Serie, and Products*. New York: Academic, 2007.

[100] A. Lauschke, *Convergence Acceleration with Canonical Contractions of Continued Fractions: Incomplete Gamma Function* [Online]. available: http://216.80.120.13:8080/webMathematica/LC/gamma.jsp

ORIGINAL PAPERS

PI

RADIO RESOURCE ALLOCATION FOR RELAY-ASSISTED OFDMA WIRELESS NETWORKS

by

Zheng Chang and Tapani Ristaniemi 2011

Proc. of 3rd IEEE International Workshop on Cross-layer Design (IWCLD)

Radio Resource Allocation for Cooperative Relay-assisted OFDMA Wireless Networks

Zheng Chang and Tapani Ristaniemi
Department of Mathematical Information Technology
University of Jyväskylä
P.O.Box 35, Jyväskylä, FIN-40014 Finland
Email: zheng.chang@jyu.fi, tapani.ristaniemi@jyu.fi

***Abstract*—This paper considers a wireless cooperative OFDMA network with a base station and some relays. The relays adopt the decode-and-forward protocol and can assist the transmission from base station to mobile stations. The objective is to maximize the system transmission rate of downlink under various constraints. The optimal solution for such radio resource allocation problem has high computational complexity. Thus we divide our solution scheme into three steps. The first step is to select the relay that can achieve best transmission rate. Then the subcarrier is distributed to the selected relays. For each hop, the same subcarrier should not be used. Next, power allocation is adopted under the individual power constraints for each node. Simulation studies are conducted to evaluate the system performance. It confirms that our proposed algorithm can enhance the performance compared with newly proposed resource allocation schemes.**

***Index Terms*—OFDMA, relay selection, subcarrier allocation, power allocation and cooperative communications**

I. Introduction

The demand for higher data speed transmission increases rapidly due to the fast grow wireless market. Orthogonal Frequency-Division Multiple Access(OFDMA) is an effective technique for combating channel noise, multipath effects and enabling high data rate transmissions over fading channels. In addition, OFDMA is able to provide good bandwidth scalability as the number of subcarriers can be flexibly configured. Therefore, OFDMA have been widely applied to many upcoming wireless communication systems, such as Long Term Evaluation(LTE)/LTE-Advanced (LTE-A) [1].

Meanwhile, cooperative relay transmission has many attractive features for high throughput, low power consumption and wide cell coverage. Cooperative communication has the trend to replace the traditional point-to-multipoint cellular networks in LTE-A. Therefore, the incorporation of OFDMA and cooperative relay can provide a promising structure that offers more reliable service for the next generation wireless networks.

Since future wireless communication system is expected to offer high data transmission under limitation of existing radio resource, such as power consumption and frequency bandwidth, the radio resource allocation (RRA) issue is crucial for guaranteeing the whole system performance under various resource constraints. The system capacity and throughput can be enhanced by proper RRA schemes, such as routing, subcarrier and power allocation. This work addresses an optimal cross-layer resource allocation problem for OFDMA network with cooperative relays.

The related works have been widely done in several different areas. In [2], a very general model for resource allocation in multicarrier system is proposed. A cross-layer optimization algorithm for resource allocation in conventional OFDMA network has been presented in [3] without considering relaying. An iterative algorithm is proposed to solve the subcarrier assignment together with relay selection in [4]. Then, the power allocation problem can be solved by another iterative method. Similar to [4], the optimization scheme is divided into two subproblems without considering relay selection in [5]. Then two iterative methods are used with high computational complexity to solve these two subproblems respectively. Authors in [6] introduces closed-form solution for radio resource allocation for multihop cooperative relay network. However, the per-tone power constraint is used which is not practical. Scheme used in [7] considers fairness constraints when selecting relays. In [8], a threshold method is used to solve two subproblems, subcarrier allocation and power allocation. Although the performance is improved comparing to some other algorithms, the total power constraint is considered, which is not a realistic case since each node has its own power limitation.

As we can see, the optimization for radio resource allocation is still an open research area since most algorithms are based on iterative schemes and only can obtain closed-form solutions. The proposed algorithms have their major drawbacks which need to be improved. In this paper, we investigate a new resource allocation scheme which can effectively solve the problems of joint relay, subcarrier and power allocation. In this work, relays are deployed for extending the cell coverage. We propose a relay selection scheme, where one set of relays that can obtain the best link data rate is selected. The system data rate depends on the the number of relays. The sets of orthogonal frequency subcarriers are then assigned to the selected relays in each hop to achieve better channel gain. Power is allocated to the source and relays under per-node constraints, which is more realistic than the scheme in [8] where only whole system power summit is considered.

The rest of this paper is organized as follows. Section II describes our relay-assisted OFDMA cooperative wireless networks and formulates the problem. We consider downlink only in this work, but it can be extended further to the uplink case. In Section III, the proposed resource allocation scheme is presented. We demonstrate the benefits of our proposed algorithm in section IV and finally conclude the paper in Section V.

II. Problem Formulation

We consider several relay nodes between source(i.e. Base Station) and destination node(i.e. Mobile Station). We assume this is a two-hop transmission. The first hop is so called broadcast phase, where BS broadcasts information to a cluster of decode-and-forward (DF) relays. In the second hop, the relays cooperate to transmit the information data to the MS, so that, i.e., spatial diversity gain can be achieved (relays are assumed to be far away enough to each other). Assuming there are total Z relays in the networks, and the selected relay cluster $\mathcal{K}$ contains K potential half-duplex relays. The presented relay-assist cooperative OFDMA system is as shown in Fig. 2 in Section IV.

Let $x^{(i)}(t)$ be the transmit data from source node (transmitter) over subcarrier i at time t. Suppose $h^{(i)}(t)$ is the wireless channel gain from transmitter to destination node (receiver) and we assume the channel is static in a time slot t. We also assume that the channel state information (CSI) is fully known at the transmitter. For example, $h^{(i)}_{s,k}(t)$ means the channel gain from BS s to relay node k over OFDM subcarrier i at time t. L is the path loss factor. We denote the transmit power assigned to subcarrier i at time t for transmitting data as $P^{(i)}(t)$. In this work, we do not consider the direct link from BS to MS. This assumption is practical in the case that relays are used for cell extension. Therefore, the received signal at the relay can be expressed as:

$$y^{(i)}_k(t) = \sqrt{L_{s,k}} h^{(i)}_{s,k}(t) \sqrt{P^{(i)}_{s,k}(t)} x^{(i)}(t) + n^{(i)}_{s,k}(t) \qquad (1)$$

In the second hop, the received signal at the receiver is

$$y^{(j)}_d(t) = \sqrt{L_{k,d}} h^{(j)}_{k,d}(t) \sqrt{P^{(j)}_{k,d}(t)} x^{(j)}(t) + n^{(j)}_{k,d}(t) \qquad (2)$$

where $n^{(i)}_{s,k}(t)$ and $n^{(j)}_{k,d}(t)$ are independent and identically distributed Gaussian noise, with variance σ^2_k and $\sigma^2_d, i, j \subseteq \mathcal{M}$, where $\mathcal{M}$ is the subcarrier set of the whole bandwidth. One relay k occupies subcarrier i in the first hop and j in the second hop.

Therefore, for the first hop, the data rate of the broadcast phase is determined by the minimum rate of each link between BS and relays. For simplicity, we assume the same time slot so we do not use t here. The achieved data rate of the first hop is as follows:

$$R^{\mathcal{I}}_{s,\mathcal{K}} = \min_{k \in \mathcal{K}} \{ log(1 + \frac{L_{s,k} P^{(i)}_{s,k} G^{(i)}_{s,k}}{\sigma^2_k}) \} \qquad (3)$$

where $G_{s,k} = |h_{s,k}|^2$. $\mathcal{I}$ is the subcarrier set which contains the subcarriers that are allocated to the selected relays at the first hop. It is assumed that the relays are perfectly synchronized and transmitted at the same time. Therefore, the second hop can be viewed as virtual MISO link. The link rate can be expressed as :

$$R^{(\mathcal{J})}_{\mathcal{K},d} = log(1 + \frac{\sum_{k=1}^{K} L_{k,d} P^{(j)}_{k,d} G^{(j)}_{k,d}}{\sigma^2_d}) \qquad (4)$$

$\mathcal{J}$ is the subcarrier set which contains the subcarriers that are allocated to the selected relays at the second hop. The total achieved rate of relay k is [8]:

$$R_k = \frac{1}{2} min\{ R^{(\mathcal{I})}_{s,\mathcal{K}}, R^{(\mathcal{J})}_{\mathcal{K},d} \} \qquad (5)$$

We define ω is the indicator whether certain subcarrier is assigned to relay k, and ρ_k indicates that whether relay k is chosen for subcarrier allocation. For example:

$$\omega^{(i)}_{s,k} = \begin{cases} 1 & \text{if } i \text{ is assigned to } k \text{ at the first stage} \\ 0 & \text{otherwise} \end{cases}$$

$$\rho_k = \begin{cases} 1 & \text{if } k \text{ is chosen for relaying} \\ 0 & \text{otherwise} \end{cases}$$

Then, we can formulate our problem as:

$$\max \sum_{i=1}^{M} \sum_{j=1}^{M} \sum_{k=1}^{K} \rho_k \omega^{(i)}_{s,k} \omega^{(j)}_{k,d} R_k \qquad (6)$$

subject to

$$\begin{aligned} &\sum_{i=1}^{M} \sum_{k=1}^{K} \omega^{(i)}_{s,k} P^{(i)}_{s,k} \leq P_{s,max} \\ &\sum_{j=1}^{M} \omega^{(j)}_{k,d} P^{(j)}_{k,d} \leq P_{k,max} \\ &\sum_{k=1}^{K} \omega^{(i)}_{s,k} = 1, \omega^{(i)}_{s,k} \in \{0,1\} \\ &\sum_{k=1}^{K} \omega^{(j)}_{k,d} = 1, \omega^{(j)}_{k,d} \in \{0,1\} \\ &\sum_{k=1}^{K} \rho_k = 1, \rho_k \in \{0,1\} \end{aligned} \qquad (7)$$

where $P_{s,max}$ is the maximum transmit power of BS and $P_{k,max}$ is the maximum power of relay.

III. Resource Allocation Scheme

In this section, we introduce adaptive algorithms to solve existing problems which are described in the last section. The

Lagrangian of problem (6) is [10]:

$$\mathcal{L}(\mathbf{p},\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda}) = \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{k=1}^{K}\rho_k\omega_{s,k}^{(i)}\omega_{k,d}^{(j)}R_k \\ -\lambda_s(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega_{s,k}^{(i)}P_{s,k}^{(i)} - P_{s,max}) \\ -\sum_{k=1}^{K}\lambda_{k,d}(\sum_{j=1}^{M}\omega_{k,d}^{(j)}P_{k,d}^{(j)} - P_{k,max}) \tag{8}$$

where $\mathbf{p} = \{P_{s,k}^{(i)}, P_{k,d}^{(j)}\}$ is for the set of power allocation, $\boldsymbol{\omega} = \{\omega_{s,k}^{(i)}, \omega_{k,d}^{(j)}\}$ denotes the subcarrier allocation, and $\boldsymbol{\rho} = \{\rho_k\}$ is the relay assignment. Then the Lagrange dual function can be written as [10]:

$$g(\lambda) = \max\mathcal{L}(\mathbf{p},\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda}) \tag{9}$$

We assume the number of subcarrier is sufficiently large, so the duality gap between primal problem and dual function can be negligible [11]. Therefore, we can solve the problem (6) by minimizing the dual function:

$$\min g(\lambda) \tag{10}$$

A. Evaluating Dual Variable

Since a dual function is always convex [10], then for example, two methods can be used to minimize $g(\lambda)$ with guaranteed convergence, which are subgradient method and ellipsoid method [11].

We use the subgradient method in [12] to derive the subgradient $g(\lambda)$ with the optimal power allocation p^* that will be presented in the following subsection.

The subgradient method is as follows:

1) Initialize λ^0

2) Obtain $g(\lambda^a)$ at the ath iteration.

3) Update a subgradient for λ^{a+1}, by $\lambda^{a+1} = \lambda^a + \upsilon^a \triangle\lambda$

4) Go to 2) until convergence. where $\triangle\lambda = (\triangle\lambda_s, \triangle\lambda_{1,d}, ...\triangle\lambda_{K,d})$, $\triangle\lambda_s$ and $\triangle\lambda_{k,d}$ can be expressed as:

$$\triangle\lambda_s = P_{s,max} - \sum_{m=1}^{M}\sum_{k=1}^{K}(P_{s,k}^{(i)})^* \tag{11}$$

and

$$\triangle\lambda_{k,d} = P_{k,max} - \sum_{j=1}^{M}(P_{k,d}^{(i)})^* \tag{12}$$

υ^a is the stepsize. Since (9) can be viewed as integer programming problem, whose optimal solution requires high computational cost. Therefore, we are aiming to solve the optimization problem by solving three subproblems, which are relay, subcarriers and power allocation.

B. Relay Selection

We consider relay selection in this work, unlike some traditional single relay selection algorithms in [9], as multiple-relays selection. The proposed algorithm is to select K relays to form a cluster that maximize the received Signal to Noise Ratio(SNR) for both hops. In other word, we want to maximize the achieved data rate in (5):

$$\max R_k \tag{13}$$

Since $R_k = \frac{1}{2}min\{R_{s,\mathcal{K}}^{(\mathcal{I})}, R_{\mathcal{K},d}^{(\mathcal{J})}\}$, the above problem can be formulated as finding a relay set $\mathcal{K}$ that maximizes the lower bound of (3) and (4), which can be expressed as:

$$\mathcal{K} = \{k^* | \underset{\text{k}}{\text{argmax}} \min\{R_{s,\mathcal{K}}^{(\mathcal{I})}, R_{\mathcal{K},d}^{(\mathcal{J})}\}\}; \tag{14}$$

where k^* means the optimal selection of relay k. Here, we assume that the power and subcarrier allocation are done, so only channel effect should be considered. From (4) we can see that the data rate will increase as long as more relays are chosen for transmission. However, meanwhile we also want to achieve the best result of (3). Therefore, (14) can be viewed as multi-objective optimization problem, which aims at obtaining the trade-off of the first term and second term of (14).

After the above analysis, we propose an iterative algorithm to solve the relay selection problem. The relay selection algorithm can be described as follow:

1)**Definition**

$\mathcal{Z}$: the set of all Z relays in the system;

$\mathcal{K}$: the set of selected relays;

$R_{k,1}$: the first hop data rate of relay k;

$R_{\mathcal{K}}$: the second hop data rate of relay set $\mathcal{K}$;

2)**Initialization**

$R_{k,1} = 0$ for $k = 1, ..., K$;

$R_{\mathcal{K}} = 0$ for $\forall k \in \mathcal{K}$;

3)**Iteration**

a) For $z = 1 : Z$,

b) find k satisfying $R_{k,1} \geq R_{z,1}, \forall\ z \in \mathcal{Z}$;

c)$\mathcal{Z} = \mathcal{Z} - \{k\}$, and $\mathcal{K} = \mathcal{K} + \{k\}$;

end for

d) Get $R_{\mathcal{K}}$;

e)$R_{s,r} = min\{R_{k,1}, \forall k \in \mathcal{K}\}$, if $R_{s,r} \leq R_{\mathcal{K}}$, the algorithm stops, otherwise goes to a).

where $R_{\mathcal{K}}$ can be obtained by (4) and $R_{k,1}$ is the normal value in (3) without choosing the minimum value.

C. Subcarrier Allocation

The goal of subcarrier allocation strategy is to assign a subcarrier to a given relay that can obtain best channel gain, which means to maximize $G_{s,k}^{(i)} = |h_{s,k}^{(i)}|^2$ and $G_{k,d}^{(j)} = |h_{k,d}^{(j)}|^2$,

Then the searching algorithm can be used as follows:

1)**Definition**

c_1: the set of subcarriers in the first hop;

c_2: the set of subcarriers in the second hop;

$s_k(i,j)$: relay k use subcarrier i in the first hop and j in the second hop;

S_k: the set of subcarriers assigned to relay k;

R_{min}: the minimum request data rate.

2)**Initialization**

$c_1 = \{1, ..., M\}$ and $c_2 = \{1, ...M\}$;
$R_{k,1} = 0$ for $k = 1, ..., N$,
$R_{\mathcal{K}} = 0$ for $\forall k \in \mathcal{K}$;
$S_k = \varnothing$;
3)**Iteration**
a) For $k = 1 : K$;
b)find $s_k(i,j)(i \neq j)$ satisfying $G(s,k)^{(i)} \geq G(s,k)^{(m)}; i, m \in c_1$ and $G(k,d)^{(j)} \geq G(k,d)^{(n)}, j, n \in c_2$;
c)$S_k = S_k \cup s_k(i,j)$;
d)$c_1 = c_1 - \{i\}$ and $c_2 = c_2 - \{j\}$;
end for
e) Get $R_{\mathcal{K}}$ and $R_{k,1}$;
f)$R_{s,r} = \frac{1}{2} min\{min\{R_{k,1}, \forall k \in \mathcal{K}\}, R_{\mathcal{K}}\}$, if $R_{s,r} \leq R_{min}$, the algorithm stops, otherwise goes to a).

D. Power Allocation

We could then analyze the optimal power allocation $\mathbf{p}^*$ for given subcarrier and relay assignment $\boldsymbol{\omega}^*, \boldsymbol{\rho}^*$. We assume subcarrier set $S_k(i,j)$ is assigned to relay k and recall the Lagrange dual function of (9). Then the optimal power allocation problem can be determined by solving problem (8) over variables $P_{(s,k)}^{(i)}$ and $P_{k,d}^{(j)}$

$$\mathbf{max_p} \mathcal{L}(\mathbf{p}, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}) \quad (15)$$

Applying Karush-Kuhn-Tucker (KKT) conditions [10], we obtain the optimal power allocation for the first hop:

$$(P_{s,k}^{(i)})^* = \{\frac{1}{\lambda_s} - \frac{\sigma_k^2}{G_{s,k}^{(i)} L_{s,k}}\}^+ \quad (16)$$

where $\{x\}^+ \triangleq max\{0, x\}$. Similarly, for the cooperation phase, the optimal relay power allocation is

$$(P_{k,d}^{(j)})^* = \{\frac{1}{\lambda_{k,d}} - \frac{\sigma_d^2}{G_{k,d}^{(j)} L_{k,d}} - \frac{\sum_{m=1,m\neq k}^{K} G_{m,d}^{(l)} P_{m,d}^{(l)}}{G_{k,d}^{(j)} L_{k,d}}\}^+ \quad (17)$$

In (16) and (17), the subcarriers i, j and l are assigned to certain relays, they are different for different relays.

E. Joint Relay, Subcarrier and Power Allocation

We have described the algorithms about relay selection, subcarrier and power allocation in the previous subsections. The flow chart of the whole algorithm is shown in Fig. 1. We can see these three steps are conducted alternatively until the convergence is reached. The computational complexity of relay selection and subcarrier allocation for an iteration is O(MK). Simulation results will be shown to demonstrate the system performance in the following section.

IV. Performance Evaluation

Performance of the proposed algorithm is presented in this section. It is assumed that five relays are located at the distance 2km-2.5km from BS, and MS is 3km away from BS. The relay node distribution is shown in Fig. 2 when four relays are selected for transmission. The signal fading follows Rayleigh distribution and we choose number of subcarriers M to be 64 thus all subcarriers can be regarded to experience flat fading. The noise variance of the two hops are set to be 1 for simplicity. The path loss factor varies according to the different distances from relays to BS and MS. The maximum transmit power of BS and relay are 30 dBm and 10 dBm respectively.

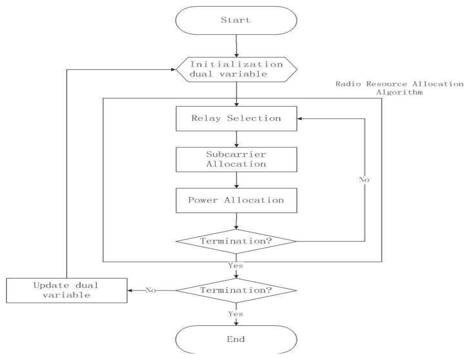


Figure 1. Algorithm flow chart

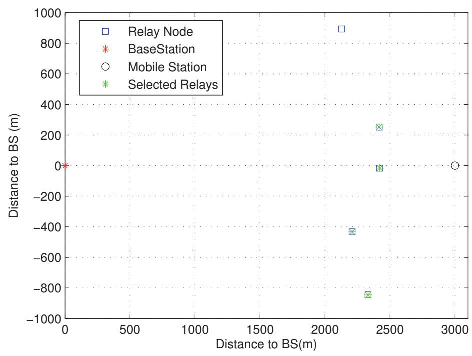


Figure 2. Relay node distribution and 4 relays are selected

In Fig. 3, we compare the performance of our proposed resource allocation algorithm with two other schemes by only changing the subcarrier allocation method. The first one is to randomly distribute subcarriers to selected relays and second one is to allocate subcarrier with lowest channel gain when fairness is taken into account. The results are based on 1000 realizations of relay and channel distribution. Analyzing the results in Fig. 3, we first find that the iterative process converge to the optimal solution for every considered subcarrier allocation scheme and our proposed algorithm has slightly faster speed. Another important observation is that the capacity of our proposed subcarrier allocation scheme is better than that of the other two methods.

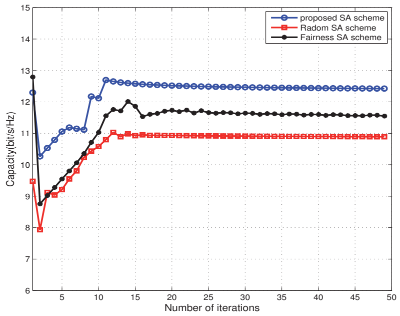


Figure 3. Performance of three subcarrier allocation schemes

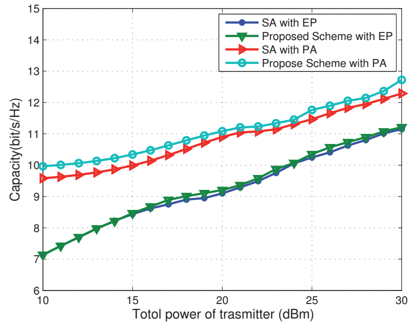


Figure 4. Total power vs. Capacity

In Fig. 4, we can obtain the performance of our proposed algorithm by comparing with other scheme, which chooses the relays that can offer minimum capacity and then allocate subcarrier to them, i.e. used in [8]. The threshold method proposed in [8] has some drawbacks, i.e., the total power constraint is considered, which is not a realistic and how to choose threshold is problematic. The relay selection scheme where the relay that has the minimum ratio of the actual capacity and the maximum obtainable capacity is selected may not ultimate the resource. Both equal power(EP) allocation and proposed power allocation methods are checked in Fig. 4. We can see from Fig. 4, when same relay and subcarrier allocation algorithm are used, our proposed PA scheme can significantly improve the system capacity compared with one of EP distribution. Meanwhile, we could find that when comparing with the scheme used in [7] and [8], the obtained capacity of the proposed schemes is better. However, the system performance of both schemes with EP distribution are almost the same. This is because power is equal distributed without considering channel status. Thus the channel effect is only taken into account when calculating (3) and (4), which can not lead to much difference for both scheme when only five relays are deployed.

V. Conclusion

Radio resource allocation can significantly increase the system performance by letting the transceiver adapt the transmission parameter to channel conditions. Cooperative relays scheme provides the potential to improve the coverage, throughput, and reliably of the overall system. In this paper, we propose a effective algorithm to solve the radio resource allocation problem in cooperative relay-assisted OFDMA networks. The optimization problem is divided into three subproblems including relay selection, subcarrier and power allocation with the objective of maximizing the transmission rate. At first relay and subcarrier are allocated with best channel gain respectively, which can provide better data rate. Then power allocation algorithm is proposed by solving KKT condition. Therefore, the closed-form solution can be achieved with low computational cost. Simulation results show that the achieved system performance of proposed schemes is better than that of other exiting schemes.

Acknowledgment

The authors would like to thank Jyväskylä Graduate School in Computing and Mathematical Sciences (COMAS) and Ulla Tuominen Foundation for supporting.

References

[1] *3rd Generation Partnership Project Specifications Home Pages.* [Online]. available: http://www.3gpp.org/specs/specs.htm

[2] L. Xiao, M. Johansson, and S. P. Boyd, "Simultaneous Routing and Resource Allocation Via Dual Decomposition," *IEEE Transaction on Communications*, Vol.52, No.7, pp.1136-1144, July 2004.

[3] G. Song and Y. Li, "Cross-layer Optimization for OFDM Wireless Networks-Part 1: Theoretical Framework," *IEEE Transaction on Wireless Communications*, Vol.4, No.2, pp.614-624, Mar. 2005.

[4] T.C-Y. Ng and W. Yu, "Joint Optimization of Relay Strategies and Resource Allocation in Cooperative Cellular Networks," *IEEE Journal on Selective Area in Communications*, Vol.25, No.2, pp.328-339 ,Feb. 2007.

[5] C. Jeong and H-M. Kim, "Radio Resource Allocation in OFDMA Multihop Cellular Cooperative Networks," *Proc. of IEEE PIMRC 2008*, Cannes, France, Sep. 2008.

[6] S-K. Kim, X. Wang, and M. Madihian, "Optimal Resource Allocation in Multi-hop OFDMA Wireless Networks with Cooperative Relay," *IEEE Transaction on Wireless Communications*, Vol.7, No.5, pp.1833-1838, May 2008.

[7] H. Jeong and J. H. Lee, "Adaptive Relay Selection for Regenerative OFDMA Relay Networks with Fairness Constraints," *Proc. of IEEE VTC 2008-fall*, Calgary, Canada, Sep. 2008.

[8] M. Tang, X. Wang, Y. Wang and J. Liao, "Dynamic Resource Allocation with Threshold in OFDMA-based Relay Networks," *Proc. of IEEE VTC 2010-Spring*, Taipei, Taiwan, May 2010.

[9] S. S. Ikki and M. H. Ahmed, "Performance Analysis of Adaptive Decode-and-Forward Cooperative Diversity Networks with Best-Relay Selection," *IEEE Transaction on Communications*, Vol.58, No.1, pp.68-72, Jan. 2010.

[10] S. Boyd, and L. Vandenberghe, *Convex Optimization* ,Cambridge UK: Cambridge University Press, 2004.

[11] W. Yu and R. Lui, "Dual Methods for Nonconvex Spectrum Optimization in Multicarrier System," *IEEE Transaction on Communications* , Vol.54, No.7, pp.1310-1322, Jul. 2006.

[12] W. Dang, M.Tao, H. Mu and J. Huang, "Subcarrier-Pair Based Resource Allocation for Cooperative Multi-Relay OFDM systems," *IEEE Transaction on Wireless Communications*, Vol.9, No.5, pp. 1640-1649, May 2010.

PII

RESOURCE ALLOCATION FOR COOPERATIVE RELAY-ASSISTED OFDMA NETWORKS WITH IMPERFECT CSI

by

Zheng Chang and Tapani Ristaniemi 2012

Proc. of 2012 IEEE Military Communication Conference (MILCOM'12)

Resource Allocation for Cooperative Relay-assisted OFDMA Networks with Imperfect CSI

Zheng Chang and Tapani Ristaniemi
Department of Mathematical Information Technology, University of Jyväskylä,
P.O.Box 35, FIN-40014 Jyväskylä, Finland
Email: {zheng.chang, tapani.ristaniemi}@jyu.fi

***Abstract*—This work addresses the radio resource allocation (RRA) problem for cooperative relay assisted OFDMA wireless networks. The relays adopt the decode-and-forward protocol and can cooperatively assist the transmission from source to destination. The RRA scheme addresses practical implementation issues of resource allocation in OFDMA networks: the inaccuracy of channel-state information (CSI) available to the source. Instead, the source only knows estimated channel status and distributions of related estimation errors. The objective is to maximize the system throughput of the source-to-destination link under various constraints. Since the optimization problem is known as NP-hard, we divide the original problem to three subproblems including relay selection, subcarrier and power allocations. We derive theoretical expressions for the solutions and illustrate them through simulations. Results validate clearly that our proposed RRA algorithm can enhance the performance of system with imperfect CSI compared to the other newly proposed resource allocation schemes.**

***Index Terms*—OFDMA, relay selection, subcarrier allocation, power allocation, imperfect CSI, cooperative communications.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is an effective technique that exploits the benefits of Orthogonal Frequency Division Multiplexing (OFDM) for combating against channel noise and multipath effects and finally enables high data rate transmissions over fading channels. Meanwhile, cooperative communication has emerged as one of the main trends to reach even better system performance in terms of throughput, energy efficiency or cell coverage. Therefore, the incorporation of OFDMA and cooperative relays is foreseen to result in a promising structure that offers a possibility to reach many desirable objectives for the future wireless networks. However, a combination of a conventional one-to-many (single hop) OFDMA system and a relay network calls for a careful design of the radio resource allocation (RRA) principles. This means a carefully design and coordination of the power and subcarrier allocation, selection of relay(s) across different hops and optimizing the resource between the hops.

The RRA algorithm plays an important role in the developments of both conventional and relay-aided OFDMA systems. The related works have been widely done in several different areas [1]-[6] when assuming perfect channel state information (CSI) is known to the source. A cross-layer optimization algorithm for resource allocation in conventional OFDMA network has been presented in [1] without considering relaying. An iterative algorithm is proposed to solve the subcarrier assignment together with relay selection in [2]. Then, the power allocation problem can be solved by another iterative method based on waterfilling algorithm. Authors in [3] introduces closed-form solution for radio resource allocation for multihop cooperative relay network. However, the per-tone power constraint is used which is not practical. Scheme used in [4] considers fairness constraints when selecting relays. In [5], a threshold method is used to solve two subproblems, subcarrier allocation and power allocation. Although the performance is improved comparing to some other algorithms, the total power constraint is considered, which is not a realistic case since each node has its own power limitation. The work in [6] also proposed a subcarrier and relay pairing algorithm to solve the existing RRA problem, which requires high complexity. [7]-[9] present the work about RRA with imperfect CSI. [7] consider the RRA algorithm for conventional OFDMA networks. [8] investigates the issue of joint RRA and relay selection with imperfect CSI. However, authors use mean rate to characterize the CSI uncertainty which results in different interpretations. Recent work about RRA for OFDMA relay networks with imperfect CSI is introduced in [9], where only one relay is selected for assisting the transmission.

As we can see, the existed algorithms have their major drawbacks which need to be improved. In this paper, we investigate a new resource allocation scheme for OFDMA cooperative network with imperfect CSI, which can effectively solve the problems of joint relay selection, subcarrier and power allocation and thus, enhance the system throughput when estimated error existed. In this work, relays are deployed for extending the cell coverage, so we do not consider direct link from source to destination. Conditional expected throughput is considered as our performance evaluation metric. We propose a relay selection and subcarrier allocation schemes, where one set of relays that can obtain the best link data rate is selected. Power is allocated to the source and relays under per-node constraints, which is more realistic than the scheme , e.g., in [5] where only sum of the whole system power is considered. To the best of our knowledge, such joint optimization for assumed two hop OFDMA network with imperfect CSI has not been studied in the literatures and is important for achieving the better overall system performance.

The rest of this paper is organized as follows. Section II describes our relay-assisted OFDMA cooperative wireless networks and formulates the problem. We consider downlink

978-1-4673-3/12/$31.00 ©2013 IEEE

only in this work, but it can be extended further to the uplink case. In Section III, the proposed resource allocation scheme is presented. We demonstrate the benefits of our proposed algorithm in section IV and finally conclude the paper in Section V.

II. System Model and Problem Formulation

A. System model and Assumptions

We consider our system as a two-hop downlink OFDMA relay network. The whole system consists of source(i.e. access point, AP), destination node(i.e. mobile terminal, MT) and several relays. The first hop is so called broadcast phase, where AP broadcasts information to a cluster of decode-and-forward (DF) relays. In the second hop, relays cooperate to transmit the information data to the MT, so that, e.g., spatial diversity gain can be achieved [1]. The estimated CSI is assumed to be known at MT through estimator and then feed back to the transmitter perfectly. We also assume that channel estimation error pertains to the amplitude of the correct channel gain, while the phase of the channel gain can be perfectly obtained. As a result, estimated channel gain with an estimation error is available to both the transmitter and the receiver. The AP acts as a central controller to carry out all resource allocation related operations based on the feedbacks from the MT.

In this work, we consider there are total Z relays in the networks, and the selected relay cluster $\mathcal{K}$ contains K potential half-duplex relays. The presented relay-assisted cooperative OFDMA network is as shown in Fig. 1 when $K = 3$.

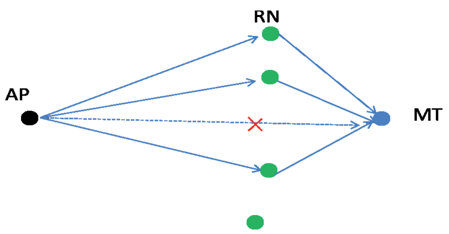


Figure 1. Wireless cooperative relay networks

B. Problem Formulation

Let x be the transmit data from transmitter to receiver and P is the transmit power gain. So regardless of the path loss, the received data after estimator at receiver is

$$y = h\sqrt{P}x + n, \tag{1}$$

and we have

$$h = \hat{h} + \tilde{h}, \tag{2}$$

where $\hat{h}$ is the estimated channel function and $\tilde{h}$ is the independent estimation error which can be modeled as zero mean Gaussian random variable with variance $\sigma^2_{\tilde{h}}$. Thus, the imperfect CSI h is assumed to follow $\mathcal{CN}(\hat{h}, \sigma^2_{\tilde{h}})$. n is the additive noise which can be also modeled as complex Gaussian random variable with variance σ^2_n. Therefore, the square of imperfect CSI h follows a noncentral chi-square probability density function (PDF) given by

$$f(G|\hat{G}) = \frac{1}{\sigma^2_{\tilde{h}}} e^{-\frac{\hat{G}+G}{\sigma^2_{\tilde{h}}}} \mathcal{J}_0\Big(2\sqrt{\frac{\hat{G}G}{\sigma^4_{\tilde{h}}}}\Big) \tag{3}$$

where we denote $G = |h|^2, \hat{G} = |\hat{h}|^2$. $\mathcal{J}_0$ is the 0th order modified Bessel Function of the first kind.

In our proposed system model, we suppose h^i is the channel transfer function from transmitter to receiver and we assume the channel is static in a time slot. For example, $\hat{h}^i_{s,k}$ means the channel estimate from AP s to relay node (RN) k over OFDM subcarrier i and $\hat{h}^j_{k,d}$ means the channel estimate from RN k to destination d over OFDM subcarrier j. We have channel gain of the first hop $\hat{G}^i_{s,k} = |\hat{h}^i_{s,k}|^2$ and second hop $\hat{G}^j_{k,d} = |\hat{h}^j_{k,d}|^2$. L is the path loss factor and the noise variance for two hops are σ^2_k and σ^2_d. The variance of related estimation error for two hops are $\sigma^2_{\tilde{h},k}$ and $\sigma^2_{\tilde{h},d}$ and we assume $\sigma^2_{\tilde{h}} = \sigma^2_{\tilde{h},k} = \sigma^2_{\tilde{h},d}$. We denote the transmit power assigned to subcarrier i for transmitting data as P^i. In this work, we do not consider the direct link from AP to MT due to distance or obstacles. This assumption is practical for the case that RNs are deployed for cell extension. One RN k occupies subcarrier i in the first hop and j in the second hop. Therefore, at first hop, the data rate of the broadcast phase is determined by the minimum rate of each link between AP and selected RNs. Since transmitter only knows the CSI conditioned on the feedback of receiver, we could obtain the expected achievable throughput of the first hop as follows:

$$R^{\mathcal{I}}_{s,\mathcal{K}} = \min_{k\in\mathcal{K}} \Big\{ \mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}} \Big[log(1 + \sum_{i=1}^{M} \omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k}) \Big] \Big\}, \tag{4}$$

where $\gamma^i_{s,k} = \frac{L_{s,k}G^i_{s,k}}{\sigma^2_k}$ and $\hat{\gamma}^i_{s,k} = \frac{L_{s,k}\hat{G}^i_{s,k}}{\sigma^2_k}$. The notation $\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}$ means expectation with respect to $\gamma^i_{s,k}$ conditioned on $\hat{\gamma}^i_{s,k}$. $\mathcal{M}$ is the subcarrier set of the system that contains M subcarriers. $\mathcal{I}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at first hop. We further refer the link throughput and its expectation interchangeably for simplicity. ρ_k indicates that whether RN k is chosen for subcarrier allocation, so we obtain

$$\rho_k = \begin{cases} 1 & \text{if } k \text{ is chosen for relaying,} \\ 0 & \text{otherwise.} \end{cases}$$

We also define ω is the indicator whether certain subcarrier is assigned to RN k, for example,

$$\omega^i_{s,k} = \begin{cases} 1 & \text{if } i \text{ is assigned to } k \text{ at first hop,} \\ 0 & \text{otherwise.} \end{cases}$$

[1]relays are assumed to be far enough to each other

For the second hop, it is assumed that the RNs are perfectly synchronized and transmitted at the same time. Therefore, the second hop can be viewed as a virtual MISO link. The link throughput can be expressed as

$$R^{\mathcal{J}}_{\mathcal{K},d} = \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}\Big[log\big(1+\sum_{j=1}^{M}\sum_{k=1}^{K}\omega^j_{k,d}\rho_k P^j_{k,d}\gamma^j_{k,d}\big)\Big], \quad (5)$$

where $\gamma^j_{k,d} = \frac{L_{k,d}G^j_{k,d}}{\sigma^2_d}$ and $\hat{\gamma}^j_{k,d} = \frac{L_{k,d}\hat{G}^j_{k,d}}{\sigma^2_d}$. $\mathcal{J}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at the second hop. For indicator $\omega^j_{k,d}$, we also have

$$\omega^j_{k,d} = \begin{cases} 1 & \text{if } j \text{ is assigned to } k \text{ at second hop,} \\ 0 & \text{otherwise.} \end{cases}$$

Therefore, the total achieved end-to-end throughput of source s to destination d through RN set $\mathcal{K}$ is [5]

$$R_{sd} = min \ \frac{1}{2}\Big\{R^{\mathcal{I}}_{s,\mathcal{K}}, R^{\mathcal{J}}_{\mathcal{K},d}\Big\}. \quad (6)$$

To proceed, we can formulate our problem as

$$max \ R_{sd}, \quad (7)$$

subject to

$$\begin{aligned} &\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k} \le P_{s,max} \\ &\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d} \le P_{k,max} \\ &\sum_{k=1}^{K}\omega^i_{s,k} = 1, \omega^i_{s,k} \in \{0,1\} \\ &\sum_{k=1}^{K}\omega^j_{k,d} = 1, \omega^j_{k,d} \in \{0,1\} \end{aligned} \quad (8)$$

where $P_{s,max}$ is the maximum transmit power of AP and $P_{k,max}$ is the maximum power of RN. Therefore, our goal is to find the optimal solutions of relay, subcarrier and power allocations which satisfy the problem of (7).

It can be deduced that (6) can achieve maximum only when $R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}$ [10]. Thus, (7) can be modified to

$$\arg\max \ \Big(R^{\mathcal{I}}_{s,\mathcal{K}} + R^{\mathcal{J}}_{\mathcal{K},d}\Big), \quad (9)$$

subject to conditions in (8) and

$$R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}. \quad (10)$$

III. Resource Allocation Scheme

In this section, we introduce the adaptive algorithms to solve existing problem (9). Although the resource allocation problem is combinatorial in nature with nonconvex structure, as the number of subcarriers becomes sufficient large, the dual gap tends to be zero [12]. Therefore, it can be solved in dual domain. The Lagrangian of (9) is [11]

$$\begin{aligned} \mathcal{L}(\mathbf{P},\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}) = &\Big(R^{\mathcal{I}}_{s,\mathcal{K}} + R^{\mathcal{J}}_{\mathcal{K},d}\Big) \\ &-\lambda_s\Big(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k} - P_{s,max}\Big) \\ &-\sum_{k=1}^{K}\lambda_{k,d}\Big(\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d} - P_{k,max}\Big) \\ &-\mu(R^{\mathcal{I}}_{s,\mathcal{K}} - R^{\mathcal{J}}_{\mathcal{K},d}), \end{aligned} \quad (11)$$

where $\mathbf{P} = \{P^i_{s,k}, P^j_{k,d}\}$ is the set of power allocation, $\boldsymbol{\omega} = \{\omega^i_{s,k}, \omega^j_{k,d}\}$ denotes the subcarrier allocation, and $\boldsymbol{\rho} = \{\rho_k\}$ is the relay assignment. The $\boldsymbol{\lambda} = \{\lambda_s, \lambda_{k,d}\}$ and $\boldsymbol{\mu} = \{\mu\}$ are Lagrange multipliers. Then it can be derived that $\lambda_s, \lambda_{k,d} \ge 0$ and $\mu \in (-1, 1)$. The Lagrange dual function can be written as

$$g(\boldsymbol{\lambda},\boldsymbol{\mu}) = \max \mathcal{L}(\mathbf{P},\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}). \quad (12)$$

Since we assume the number of subcarrier is sufficient large, so that the duality gap between primal problem and dual function can be negligible [12]. Consequently, we can solve the problem (7) by minimizing the dual function

$$\min \ g(\boldsymbol{\lambda},\boldsymbol{\mu}). \quad (13)$$

A. Evaluating Dual Variable

As a dual function is always convex [11], for example, two methods can be used to minimize $g(\boldsymbol{\lambda},\boldsymbol{\mu})$ with guaranteed convergence, which are subgradient method and ellipsoid method [12].

We follow the subgradient method in [12] to derive the subgradient $g(\boldsymbol{\lambda},\boldsymbol{\mu})$ with the optimal power allocation p^* that will be presented in the following subsection.

Algorithm 1 Evaluating Dual Variable

```
1: Initialize λ^0 and μ^0
2: while (!Convergance) do
3:    Obtain g(λ^a, μ^a) at the ath iteration;
4:    Update a subgradient for λ^{a+1} and μ^{a+1}, by λ^{a+1} =
      λ^a + υ^a △λ and μ^{a+1} = μ^a + υ^a △μ;
5: end while
```

where $\triangle\boldsymbol{\lambda} = \{\triangle\lambda_s, \triangle\lambda_{1,d}, ...\triangle\lambda_{K,d}\}$, $\triangle\lambda_s$, $\triangle\lambda_{k,d}$ and $\triangle\mu$ can be expressed as

$$\begin{aligned} \triangle\lambda_s &= P_{s,max} - \sum_{i=1}^{M}\sum_{k=1}^{K}(P^i_{s,k})^* \\ \triangle\lambda_{k,d} &= P_{k,max} - \sum_{j=1}^{M}(P^j_{k,d})^* \\ \triangle\mu &= (R^{\mathcal{I}}_{s,\mathcal{K}})^* - (R^{\mathcal{J}}_{\mathcal{K},d})^*. \end{aligned} \quad (14)$$

Here, v^a is the stepsize and a is the number of iterations. The subgradient algorithm in Algorithm 1 is guaranteed to converge to the optimal $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$. The computational complexity of Algorithm 1 is polynomial in the number of dual variable $K+1$ [12]. Since (12) can be viewed as nonlinear integer programming problem, whose optimal solution requires high computational cost. Therefore, we are aiming to solve the optimization problem by solving three subproblems, which are relay selection, subcarriers and power allocation. We firstly introduce power allocation scheme.

B. Power Allocation Scheme

In order to obtain the optimal solution of power allocation, we are aiming to solve the problem solving problem (11) over variables $P^i_{s,k}$ and $P^j_{k,d}$. However, from (5) and (4), we see that problem (11) involves the conditional expectation of achievable throughput with respect to estimated CSI. Applying Karush-Kuhn-Tucker (KKT) conditions [11] and equations in [14], we could obtain the optimal power allocation schemes by solving following equation numerically.

$$\frac{\alpha^i_{s,k}}{P^i_{s,k}}\big(\frac{\sigma^2_k\beta^i_{s,k}}{L_{s,k}P^i_{s,k}}\big)^{\alpha^i_{s,k}}e^{\frac{\sigma^2_k\beta^i_{s,k}}{L_{s,k}P^i_{s,k}}}\Gamma\big(-\alpha^i_{s,k},\frac{\sigma^2_k\beta^i_{s,k}}{L_{s,k}P^i_{s,k}}\big)=\frac{\lambda_s}{1-\mu}. \tag{15}$$

where $\Gamma(a,b)$ is the incomplete Gamma function. $\alpha^i_{s,k}=(\eta^i_{s,k}+1)^2/(2\eta^i_{s,k}+1)$ is the Gamma shape parameter with $\eta^i_{s,k}=\hat{G}^i_{s,k}/\sigma^2_{\tilde{h}}$ and $\beta^i_{s,k}=\alpha^i_{s,k}/(\hat{G}^i_{s,k}+\sigma^2_{\tilde{h}})$ is Gamma PDF rate parameter. Similarly, for the cooperation phase, the optimal RN power allocation is obtained by solving

$$\frac{\alpha^j_{k,d}}{P^j_{k,d}}(c_1\beta^j_{k,d})^{\alpha^j_{k,d}}e^{c_1\beta^j_{k,d}}\Gamma\big(-\alpha^j_{k,d},c_1\beta^j_{k,d}\big)=\frac{\lambda_{k,d}}{1+\mu}, \tag{16}$$

where $\alpha^j_{k,d}=(\eta^j_{k,d}+1)^2/(2\eta^j_{k,d}+1)$ with $\eta^j_{k,d}=\hat{G}^j_{k,d}/\sigma^2_{\tilde{h}}$ and $\beta^j_{k,d}=\alpha^j_{k,d}/(\hat{G}^j_{k,d}+\sigma^2_{\tilde{h}})$. We have $c_1=\frac{\sigma^2_d+\sum_{m=1,m\neq k}^{K}P_{m,d}L_{m,d}G_{m,d}}{L_{k,d}P^j_{k,d}}$. $P_{m,d}$ and $G_{m,d}$ is the power allocation and channel gain from relay m to MT d. By using approximation method, e.g. , in [15], we are able to obtain the power allocation with imperfect CSI. One example can be found in Fig. 2 where different value of $\sigma^2_{\tilde{h}}$ is considered. We can see that when estimated error is relative small, the power allocation achieved by imperfect CSI is very close to the one when perfect CSI is assumed at AP.

C. Optimal Relay Selection (ORS)

We consider ORS in this work, unlike some traditional single relay selection algorithms in [6] and [13], as the multiple RNs selection. The proposed algorithm is to select K RNs to form a cluster that can maximize the achieved throughput in (6) based on the imperfect CSI.

Assuming the subcarrier and power allocation are done, we can rewrite (11) as

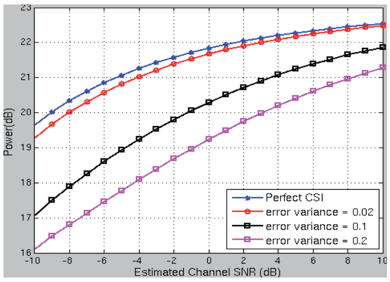


Figure 2. One example of power allocation as function of estimated channel SNR for various value of $\sigma^2_{\tilde{h}}$.

$$\begin{aligned}\mathcal{L}(\mathbf{P},\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda}) =& \min_{k\in\mathcal{K}}\Big\{\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}[log(1+\sum_{i=1}^{M}\omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k})]\Big\}\\ &+\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}[log(1+\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d})]\\ &-\mu\Big(\min_{k\in\mathcal{K}}\Big\{\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}[log(1+\sum_{i=1}^{M}\omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k})]\Big\}\\ &-\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}[log(1+\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d})]\Big)\\ &+\lambda_s(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k}-P_{s,max})\\ &-\sum_{k=1}^{K}\lambda_{k,d}(\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d}-P_{k,max}).\end{aligned} \tag{17}$$

By applying KKT condition, the RN is selected according to the following rule,

$$\begin{aligned}\mathcal{K}^* = \arg\max_{k} &\ \Big(\min_{k\in\mathcal{K}}\Big\{(1-\mu^*)\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}\Big[\frac{P_{s,k}\gamma_{s,k}}{1+P_{s,k}\gamma_{s,k}}\Big]\Big\}\\ &+(1+\mu^*)\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}\Big[\frac{P_{k,d}\gamma_{k,d}}{1+\sum_k^K P_{k,d}\gamma_{k,d}}\Big]\Big),\end{aligned} \tag{18}$$

Since we know that $\hat{\gamma}^i_{s,k}=\frac{L_{s,k}\hat{G}^i_{s,k}}{\sigma^2_k}$. The channel SNR $\gamma_{s,k}$ conditioned on $\hat{\gamma}^i_{s,k}$ is also a non-central Chi-squared distributed random variable with PDF:

$$f(\gamma^i_{s,k}|\hat{\gamma}^i_{s,k})=\frac{1}{\nu^i_{s,k}}e^{-\frac{\hat{\gamma}^i_{s,k}+\gamma^i_{s,k}}{\nu^i_{s,k}}}\mathcal{J}_0\Big(2\sqrt{\frac{\hat{\gamma}^i_{s,k}\gamma^i_{s,k}}{(\nu^i_{s,k})^2}}\Big) \tag{19}$$

$$f(\gamma_{s,k}^i|\hat{\gamma}_{k,d}^j) = \frac{1}{\nu_{k,d}^j} e^{-\frac{\hat{\gamma}_{k,d}^j+\gamma_{k,d}^j}{\nu_{k,d}^j}} \mathcal{J}_0\Big(2\sqrt{\frac{\hat{\gamma}_{k,d}^j\gamma_{k,d}^j}{(\nu_{k,d}^j)^2}}\Big) \tag{20}$$

where $\nu_{s,k}^i = \sigma_k^2/\sigma_{\tilde{h}}^2$ and $\nu_{k,d}^j = \sigma_d^2/\sigma_{\tilde{h}}^2$. Following same procedure as power allocation, we obtain

$$\mathbb{E}_{\gamma_{s,k}^i|\hat{\gamma}_{s,k}^i}\Big[\frac{P_{s,k}^i\gamma_{s,k}^i}{1+P_{s,k}^i\gamma_{s,k}^i}\Big] = \psi_{s,k}^i\big(\frac{\theta_{s,k}^i}{P_{s,k}^i}\big)^{\psi_{s,k}^i} e^{\frac{\theta_{s,k}^i}{P_{s,k}^i}} \Gamma\big(-\psi_{s,k}^i, \frac{\sigma_k^2\theta_{s,k}^i}{P_{s,k}^i}\big), \tag{21}$$

$$\mathbb{E}_{\gamma_{k,d}^j|\hat{\gamma}_{k,d}^j}\Big[\frac{P_{k,d}^j\gamma_{k,d}^j}{1+\sum_k^K P_{k,d}^j\gamma_{k,d}^j}\Big] = \psi_{k,d}^j\big(c_2\theta_{k,d}^j\big)^{\psi_{k,d}^j} e^{c_2\theta_{k,d}^j} \Gamma\big(-\psi_{k,d}^j, c_2\theta_{k,d}^j\big), \tag{22}$$

where $\psi_{s,k}^i = (\zeta_{s,k}^i+1)^2/(2\zeta_{s,k}^i+1)$ with $\zeta_{s,k}^i = \hat{\gamma}_{s,k}^i/\nu_{s,k}^i$ and $\theta_{s,k}^i = \zeta_{s,k}^i/(\hat{\gamma}_{s,k}^i+\nu_{s,k}^i)$. $\psi_{k,d}^j = (\zeta_{k,d}^j+1)^2/(2\zeta_{k,d}^j+1)$ with $\zeta_{k,d}^j = \hat{\gamma}_{k,d}^j/\nu_{k,d}^j$ and $\theta_{k,d}^j = \zeta_{k,d}^j/(\hat{\gamma}_{k,d}^j+\nu_{k,d}^j)$. We have $c_2 = (1+\sum_{m=1,m\neq k}^K P_{m,d}\gamma_{m,d})/P_{k,d}^j$. $P_{m,d}$ and $\gamma_{m,d}$ are the power allocation and channel SNR from relay m to MT. Optimal value of $\mathbf{P}$ can be given in (15) and (16). Thus, (18) can be viewed as multi-objective optimization problem, which aims at obtaining the trade-off of the throughput of first hop and second hop. (18) is also the termination criteria for the whole RRA scheme. Therefore, the relay selection strategy is

$$\rho_k = \begin{cases} 1 & \text{if } k \in \mathcal{K}^*, \\ 0 & \text{otherwise.} \end{cases}$$

D. Optimal Subcarrier Allocation (OSA)

The goal of subcarrier allocation strategy is to assign subcarriers to a given RN that can obtain best throughput performance. Following the same procedure as the relay selection, we could obtain subcarrier allocation criteria as follows:

$$\mathcal{I}^* = \arg\max \Big(\min_{k\in\mathcal{K}}\Big\{(1-\mu^*)\mathbb{E}_{\gamma_{s,k}^i|\hat{\gamma}_{s,k}^i}\Big[\frac{P_{s,k}^i\gamma_{s,k}^i}{1+P_{s,k}^i\gamma_{s,k}^i}\Big]\Big\}\Big) \tag{23}$$

$$\mathcal{J}^* = \arg\max\Big\{(1+\mu^*)\mathbb{E}_{\gamma_{k,d}^j|\hat{\gamma}_{k,d}^j}\Big[\frac{P_{k,d}^j\gamma_{k,d}^j}{1+\sum_k^K P_{k,d}^j\gamma_{k,d}^j}\Big]\Big\}, \tag{24}$$

where channel SNR $\gamma_{s,k}^i = \frac{L_{s,k}G_{s,k}^i}{\sigma_k^2}$ and $\gamma_{k,d}^j = \frac{L_{k,d}G_{k,d}^j}{\sigma_d^2}$. Therefore, the OSA indicator for the first hop and second hop can be expressed as

$$\omega_i = \begin{cases} 1 & \text{if } i \in \mathcal{I}^*, \\ 0 & \text{otherwise.} \end{cases}$$

$$\omega_j = \begin{cases} 1 & \text{if } j \in \mathcal{J}^*, \\ 0 & \text{otherwise.} \end{cases}$$

IV. Performance Evaluation

Simulations are presented to evaluate the performance of proposed algorithms in this section. It is assumed that five RNs are located between AP and MT, and MT is 1.8km away from AP. The Stanford University SUI-3 channel model is employed [16], in which the central frequency is 1.9GHz. We use a 3-tap channel and signal fading follows Rician distribution. We choose number of subcarriers N to be 32, so the duality gap can be ignored [6]. Flat quasi-static fading channels are considered, hence the channel coefficients are assumed to be constant during a complete frame, and can vary from a frame to another independently. The noise variance of the two hops are set to be 1 for simplicity. The path loss factor varies according to the different distances from RNs to AP and MT. If distance between RN and AP or RN and MT is shorter than a break point $d_{BP} = 100m$, the exponent is fixed to 2, otherwise it is 3.5. The maximum transmit power of AP and RN are 40 dBm and 20 dBm respectively. An accurate estimator with estimated variance $\sigma_{\tilde{h}}^2 = 0.02$ is assumed at the receiver.

We demonstrate our results comparing with the performance of some other schemes:

1) Equal power allocation combined with proposed subcarrier allocation scheme and relay selection(EPA);

2) Waterfilling power allocation and proposed subcarrier allocation scheme with relay selection (Waterfilling);

3) Modified proportional allocation scheme in [5] with fairness consideration(Fairness SA);

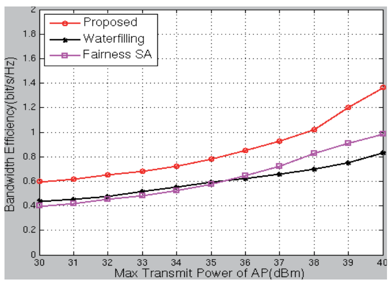


Figure 3. Impact of maximum transmit power $P_{s,max}$ on system bandwidth Efficiency

Fig. 3 demonstrates the impact of maximum transmit power of AP on the system bandwidth efficiency. We denote $D_{s,d}$ as the distance between AP and MT, and $D_{s,k}$ as the distance between AP and RNs. In Fig. 3, we have $D_{s,d} = 1800$ m and $D_{s,k}$ from 1500 m to 1600 m. The considered channel SNR at the RN k is varied from $\gamma_{s,k} = -20dB$ to $\gamma_{s,k} = -30dB$ and at MT d it is varied from $\gamma_{k,d} = -15dB$ to $\gamma_{k,d} = -25dB$. It can be seen that the proposed scheme achieves the best performance. The performance gain over other methods in comparison is up to 20%. It can also be noticed that if Waterfilling is used as the power allocation scheme (instead of our proposed scheme), the throughput performance is comparable with Fairness SA. Another performance gain can be seen in power consumption. We can see that with a fixed data rate requirement, our proposed scheme provides a clear power saving gain. For instance, at the level of 1.0 bit/s/Hz bandwidth efficiency our proposed scheme can reach a power saving around 3 dBm compared to the other schemes.

Fig. 4 shows the impact of distance between AP and RN on the system throughput. The distance between AP and RN is normalized to distance between AP and MT and vary from 0.1 to 0.9. In Fig. 4, we set maximum AP power $P_{s,max} = 40\ dBm$ and maximum RN power is $P_{k,max} = 20\ dBm$. From Fig. 4, we can see that the proposed algorithm obtain the highest system capacity when distance is less than 0.9 in Fig. 4. When the average normalized distance between AP and RN is around 0.9, we can find that performance difference between EPA and proposed scheme are smaller. This may due to the fact the some RNs are very close to the MT so that the achieved SNR is rather high. It can be concluded that the proposed algorithm can provide better performance gain over other existed algorithms.

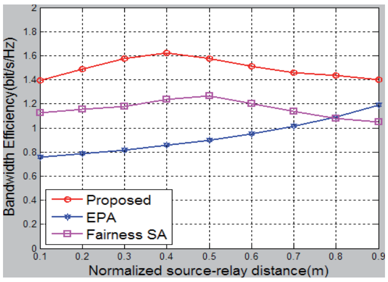


Figure 4. Impact of distance between AP and RN on the system bandwidth efficiency, maximum AP power is 40 dBm, maximum RN power is 20 dBm

Fig. 5 illustrates the convergence speed of the proposed algorithm and the Fairness SA scheme. The considered $P_{s,max}$ is fixed to 35 dBm and$P_{r,max}$ is 17.5 dBm. Our proposed algorithm reaches the steady state after several iterations, which demonstrates fast convergence speed.

V. Conclusion

In this paper we investigated the problem of resource allocation for cooperative multi-relay assisted OFDMA networks with assumption of Imperfect CSI. The joint optimization problem for radio resource allocation was solved by addressing three subproblems including optimal selection of collaborative relays, subcarriers and power with the objective of maximizing the expected system throughput. Theoretical expressions were derived for the optimal selections. It was shown that by designing RRA scheme with imperfect CSI for different hops,

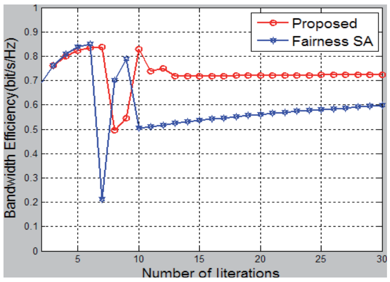


Figure 5. Impact of the number of iteration on the system bandwidth efficiency

it is possible to reach a noticeable gain in the cell-edge throughput. In addition, the results support our theoretical analysis that the proposed scheme obtain power allocation as close to the one when perfect knowledge of CSI is considered. These were also illustrated with simulation examples.

References

[1] G. Song and Y. Li, "Cross-layer Optimization for OFDM Wireless Networks-Part 1: Theoretical Framework," *IEEE Tran. on Wir. Comm.*, Vol.4, No.2, pp.614-624, Mar. 2005.

[2] T.C-Y. Ng and W. Yu, "Joint Optimization of Relay Strategies and Resource Allocation in Cooperative Cellular Networks," *IEEE Jour. on Sel. Area in Comm.*, Vol.25, No.2, pp.328-339 ,Feb. 2007.

[3] S-K. Kim, X. Wang, and M. Madihian, "Optimal Resource Allocation in Multi-hop OFDMA Wireless Networks with Cooperative Relay," *IEEE Tran. on Wir. Comm.*, Vol.7, No.5, pp.1833-1838, May 2008.

[4] H. Jeong and J. H. Lee, "Adaptive Relay Selection for Regenerative OFDMA Relay Networks with Fairness Constraints," *Proceedings of IEEE VTC 2008-fall*, Calgary, Canada, Sep. 2008.

[5] M. Tang, *et al*, "Dynamic Resource Allocation with Threshold in OFDMA-based Relay Networks," *Proceedings of IEEE VTC 2010-Spring*, Taipei, Taiwan, May 2010.

[6] W. Dang, *et al*, "Subcarrier-Pair Based Resource Allocation for Cooperative Multi-Relay OFDM systems," *IEEE Tran. on Wir. Comm.*, Vol.9, No.5, pp. 1640-1649, May 2010.

[7] M. K. Awad, *et al*, "A Dual-Decomposition-Based Resource Allocation OFDMA Networks with Impefect CSI," *IEEE Tran. on Veh. Tech.*, Vol.59, No.5, pp. 2394-2403, May 2010.

[8] M. Ahmad and M. Assaad, "Joint Resource Optimization and Relay Selection for cooperative Cellular Networks with Imperfect Channel Knowledge," *Proceedings of 11th SPAWC 2010*, Morocco, June 2010.

[9] J-H. Wang, *et al*, "Resource Allocation and Relay Selection for cooperative OFDMA Networks with Imperfect Channel Information," *Proceedings of 12th IEEE SPAWC 2011*, San Francisco, CA, June 2011.

[10] Z. Chang and T. Ristaniemi, "Asymmetric Radio Resource Allocation Scheme for OFDMA Wireless Networks with Collaborative Relays," *Wireless Networks*, DOI: 10.1007/s11276-012-0490-8, 2012.

[11] S. Boyd, and L. Vandenberghe, *Convex Optimization* , Cambridge UK: Cambridge University Press, 2004.

[12] W. Yu and R. Lui, "Dual Methods for Nonconvex Spectrum Optimization in Multicarrier System," *IEEE Tran. on Comm.*, Vol.54, No.7, pp.1310-1322, Jul. 2006.

[13] A. S. Ibrahim, *et al*, "Cooperative Communications with Relay-Selection: When to Cooperate and Whom to Cooperate With," *IEEE Transaction on Communications*, Vol.7, No.7, pp.2814-2827, July 2008.

[14] I. Gradshtein, I. Ryzhik, D. Zwillinger and A. Jeffrey, *Table of Intergrals, Serie, and Products*. New York: Academic, 2007.

[15] A. Lauschke, *Convergence Acceleration with Canonical Contractions of Continued Fractions: Incomplete Gamma Function* [Online]. available: http://216.80.120.13:8080/webMathematica/LC/gamma.jsp

[16] R. Jain, *Channel Models A Tutorial1 v1.0* , Feb. 2007.

PIII

REDUCING ENERGY CONSUMPTION VIA COOPERATIVE OFDMA MOBILE CLUSTER

by

Zheng Chang and Tapani Ristaniemi 2012

Proc. of 17th IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD'12)

Reducing Energy Consumption via Cooperative OFDMA Mobile Clusters

Zheng Chang*† and Tapani Ristaniemi†
*Magister Solutions Ltd, Hannikaisenkatu 41, FIN-40100 Jyväskylä, Finland
†Department of Mathematical Information Technology, University of Jyväskylä,
P.O.Box 35, FIN-40014 Jyväskylä, Finland
Email: zheng.chang@magister.fi, tapani.ristaniemi@jyu.fi

***Abstract*—Aggressive techniques induce high energy consumption for the circuits of MTs, which drain the batteries fast and consequently limit mobility. In order to solve such a problem, a scheme called distributed mobile cloud (DMC) is foreseen as one of the potential solutions to reduce energy consumption per node in a network. In this paper we provide a detailed analysis of the energy consumption of a terminal joining the DMC and also analyze the conditions for energy savings opportunities. Numerical results are also provided to illustrate the analysis and show the potential of significant reduction of the per-node energy consumption in the mobile cloud concept.**

***Index Terms*—OFDMA; energy consumption; energy saving; cooperative cluster**

I. Introduction

It is essential that the mobile terminals (MTs) can fully exploit the throughput gains offered by future communication system whenever possible. However, the high energy consumption limits this due to the capacity limitation of battery and the user experience of gigabits transmission would be seriously impacted. Therefore, reducing energy consumption emerges as a critical issue to prolong the battery life in the future wireless networks.

For energy saving purpose, some research works have been done by improving transmission and receiving mechanism for a single receiver. In [1], an overview of discontinuous reception (DRX) which is used in LTE to reduce receiver power consumption was presented. Meanwhile authors of [2] dedicate the work on the power saving schemes for wireless distributed computing networks. However, these contributions focus more on power saving performance of computing rather than the one of communication. [4] introduce Multi-Radio ARQ schemes for hybrid networks combining long-range and short-range communications to improve the throughput. In [5], short range cooperation among MTs was proposed as a key idea to reduce the transmit energy consumption for the transmission from MTs to AP. However, the study considers transmit energy consumption only.

In this work, we consider both transmit and receive energy consumption. Scenario under consideration includes cooperation among MTs. This scenario also known as Distributed Mobile Cloud (DMC) is modelled as a cluster of resource-constrained nodes that can perform receiving and decoding cooperatively and distributively [3]. One DMC contains several MTs that can cooperatively receive the information data from access point (AP), then exchange the received data with others through device-to-device (D2D) links. We provide detailed analysis of the energy consumption of a MT within the DMC and compare it with non-cooperative schemes. Numerical results illustrate the potential of energy saving possibilities in this context compared to the non-cooperative scenario.

The rest of the paper is organized as follows. Section II describes our system model and formulates the problem. In Section III, we analyze the power and energy consumption of using DMC as well as using traditional P2P network. Energy consumption reduction performance analysis and discussion are shown in Section IV. We finally conclude the paper in Section V.

II. System Model and Problem Formulation

A. DMC System Model

We consider there are one AP and Z MTs in the network, where K MTs can form a DMC. All MTs inside DMC require the same data from AP (e.g. a video or television channel). The scenario is depicted in Fig. 1, where $K = 3$.

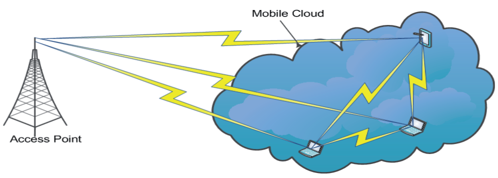


Figure 1. OFDMA network with Distributed Mobile Cloud.

B. Problem Formulation

We first denote a physical resource block unit (PRB) as a certain frequency bandwidth (e.g. 12 subcarriers in LTE) in one time slot T_k for MT k. We assume that P_k is the circuit power of MT k that is used for receiving certain amount of data in one PRB from AP. We also assume there are total M PRBs that are used for transmission from AP to a single MT. Therefore, the total receive energy consumption per node (MT) in the AP-to-MT link equals

$$E_{total} = MP_kT_k. \tag{1}$$

978-1-4673-3125-8/12/$31.00 ©2012 IEEE

Hence, the total energy consumption per node within the DMC concept can be presented as:

$$E_{node} = E_{rx} + E_{tx} + E_{part}, \tag{2}$$

where E_{part} is the receive energy consumption of single MT that is used for receiving the assigned part of the data from AP. If K MTs are assigned for equal amount of data, we would have $E_{part} = E_{total}/K$. E_{tx} and E_{rx} are the transmit and receive energy consumption for data exchange inside the DMC, respectively. One example of the DMC communication procedure is shown in Fig. 2 with a comparison to traditional point-to-point scheme. Therefore, the objective is to examine the energy saving gain due to DMC, which can be expressed as,

$$\xi = E_{total} - E_{node}. \tag{3}$$

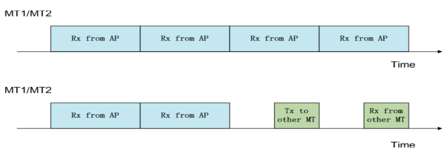


Figure 2. Traditional P2P vs. DMC

III. Analysis of Power and Energy Consumption

A. RF Front-end Power Consumption

For D2D communication inside DMC, the transmit power dissipation of RF front-end for single PRB is expressed as [2]

$$P_{tx} = \beta_1 \gamma_{min} W L + \beta_2, \tag{4}$$

where β_1 and β_2 depend on the transceiver components and channel characteristics. In particular, β_1 is related to transmitting action on/after power amplifier (PA), such as antenna and channel gain. β_2 depends on transceiver RF circuit components, e.g., local oscillator and Digital-Analog Converter (DAC)/Analog-Digital Converter (ADC) for processing data on one subcarrier. L is the path loss and W is the frequency bandwidth of one PRB. γ_{min} is the minimum required Signal-to-Noise Ratio (SNR) at the receiver, which is related to Bit-Error-Ratio (BER) requirement. Without loss of generality we can take QAM modulation as an example, which would result in [6],

$$\gamma_{min} = \frac{2}{3}(2^b - 1) ln \frac{4(1-2^{-b})}{BER_{req}} \tag{5}$$

where BER_{req} is the BER requirement at receiver. Also, β_1 and β_2 can be expressed as:

$$\begin{aligned} \beta_1 &= \frac{\eta k_B T_o NF (\sigma_s)^{-Q^{-1}(1-p_{out})} (4\pi)^2}{G_t G_r \lambda^2 d_o^{-2}} LM, \\ \beta_2 &= P_{DAC} + P_{RF} + \vartheta \end{aligned} \tag{6}$$

Table I
Tx/Rx power consumption related parameters

Parameter	Description	Value
η	Power amplifier Parameter	0.2
ϑ	Power amplifier Parameter	174 mW
k_B	Boltzmann Constant	1.3806×10^{-23} J/K
T_o	Temperature	300K
NF	Noise Figure	9 dB
σ_s	Shadow fading standard deviation	12 dB
G_t	Tx antenna gain	2 dBi
G_r	Rx antenna gain	2 dBi
λ	Signal wavelength	0.15(2GHz)
LM	Link margin	15 dB
W	Bandwidth of PRB	0.2 MHz
d_o	Near field distance	15m
p_{out}	Channl outage probability	1%
P_{DAC}	Power of DAC	15.4mW
P_{RF}	Power of other RF device	131.5 mW

where Q^{-1} is inverse Q function. The explanation and possible values of parameters are shown in Table I.

B. Baseband Processing Power Consumption

The power dissipation for baseband signal processing can be modeled as [7]:

$$P_E = (C_E + C_R \frac{R_{S,max}}{R_S}) R_S, \tag{7}$$

where R_S is the symbol rate, $R_{S,max}$ is the maximum symbol rate, C_E and C_R are related to system voltage level.

C. Total Energy Consumption

Denoting T_{tx} the time for transmitting one PRB, and the number of PRBs that are used for transmitting and receiving by I_{tx} and I_{rx}, respectively, the energy consumption can be expressed as

$$\begin{aligned} E_{tx} &= I_{tx}(P_{tx} + P_E) T_{tx} \\ &= I_{tx}[(\beta_1 \gamma_{min} L W \\ &+ \beta_2) + (C_E + C_R \frac{R_{S,max}}{R_{S,node}}) R_{S,node}] T_{tx}. \end{aligned} \tag{8}$$

Similarly, the energy consumption for receiving can be expressed as

$$\begin{aligned} E_{rx} &= I_{rx}(P_{rx} + P_E) T_{rx} \\ &= I_{rx}[\beta_2 + (C_E + C_R \frac{R_{S,max}}{R_{S,node}}) R_{S,node}] T_{rx}, \end{aligned} \tag{9}$$

where $P_{rx} = \beta_2$ is the receiving power consumption and $R_{S,node}$ is the transmission symbol rate for the nodes inside DMC. As we also have

$$P_k = \beta_2 + (C_E + C_R) R_{S,AP}, \tag{10}$$

we finally result in

$$E_{total} = M P_k T_k = M[\beta_2 + (C_E + C_R \frac{R_{S,max}}{R_{S,AP}}) R_{S,AP}] T_k, \tag{11}$$

where $R_{S,AP}$ is the symbol rate used by AP-MTs transmission.

IV. Analysis of DMC Energy Saving

For simplicity we assume that each node within DMC is assigned the same resource for transmission. Thus, we have $I_{tx} = I_{rx} = I_{node}$, and $T_{tx} = T_{rx} = T_{node}$. Thus we have,

$$E_{node} = (K-1)(P_{rx} + P_{tx})I_{node}T_{node} + E_{total}/K. \quad (12)$$

Therefore, the energy saving gain for our study can be represented as,

$$\begin{aligned}\xi =& \frac{K-1}{K} M P_k T_k - (P_{tx} + P_{rx}) I_{node} T_{node} \\ =& \frac{K-1}{K} M T_k \big(P_k - \frac{P_{tx} + P_{rx}}{\rho}\big)\end{aligned} \quad (13)$$

where we assume that and $I_{node}T_{rx} = \frac{MT_k}{K\rho}, \forall \rho > 0$. Here ρ depends on the amount of data that the subcarrier can carry, which in general, is decided by modulation and coding schemes. For example, if BPSK and code rate (CR) 1/2 is used as modulation scheme from AP to MT and QPSK CR 1/2 is used for D2D communication inside MC, we have $\rho = 2$.

A. Numerical Results and Analysis

The energy efficiency metric for examining the usage of DMC is energy saving percentage, which is defined as $\frac{\xi}{E_{total}} \times 100$. For baseband energy consumption, we have $R_{S,max} = 1MHz$ and $R_{S,node} = R_{S,AP} = 250MHz$. We also assume that $C_E = 8 \times 10^{-8}$, $C_R = 10^{-7}$, and $BER_{req} = 10^{-5}$. The D2D channel is defined according to IEEE 802.11ac , where D2D distance is assumed to be 20m.

From Fig. 3, we can see that as the number of MTs increases, the energy saving gain obtained by using DMC arises as well. The energy saving percentage reaches the saturation level when there are 20 MTs forming a DMC. It means that without any radio resource (e.g. PRBs) constraints, forming DMC can help nearby MTs to save energy if proper modulation and coding schemes (MCS) are used. We also notice that when $\rho = 5$, we reach the maximal energy saving gain for all cases in this setting. The increase of the energy saving as a function of modulation order is expected due to shorter transmit times. However, there's also a need for higher transmit powers with higher modulation order so a trade-off clearly exists.

If we fix the number of MTs inside MC to be 20, we could obtain the impact of D2D distance and value of ρ in Fig. 4. We can observe that when the D2D distance is shorter than $d_o = 15m$, the energy efficiency performance remains at the same level for same values of ρ in Fig. 4. Generally, we can see that lower order MCS should be used when D2D distance is getting larger in order to achieve energy saving. For example, when D2D distance is $20m$, we can obtain 55% when $\rho = 6$, which is the maximum energy saving percentage for that D2D distance. However, $\rho = 5$ is the best choice when distance is $25m$. For the current channel model, forming DMC does not result in energy saving gains if the D2D distance is longer than $45m$.

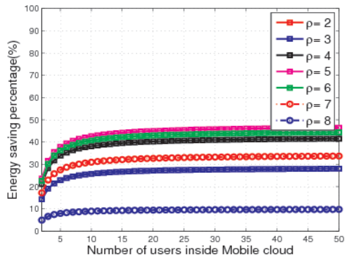


Figure 3. Number of MTs vs. energy efficiency gain with fixed D2D distance of 25m.

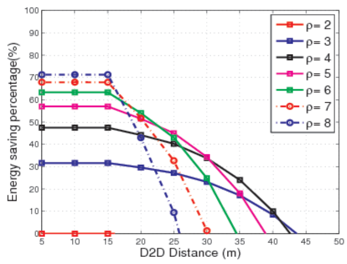


Figure 4. D2D distance vs. energy efficiency with fixed number of MTs.

V. Conclusion

In this work, we exploited the energy saving benefits of using distributed mobile cloud in an OFDMA networks. Targeting to decrease the total energy consumption of single MTs, we studied a distributed mobile cloud model, which is formed by a number of collaborating MTs. We presented a theoretical analysis on the energy consumption of MTs within the cloud. The analysis in this work serves as the foundation for our future distributed mobile cloud algorithm and protocol design.

References

[1] C. Bontu and E.Illidge, "DRX mechanism for power saving in LTE," *IEEE Communication Magazine*, Vol. 47, No. 6, pp. 48-55, June 2009.

[2] D. Datla,*et al*, "Power Efficiency in Wireless Network Distributed Computing," *IEEE VTC-spring 2009*, 2009.

[3] M. Hoyhtya, *et al*, "Cognitive engine: design aspects for mobile clouds, " Proceedings of CogART 2011, Barcelona, Spain, 26-29 October, 2011,

[4] J. Alonso-Zarate, *et al*, "Multi-Radio Cooperative ARQ in Wireless Cellular Networks: A MAC Layer Perspective," *Springer Telecommunication Systems*,DOI: 10.1007/s11235-011-9449-9.

[5] A. Radwan and J. Rodriguez, "Energy Saving in Multi-standard Mobile Terminals through Short-range Cooperation," *EURASIP Jour. Wirel. Comm. and Netw.*, 2012:159, doi:10.1186/1687-1499-2012-159.

[6] J. Prokias, *Digital Communications*, McGraw-Hill, 4 edition, 2000.

[7] C. Schurgers, *et al*, "Modulation scaling for Energy Aware Communication Systems," *Proceedings of ISLPED*, Huntington Beach, California, United States, 2001.

PIV

ENERGY EFFICIENCY OF COLLABORATIVE OFDMA MOBILE CLUSTER

by

Zheng Chang and Tapani Ristaniemi 2013

Proc. of 10th IEEE Consumer Communication and Networking Conference (CCNC'13)

Energy Efficiency of Collaborative OFDMA Mobile Clusters

Zheng Chang*† and Tapani Ristaniemi†
*Magister Solutions Ltd, Hannikaisenkatu 41, FIN-40100 Jyväskylä, Finland
†Department of Mathematical Information Technology, University of Jyväskylä,
P.O.Box 35, FIN-40014 Jyväskylä, Finland
Email: zheng.chang@magister.fi, tapani.ristaniemi@jyu.fi

***Abstract*—Future wireless communication systems are expected to offer several gigabits data rate. It can be anticipated that the advanced communication techniques can enhance the capability of mobile terminals (MTs) to support high data traffic. However, aggressive technique induces high energy consumption for the circuits of MTs, which drain the batteries fast and consequently limit mobility. In order to solve such a problem, a scheme called distributed mobile cloud (DMC) is foreseen as one of the potential solutions to reduce energy consumption per node in a network by exploiting collaboration within a cluster of nearby mobile terminals. In this paper we provide a detailed analysis of the energy consumption of a terminal joining the DMC and also analyze the conditions for energy savings opportunities. Numerical results are also provided to illustrate the analysis and show the potential of significant reduction of the per-node energy consumption in the mobile cloud concept.**

***Index Terms*—OFDMA; energy consumption; energy saving; collaborative cluster; distributed mobile cloud**

I. INTRODUCTION

Orthogonal Frequency Division Multiple Access (OFDMA) is an effective technique that exploits the benefits of Orthogonal Frequency Division Multiplexing (OFDM) for combating against channel noise and multipath effects and finally enables high data rate transmissions over fading channels. OFDMA is widely adopted in many standards of upcoming wireless communication systems, such as IEEE 802.11ac [1], LTE/LTE-A [2].

As expected, above mentioned advanced communication systems are going toward offering gigabits data rate. In order to support such high data traffic, aggressive wireless technique will be utilized to the mobile terminals (MTs), which consequently induce high energy consumption [3]. It is essential that these MTs can fully exploit the throughput gains offered by future communication system whenever possible. However, the high energy consumption limits this due to the capacity limitation of battery and the user experience of gigabits transmission would be seriously impacted. Therefore, reducing energy consumption emerges as a critical issue to prolong the battery life in the future wireless networks.

For energy saving purpose, some research works have been done by improving transmission and receiving mechanism for a single receiver [3][4]. Authors in [3] introduced a resource allocation scheme which can dynamically allocate time and frequency to reduce the receiving energy consumption per single receiver. In [4], an overview of discontinuous reception (DRX) which is used in LTE to reduce receiver power consumption was presented. Meanwhile authors of [5] and [6] dedicate the work on the power saving schemes for wireless distributed computing networks. However, these contributions focus more on power saving performance of computing rather than the one of communication. In [7], short range cooperation among MTs was proposed as a key idea to reduce the transmit energy consumption for the transmission from MTs to AP. In order to improve the throughput, [8] introduced Multi-Radio ARQ schemes for hybrid networks combining long-range and short-range communications. Energy saving gains obtained by using different combination of technologies for short range communication, such as WLAN and WiMAX, WLAN and WLAN were also derived in [7]. However, these studies consider transmit energy consumption only.

In this work, we consider both transmit and receive energy consumptions. Scenario under consideration includes cooperation among MTs, which have previously been studied for enhancing single transmissions. This scenario also known as Distributed Mobile Cloud (DMC) is modelled as a cluster of resource-constrained nodes that can perform receiving and decoding cooperatively and distributively [9]. One DMC contains several MTs that can cooperatively receive the information data from access point (AP), then exchange the received data with others. By exploiting the benefits of DMC, we can obtain the receiver energy consumption reduction. Such model can potentially offer several advantages over traditional AP-to-MT (or Point-to-Point, p2p) networks, including reduction of energy and resource consumption per node. The links within the DMC is assumed to be device-to-device (D2D) links, where the MTs can share their received data and available resource. In this paper we provide detailed analysis of the energy consumption of a MT within the DMC and compare it with non-cooperative schemes. Numerical results illustrate the potential of energy saving possibilities in this context compared to the non-cooperative scenario.

The rest of the paper is organized as follows. Section II describes our system model and formulates the problem. In Section III, we analyze the power and energy consumption of using DMC as well as using traditional P2P network. Energy consumption reduction performance analysis and discussion are shown in Section IV. We finally conclude the paper in

978-1-4673-3133-3/13/$31.00 ©2013 IEEE

Section V.

II. System Model and Problem Formulation

A. DMC System Model

We consider there is one AP and Z MTs in the network, where K MTs can form a DMC. All MTs inside DMC require the same data from AP (e.g. a video or television channel). Each MT can be dual-mode device, equipped with a short-range (e.g., WLAN, or LTE D2D) wireless communication technique for information exchange between devices and equipped with broadband access technique(e.g. LTE/LTE-A) for receiving from AP. The scenario is depicted in Fig. 1, where $K = 3$.

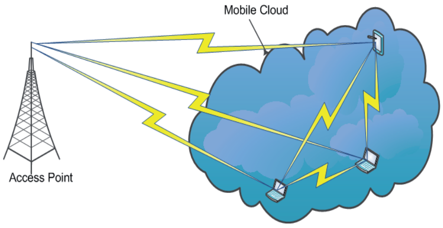


Figure 1. OFDMA network with Distributed Mobile Cloud.

B. Problem Formulation

We first denote a resource block unit (RBU) as a certain frequency bandwidth (e.g. 12 subcarriers in LTE [2]) in a time slot for MT k. We assume that P_k is the circuit power of MT k that is used for receiving certain amount of data in one RBU from AP. We also assume there are total M RBUs that are used for transmission from AP to a single MT. One example can be found in Fig. 2, in which the colored blocks represent the RBUs. Therefore, the total receive energy consumption per node (MT) in the AP-to-MT link equals

$$E_{total} = MP_kT_k. \tag{1}$$

where T_k time slot duration. Hence, the total energy consumption per node within the DMC concept can be presented as:

$$E_{node} = E_{rx} + E_{tx} + E_{part}, \tag{2}$$

where E_{part} is the receive energy consumption of single MT that is used for receiving the assigned part of the data from AP. If K MTs are assigned for equal amount of data, we would have $E_{part} = E_{total}/K$. E_{tx} and E_{rx} are the transmit and receive energy consumption for data exchange inside the DMC, respectively. One example of the DMC communication procedure is shown in Fig. 3 with a comparison to traditional point-to-point scheme. Therefore, the objective is to examine the energy saving gain due to DMC, which can be expressed as,

$$\xi = E_{total} - E_{node}. \tag{3}$$

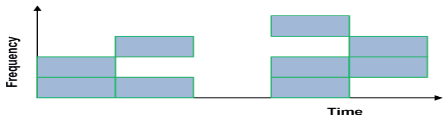


Figure 2. Allocated RBU for one MT.

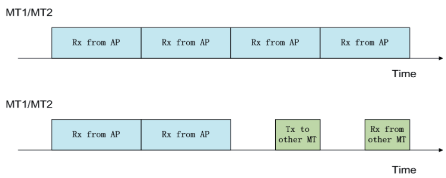


Figure 3. Traditional P2P vs. DMC

III. Analysis of Power and Energy Consumption

A. RF Front-end Power Consumption

For D2D communication inside DMC, the transmit power dissipation of RF front-end for one single RBU can be expressed as [5],

$$P_{tx} = \beta_1 \gamma_{min} WL + \beta_2, \tag{4}$$

where β_1 and β_2 depend on the transceiver components and channel characteristics. In particular, β_1 is related to transmitting action on/after power amplifier (PA), such as antenna and channel gain. β_2 depends on transceiver RF circuit components, e.g., local oscillator and Digital-Analog Converter (DAC)/Analog-Digital Converter (ADC) for processing data on one subcarrier. L is the path loss and W is the frequency bandwidth of one RBU. γ_{min} is the minimum required Signal-to-Noise Ratio (SNR) at the receiver, which is related to Bit-Error-Ratio (BER) requirement. Without loss of generality we can take QAM modulation as an example, which would result in [11],

$$\gamma_{min} = \frac{2}{3}(2^b - 1)ln\frac{4(1-2^{-b})}{BER_{req}} \tag{5}$$

where BER_{req} is the BER requirement at receiver and b is the modulation order. Also, β_1 and β_2 can be expressed as [5]

$$\begin{aligned} \beta_1 &= \frac{\eta k_B T_o NF(\sigma_s)^{-Q^{-1}(1-p_{out})}(4\pi)^2}{G_t G_r \lambda^2 d_o^{-2}} LM, \\ \beta_2 &= P_{DAC} + P_{RF} + \vartheta \end{aligned} \tag{6}$$

where Q^{-1} is inverse Q function. The explanation and possible values of parameters are shown in Table I.[12]

B. Baseband Processing Power Consumption

The power dissipation for baseband signal processing can be modeled as [13]:

Table I
TX/RX POWER CONSUMPTION RELATED PARAMETERS

Parameter	Description	Value
η	Power amplifier Parameter	0.2
ϑ	Power amplifier Parameter	174 mW
k_B	Boltzmann Constant	1.3806×10^{-23} J/K
T_o	Temperature	300K
NF	Noise Figure	9 dB
σ_s	Shadow fading standard deviation	12 dB
G_t	Tx antenna gain	2 dBi
G_r	Rx antenna gain	2 dBi
λ	Signal wavelength	0.15(2GHz)
LM	Link margin	15 dB
W	Bandwidth of RBU	0.2 MHz
d_o	Near field distance	15m
p_{out}	Channl outage probability	1%
P_{DAC}	Power of DAC	15.4mW
P_{RF}	Power of other RF device	131.5 mW

$$P_E = (C_E + C_R \frac{R_{S,max}}{R_S})R_S, \tag{7}$$

where R_S is the symbol rate, $R_{S,max}$ is the maximum symbol rate, C_E and C_R are related to system voltage level.

C. Total Energy Consumption

Denoting T_{tx} the time for transmitting one RBU, and the number of RBUs that are used for transmitting and receiving by I_{tx} and I_{rx}, respectively, the energy consumption can be expressed as

$$\begin{aligned} E_{tx} &= I_{tx}(P_{tx} + P_E)T_{tx} \\ &= I_{tx}[(\beta_1 \gamma_{min} LW \\ &+ \beta_2) + (C_E + C_R \frac{R_{S,max}}{R_{S,node}})R_{S,node}]T_{tx}. \end{aligned} \tag{8}$$

Similarly, the energy consumption for receiving can be expressed as

$$\begin{aligned} E_{rx} &= I_{rx}(P_{rx} + P_E)T_{rx} \\ &= I_{rx}[\beta_2 + (C_E + C_R \frac{R_{S,max}}{R_{S,node}})R_{S,node}]T_{rx}, \end{aligned} \tag{9}$$

where $P_{rx} = \beta_2$ is the receiving power consumption and $R_{S,node}$ is the transmission symbol rate for the nodes inside DMC. As we also have

$$P_k = \beta_2 + (C_E + C_R)R_{S,AP}, \tag{10}$$

we finally result in

$$E_{total} = MP_kT_k = M[\beta_2 + (C_E + C_R \frac{R_{S,max}}{R_{S,AP}})R_{S,AP}]T_k, \tag{11}$$

where $R_{S,AP}$ is the symbol rate used by AP-MTs transmission.

IV. ANALYSIS OF DMC ENERGY SAVING

For simplicity we assume that each node within DMC is assigned the same resource for transmission. Thus, we have $I_{tx} = I_{rx} = I_{node}$, and $T_{tx} = T_{rx} = T_{node}$. Thus we have,

$$E_{node} = (K-1)(P_{rx} + P_{tx} + 2P_E)I_{node}T_{node} + E_{total}/K. \tag{12}$$

Therefore, the energy saving gain for our study can be represented as,

$$\begin{aligned} \xi =& E_{total} - E_{tx} - E_{rx} - E_{part} \\ =& \frac{K-1}{K} MP_kT_k - (P_{tx} + P_{rx} + 2P_E)I_{node}T_{node} \\ =& \frac{K-1}{K} MT_k\big(P_k - \frac{P_{tx} + P_{rx}}{\rho} + \frac{\rho - 2}{\rho}\big) \end{aligned} \tag{13}$$

where we assume that and $I_{node}T_{rx} = \frac{MT_k}{K\rho}, \forall \rho > 0$. Here ρ depends on the amount of data that the subcarrier can carry, which in general, is decided by modulation and coding schemes. For example, if BPSK and code rate (CR) 1/2 is used as modulation scheme from AP to MT and QPSK CR 1/2 is used for D2D communication inside MC, we have $\rho = 2$.

A. Numerical Results and Analysis

The energy saving performance is presented in this section. The energy efficiency metric for examining the usage of DMC is energy saving percentage, which is defined here as:

$$\frac{\xi}{E_{total}} \times 100\% \tag{14}$$

For baseband energy consumption, we have $R_{S,max} = 1MHz$ and $R_{S,node} = R_{S,AP} = 250MHz$. We also assume that $C_E = 8 \times 10^{-8}$, $C_R = 10^{-7}$, and $BER_{req} = 10^{-5}$. We examine the impact of size of the DMC in terms of number and distances of MTs within the cloud. Also, the effect of modulation order ρ to the energy saving performance is studied. The D2D channel is defined according to IEEE 802.11ac [1], where D2D distance is assumed to be 20m.

From Fig. 4, we can see that as the number of MTs increases, the energy saving gain obtained by using DMC arises as well. The energy saving percentage reaches the saturation level when there are 20 MTs forming a DMC. It means that without any radio resource (e.g. RBUs) constraints, forming DMC can help nearby MTs to save energy if proper modulation and coding schemes (MCS) are used. In Fig. 5, we notice that when $\rho = 5$, we reach the maximal energy saving gain for all cases in this setting. The increase of the energy saving as a function of modulation order is expected due to shorter transmit times. However, there's also a need for higher transmit powers with higher modulation order so a trade-off clearly exists. As we see from the figure, when $\rho > 5$, the growth of transmit power appears to dominate the increase of E_{node}, and thus, energy saving percentage begins to decrease from its maximum.

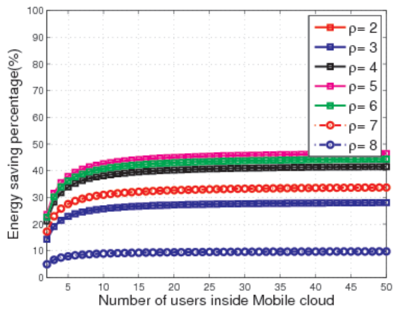


Figure 4. Number of MTs vs. energy efficiency gain with fixed D2D distance of 25m.

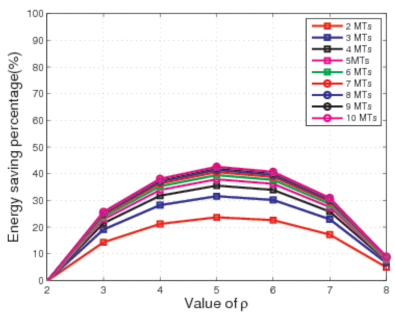


Figure 5. ρ vs. energy efficiency gain with a fixed D2D distance of 25m.

If we fix the number of MTs inside MC to be 20, we could obtain the impact of D2D distance and value of ρ in Figs. 6 and 7. We can observe that when the D2D distance is shorter than $d_o = 15m$, the energy efficiency performance remains at the same level for same values of ρ in Fig. 6. Generally, we can see that lower order MCS should be used when D2D distance is getting larger in order to achieve energy saving. For example, when D2D distance is $20m$, we can obtain 55% when $\rho = 6$, which is the maximum energy saving percentage for that D2D distance. However, $\rho = 5$ is the best choice when distance is $25m$. For the current channel model, forming DMC does not result in energy saving gains if the D2D distance is longer than $45m$. From Fig. 7, we can see that the energy saving percentage can reach up to of 70% when D2D distance is shorter than d_o. In general, for same value of ρ, shorter D2D distance can obtain higher energy saving percentage.

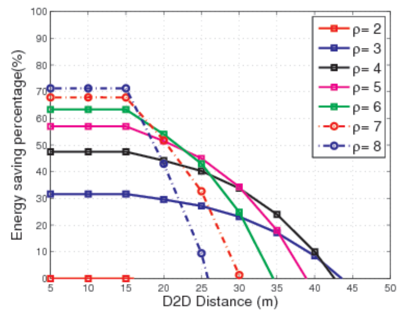


Figure 6. D2D distance vs. energy efficiency with fixed number of MTs.

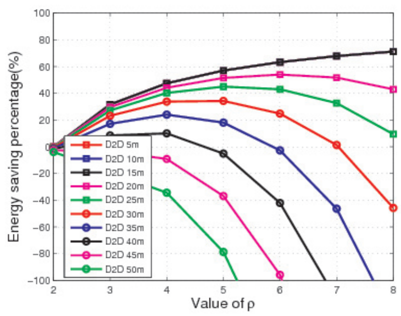


Figure 7. ρ vs. energy efficiency with fixed number of MTs.

Finally, if we fix the value of ρ to be 5, we could obtain the impact of D2D distance and numbers of MTs in Figs. 8 and 9. When $\rho = 5$, we notice that the D2D distance should not be longer that $38m$. The same situation as in Fig. 4 can be observed in Figs. 8 and 9, namely, larger size for DMC results in higher energy saving gains. For instance, in Fig. 8, we see that a DMC with 4 MTs can obtain up to of 1.5 times energy saving gain that a DMC with 2 MTs. However, the difference is not so obvious when there are more MTs forming a DMC, e.g., a DMC with 20 MTs can only achieve a slight better (up to of around 4%) energy saving performance than that of a DMC formed by 10 MTs.

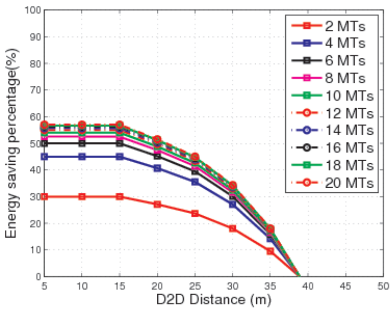


Figure 8. D2D distance vs. energy efficiency gain with $\rho = 5$.

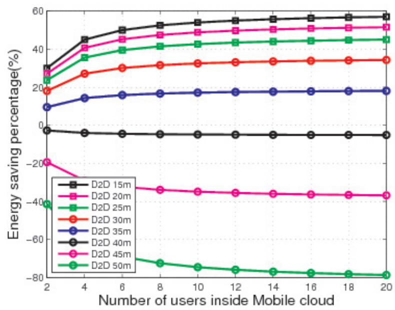


Figure 9. Number of MTs vs. energy efficiency gain with $\rho = 5$

V. Conclusion

In this work, we exploited the energy saving benefits of using distributed mobile cloud in an OFDMA networks. Targeting to decrease the total energy consumption of single MTs, we studied a distributed mobile cloud model, which is formed by a number of collaborating MTs. The benefits achieved from distributed mobile cloud may be negated by the communication overhead inside it. Therefore, we presented a theoretical analysis on the energy consumption of MTs within the cloud. In addition, we illustrated the energy efficiency performance with respect to the number of MTs inside distributed mobile cloud, modulation scheme used in D2D transmissions inside the distributed mobile cloud, as well as D2D distance between each of the node pairs. The analysis in this work serves as the foundation for our future distributed mobile cloud algorithm and protocol design.

References

[1] IEEE P802.11ac. Specification Framework for TGac.
[2] *3rd Generation Partnership Project Specifications Home Pages.* [Online]. available: http://www.3gpp.org/specs/specs.htm
[3] F-S. Chu, K-C. Chen, and G. Fettweis, "Green Resource Allocation to Minimize Receiving Energy in OFDMA Cellular Systems," *IEEE Comm. Lett.*, Vol.16, No. 30, pp.372-375, March 2012.
[4] C. Bontu and E.Illidge, "DRX mechanism for power saving in LTE," *IEEE Communication Magazine*, Vol. 47, No. 6, pp. 48-55, June 2009.
[5] D. Datla, X. Chen, T. R. Newman, J. H. Reed, and T. Bose, "Power Efficiency in Wireless Network Distributed Computing," *IEEE VTC-spring 2009*, 2009.
[6] D. Datla, *et al*, "Wireless Distributed Computing in cognitive radio networks," *Ad Hoc Networks*, 10 (2012), pp. 845-857, April 2012.
[7] A. Radwan and J. Rodriguez, "Energy Saving in Multi-standard Mobile Terminals through Short-range Cooperation," *EURASIP Journal on Wireless Communications and Networking*, 2012:159, doi:10.1186/1687-1499-2012-159.
[8] J. Alonso-Zarate, *et al*, "Multi-Radio Cooperative ARQ in Wireless Cellular Networks: A MAC Layer Perspective," *Springer Telecommunication Systems*,DOI: 10.1007/s11235-011-9449-9.
[9] M. Hoyhtya, M. Palola, M. Matinmikko, and M. Katz, "Cognitive engine: design aspects for mobile clouds, " Proceedings of CogART 2011, Barcelona, Spain, 26-29 October, 2011.
[10] M. V. Pederson and F. H. P. Fitzek, "Mobile Clouds: The New Content Sharing Platform", *Proceeding of IEEE*, Vol. 100, pp. 1400-1403, 2012.
[11] J. Prokias, *Digital Communications*, McGraw-Hill, 4 edition, 2000.
[12] S. Haloka, T. Chen, J. lehtomaki and T. Koskela, "Device-to-Device(D2D) Communication in Cellular Network- Performance Analysis of Optimal and Practical Communication Mode Selection," *Proc. of IEEE WCNC 2010*, Sydney, Australia, April 2010.
[13] C. Schurgers, O. Aberthorne and M. Srivastava, "Modulation scaling for Energy Aware Communication Systems," *Proceedings of International symposium on Low power electronics and design*, Huntington Beach, California, United States, 2011.

PV

ASYMMETRIC RESOURCE ALLOCATION FOR OFDMA NETWORKS WITH COLLABORATIVE RELAYS

by

Zheng Chang and Tapani Ristaniemi 2013

Proc. of 10th IEEE Consumer Communication and Networking Conference (CCNC'13)

Asymmetric Resource Allocation for OFDMA Networks with Collaborative Relays

Zheng Chang*† and Tapani Ristaniemi*
*Department of Mathematical Information Technology, University of Jyvaskylä,
P.O.Box 35, FIN-40014 Jyväskylä, Finland
† Magister Solutions Ltd, Hannikaisenkatu 41, FIN-40100 Jyväskylä, Finland
Email: {zheng.chang, tapani.ristaniemi}@jyu.fi

***Abstract*—This work addresses the radio resource allocation problem for cooperative relay assisted OFDMA wireless network. The relays adopt the decode-and-forward protocol and can cooperatively assist the transmission from source to destination. Recent works on the subject have mainly considered symmetric source-to-relay and relay-to-destination resource allocations, which limits the achievable gains through relaying. In this paper we consider the problem of asymmetric radio resource allocation, where the objective is to maximize the system throughput of the source-to-destination link under various constraints. In particular, we consider optimization of the set of cooperative relays and link asymmetries together with subcarrier and power allocations. We derive theoretical expressions for the solutions and illustrate them through simulations. The results validate clearly the additional performance gains through asymmetric cooperative scheme compared to the other recently proposed resource allocation schemes.**

***Index Terms*—OFDMA, relay selection, subcarrier allocation, asymmetric power allocation, and cooperative communications**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is an effective technique that exploits the benefits of Orthogonal Frequency Division Multiplexing (OFDM) for combating against channel noise and multipath effects and finally enables high data rate transmissions over fading channels. In addition, OFDMA is able to provide good bandwidth scalability as the number of subcarriers can be flexibly configured. Therefore, OFDMA is widely adopted in many standards of upcoming wireless communication systems, such as IEEE 802.11ac [1], LTE/LTE-A [2] and WiMAX [3].

Meanwhile, cooperative communication has emerged as one of the main trends to reach even better system performance in terms of throughput, energy efficiency or cell coverage. Therefore, the incorporation of OFDMA and cooperative relays is foreseen to result in a promising structure that offers a possibility to reach many desirable objectives for the future wireless networks. However, a combination of a conventional one-to-many (single hop) OFDMA system and a relay network calls for a careful design of the radio resource allocation (RRA) principles. This means a careful design and coordination of the power and subcarrier allocation, selection of relay(s) across different hops and optimizing the resource asymmetries between the hops.

The RRA algorithm plays an important role in the developments of both conventional and relay-aided OFDMA systems. The related works have been widely done in several different areas [4]-[10]. A cross-layer optimization algorithm for resource allocation in conventional OFDMA network has been presented in [4] without considering any relays and an iterative algorithm has proposed to solve the subcarrier assignment together with relay selection in [5]. Then, the power allocation problem is supposed to be solved by another iterative method based on waterfilling algorithm. Authors in [6] introduced a closed-form solution for radio resource allocation for multi-hop cooperative relay network. However, the per-tone power constraint was assumed. The scheme used in [7] considered fairness constraints when selecting relays. In [8], a threshold method was proposed to solve two subproblems, subcarrier allocation and power allocation. Although the performance was shown to improve compared to some other algorithms, the total power constraint was considered instead of per-node power limitation. The work in [9] also proposed a subcarrier and relay pairing algorithm to solve the existing RRA problem but results in higher computational complexity. Moreover, all the previous works have assumed the transmission durations of base-to-relay and relay-to-source links to be equal, which may result in reduced achievable gains. Recently, a study on the asymmetric resource allocation was presented in [10]. However, that work considered single relay in the OFDMA networks without exploring cooperative diversity.

In this paper we take into consideration the shortcomings of the above mentioned approaches. In particular, we consider asymmetric link allocations meaning that the source-to-relay link (first hop) and relay-to-destination link (second hop) are not necessary equal. We then investigate the RRA problem in this setting and propose a method to solve the joint relay set selection for cooperation in addition to asymmetry, subcarrier and power allocations, and hence target to enhance the total system throughput. The use case selected in this paper is cell coverage extension, so we do not consider direct link from source to destination to be utilized. We propose a relay selection scheme, where the selected set of relays will obtain the best overall link data rate through collaboration. The sets of orthogonal frequency subcarriers are then assigned to the selected relays at each hop. Power allocation is performed to the source and relays under per-node constraints, which is more realistic than the scheme e.g. in [8] where only the whole system power sums are considered. We consider only

978-1-4673-3133-3/13/$31.00 ©2013 IEEE

downlink direction in this work, but it can be extended further to the uplink case as well. To the best of our knowledge, such joint optimization for asymmetric two hop OFDMA network has not been reported so far.

The rest of the paper is organized as follows. Section II describes the relay-assisted OFDMA cooperative wireless network and formulates the problem. In Section III, the proposed resource allocation schemes are presented. We demonstrate the benefits of our proposed algorithm in section IV and finally conclude the paper in Section V.

II. Problem Formulation

This paper investigates the RRA problem for OFDMA network with cooperative relays in the downlink. We consider a two-hop time-division duplex downlink relay system. The whole system consists of source (i.e., access point, AP), destination node (i.e., mobile terminal, MT) and several relays. The first hop is so called broadcast phase, where AP broadcasts information to a cluster of decode-and-forward (DF) relays. At second hop, relays cooperate to transmit data to the MT, so that, e.g., spatial diversity gain can be achieved (relays are assumed to be far enough to each other). The channel state information (CSI) is assumed to be known at receiver and then fed back to the transmitter perfectly. We assume a total of Z relays in the networks, and the selected relay cluster $\mathcal{K}$ contains K potential half-duplex relays. The presented relay-assisted cooperative OFDMA network is as shown in Fig. 1, where $K = 3$.

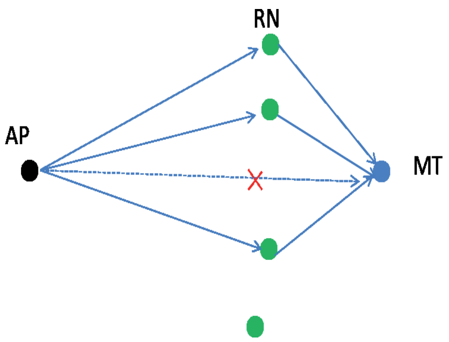


Figure 1. Wireless cooperative relay network scenario.

Suppose h^i is the channel transfer function from transmitter to receiver and we assume the channel to be static within a time slot. For example, $h^i_{s,k}$ means the channel transfer function from AP s to relay node (RN) k over OFDM subcarrier i and $h^j_{k,d}$ means the channel transfer function from RN k to destination d over OFDM subcarrier j. Thus we have the channel gain of the first hop $G^i_{s,k} = |h^i_{s,k}|^2$ and the second hop $G^j_{k,d} = |h^j_{k,d}|^2$. L is the path loss factor and the noise variance for the first and second hops are σ^2_k and σ^2_d, respectively. We denote the transmit power assigned to subcarrier i for transmitting data as P^i. In this work, we do not consider the direct link from AP to MT. This assumption is practical in the case that RNs are used for cell extension or cell edge optimization. One RN k occupies subcarrier i in the first hop and j in the second hop. In this work, we assume that the transmission durations for the first hop and second hop are allowed to differ. We denote these durations as T_1 and T_2. Therefore, in the first hop, the data rate of the broadcast phase is determined by the minimum rate of each link between AP and selected RNs. The achieved throughput of the first hop is as follows:

$$R^{\mathcal{I}}_{s,\mathcal{K}} = \min_{k\in\mathcal{K}} \Big\{ \frac{T_1}{T} log(1+\sum_{i=1}^{M} \omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k})\Big\}, \qquad (1)$$

where $\gamma^i_{s,k} = \frac{L_{s,k}G^i_{s,k}}{\sigma^2_k}$ is the channel SNR and $T = T_1 + T_2$. $\mathcal{M}$ is the subcarrier set of the system that contains M subcarriers. $\mathcal{I}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at the first hop. ρ_k indicates that whether RN k is chosen for subcarrier allocation,

$$\rho_k = \begin{cases} 1 & \text{, if } k \text{ is chosen for relaying,} \\ 0 & \text{, otherwise.} \end{cases}$$

We also define ω as the indicator whether certain subcarrier is assigned to RN k, for example,

$$\omega^i_{s,k} = \begin{cases} 1 & \text{, if } i \text{ is assigned to } k \text{ at first hop,} \\ 0 & \text{, otherwise.} \end{cases}$$

For the second hop, it is assumed that the RNs are perfectly synchronized. Therefore, the second hop can be viewed as a virtual MISO link and the throughput can be expressed as [11]

$$R^{\mathcal{J}}_{\mathcal{K},d} = \frac{T_2}{T} log(1+\sum_{j=1}^{M}\sum_{k=1}^{K} \omega^j_{k,d}\rho_k P^j_{k,d}\gamma^j_{k,d}), \qquad (2)$$

where $\gamma^j_{k,d} = \frac{L_{k,d}G^j_{k,d}}{\sigma^2_d}$. $\mathcal{J}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs. For indicator $\omega^j_{k,d}$, we also have

$$\omega^j_{k,d} = \begin{cases} 1 & \text{if } j \text{ is assigned to } k \text{ at second hop,} \\ 0 & \text{otherwise,} \end{cases}$$

Therefore, the total achieved end-to-end throughput of source s to destination d through RN set $\mathcal{K}$ is [12]

$$R_{sd} = min\ \Big\{ R^{\mathcal{I}}_{s,\mathcal{K}}, R^{\mathcal{J}}_{\mathcal{K},d} \Big\}. \qquad (3)$$

To proceed, we can formulate our RRA problem as

$$max\ \ R_{sd}, \qquad (4)$$

subject to

$$
\begin{aligned}
&T = T_1 + T_2, \\
&\sum_{i=1}^{M}\sum_{k=1}^{K}\omega_{s,k}^{i}P_{s,k}^{i} \le P_{s,max}, \\
&\sum_{j=1}^{M}\omega_{k,d}^{j}P_{k,d}^{j} \le P_{k,max}, \\
&\sum_{k=1}^{K}\omega_{s,k}^{i} = 1, \omega_{s,k}^{i} \in \{0,1\}, \\
&\sum_{k=1}^{K}\omega_{k,d}^{j} = 1, \omega_{k,d}^{j} \in \{0,1\},
\end{aligned} \tag{5}
$$

where $P_{s,max}$ is the maximum transmit power of AP and $P_{k,max}$ is the maximum power of RN k. Therefore, our goal is to find the optimal solutions for relay set, link asymmetry, and subcarrier and power allocations which satisfy the problem (4).

It can be deduced that achieving maximum for (3) implies $R_{s,\mathcal{K}}^{\mathcal{I}} = R_{\mathcal{K},d}^{\mathcal{J}}$ [8]. Thus, (4) can be modified as

$$
\arg\max \ \left(R_{s,\mathcal{K}}^{\mathcal{I}} + R_{\mathcal{K},d}^{\mathcal{J}}\right), \tag{6}
$$

subject to conditions in (5) and

$$
R_{s,\mathcal{K}}^{\mathcal{I}} = R_{\mathcal{K},d}^{\mathcal{J}}. \tag{7}
$$

III. Resource Allocation Scheme

In this section, we introduce an adaptive RRA algorithms to solve the existing problems described in the previous section. Although the resource allocation problem is combinatorial in nature with a non-convex structure, it has been shown in [14] that the duality gap of the optimization problem becomes zero under the condition of time-sharing regardless of its convexity. For the general OFDM system, the condition of time-sharing is always fulfilled as the number of subcarriers is large enough. Therefore, the problem can be solved in the dual domain. The Lagrangian [13] of (6) is

$$
\begin{aligned}
\mathcal{L}(\mathbf{P}, T, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}) = &\left(R_{s,\mathcal{K}}^{\mathcal{I}} + R_{\mathcal{K},d}^{\mathcal{J}}\right) \\
&-\lambda_s\left(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega_{s,k}^{i}P_{s,k}^{i} - P_{s,max}\right) \\
&-\sum_{k=1}^{K}\lambda_{k,d}\left(\sum_{j=1}^{M}\omega_{k,d}^{j}P_{k,d}^{j} - P_{k,max}\right) \\
&-\mu(R_{s,\mathcal{K}}^{\mathcal{I}} - R_{\mathcal{K},d}^{\mathcal{J}}),
\end{aligned} \tag{8}
$$

where $\mathbf{P} = \{P_{s,k}^{i}, P_{k,d}^{j}\}$ is the set of power allocations, $\boldsymbol{\omega} = \{\omega_{s,k}^{i}, \omega_{k,d}^{j}\}$ denotes the subcarrier allocations and $\boldsymbol{\rho} = \{\rho_k\}$ is the relay assignment. The λ_s, $\lambda_{k,d}$ and μ are Lagrange multipliers. Then it can be seen that $\boldsymbol{\lambda} = \{\lambda_s, \lambda_{k,d}\} \ge 0$ and $\boldsymbol{\mu} = \{\mu\} \in (-1, 1)$ [10]. The Lagrange dual function can be written as

$$
g(\boldsymbol{\lambda}, \boldsymbol{\mu}) = \max \mathcal{L}(\mathbf{P}, T, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}). \tag{9}
$$

We assume the number of subcarrier is sufficiently large, so that the duality gap between primal problem and dual function can be assumed negligible [14]. Consequently, we can solve the problem (4) by minimizing the dual function,

$$
\min \ g(\boldsymbol{\lambda}, \boldsymbol{\mu}). \tag{10}
$$

A. Evaluating Dual Variable

Since the dual function is always convex [13], we can choose e.g. sub-gradient or ellipsoid method [14] with guaranteed convergence to minimize $g(\boldsymbol{\lambda}, \boldsymbol{\mu})$. We follow the subgradient method in [14] to derive the subgradient $g(\boldsymbol{\lambda}, \boldsymbol{\mu})$ with the optimal power allocation p^* that will be presented in the following subsection.

Algorithm 1 Evaluating Dual Variable

1: Initialize $\boldsymbol{\lambda}^0$ and $\boldsymbol{\mu}^0$
2: **while** (!Convergence) **do**
3: Obtain $g(\boldsymbol{\lambda}^a, \boldsymbol{\mu}^a)$ at the ath iteration;
4: Update a subgradient for $\boldsymbol{\lambda}^{a+1}$ and $\boldsymbol{\mu}^{a+1}$, by $\boldsymbol{\lambda}^{a+1} = \boldsymbol{\lambda}^a + \upsilon^a \triangle\boldsymbol{\lambda}$ and $\boldsymbol{\mu}^{a+1} = \boldsymbol{\mu}^a + \upsilon^a \triangle\mu$;
5: **end while**

Here $\triangle\boldsymbol{\lambda} = \{\triangle\lambda_s, \triangle\lambda_{1,d}, ...\triangle\lambda_{K,d}\}$, and moreover $\triangle\lambda_s$, $\triangle\lambda_{k,d}$ and $\triangle\mu$ can be expressed as

$$
\begin{aligned}
&\triangle\lambda_s = P_{s,max} - \sum_{i=1}^{M}\sum_{k=1}^{K}(P_{s,k}^{i})^* \\
&\triangle\lambda_{k,d} = P_{k,max} - \sum_{j=1}^{M}(P_{k,d}^{j})^* \\
&\triangle\mu = (R_{s,\mathcal{K}}^{\mathcal{I}})^* - (R_{\mathcal{K},d}^{\mathcal{J}})^*.
\end{aligned} \tag{11}
$$

Here υ^a is the stepsize and a is the number of iterations. The sub-gradient algorithm (Algorithm 1) is guaranteed to converge to the optimal $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$. The computational complexity of Algorithm 1 is polynomial in the number of dual variable $K+1$ [14]. Since (9) can be viewed as a nonlinear integer programming problem, its optimal solution requires high computational cost. Therefore, we are aiming to solve the optimization problem by solving three subproblems, which are relay selection, subcarriers and power allocation. Firstly, we introduce asymmetric power allocation scheme.

B. Asymmetric Power Allocation

By assuming the relay selection and subcarrier allocation are done, the optimal time slot for each hop can be achieved by using Karush-Kuhn-Tucker (KKT) conditions [13]. This results in

$$
T_1 = \frac{1-\mu^*}{2}T, \tag{12}
$$

$$
T_1 = \frac{1+\mu^*}{2}T. \tag{13}
$$

Recalling the Lagrange dual function of (9), the optimal power allocation problem can be determined by solving problem (8) over variables $P_{s,k}^i$ and $P_{k,d}^j$. Applying KKT conditions we obtain the optimal power allocation for the first hop:

$$(P_{s,k}^i)^* = \{\frac{(1-\mu^*)^2}{2\lambda_s^*} - \frac{1}{\gamma_{s,k}^i}\}^+, \tag{14}$$

where $\{x\}^+ \triangleq max\{0,x\}$. Similarly, for the cooperation phase (second hop), the optimal RN power allocation is

$$(P_{k,d}^j)^* = \{\frac{(1+\mu^*)^2}{2\lambda_{k,d}^*} - \frac{1}{\gamma_{k,d}^j} - \frac{\sum_{m=1,m\neq k}^K L_{m,d}G_{m,d}P_{m,d}}{G_{k,d}^j L_{k,d}}\}^+. \tag{15}$$

where $G_{m,d}$ denotes the channel gain from relay m to MT and $P_{m,d}$ is the power allocation for relay m on other subcarriers.

C. Optimal Relay Selection (ORS)

We consider a multiple relay selection in this work, unlike some traditional single relay selection algorithms in [9] and [15]. The proposed algorithm is to select K RNs to form a cluster that can maximize the achieved throughput in (3). We can rewrite (8) as

$$\begin{aligned}\mathcal{L}(\mathbf{P},T,\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda}) = &\min_{k\in\mathcal{K}}\Big\{\frac{T_1}{T}log(1+\sum_{i=1}^M \omega_{s,k}^i\rho_k P_{s,k}^i\gamma_{s,k}^i)\Big\}\\ &+\frac{T_2}{T}log(1+\sum_{i=1}^M\sum_{k=1}^K \omega_{s,k}^i\rho_k P_{k,d}^j\gamma_{k,d}^j\sigma_d^2)\\ &-\mu\Big(\min_{k\in\mathcal{K}}\Big\{\frac{T_1}{T}log(1+\sum_{i=1}^M \omega_{s,k}^i\rho_k P_{s,k}^i\gamma_{s,k})\Big\}\\ &-\frac{T_2}{T}log(1+\sum_{i=1}^M\sum_{k=1}^K \omega_{s,k}^i\rho_k P_{k,d}^j\gamma_{k,d}^j)\Big)\\ &+\lambda_s(\sum_{i=1}^M\sum_{k=1}^K \omega_{s,k}^i P_{s,k}^i - P_{s,max})\\ &-\sum_{k=1}^K\lambda_{k,d}(\sum_{j=1}^M \omega_{k,d}^j P_{k,d}^j - P_{k,max}).\end{aligned} \tag{16}$$

Assuming the subcarrier and power allocations done, then applying KKT condition the RN is selected according to the following rule:

$$\begin{aligned}k^* = \arg\max_k &\Big(\min_{k\in\mathcal{K}}\Big\{\frac{(1-\mu^*)^2}{2}\Big(\frac{P_{s,k}^i\gamma_{s,k}^i}{1+P_{s,k}^i\gamma_{s,k}^i}\Big)\Big\}\\ &+\frac{(1+\mu^*)^2}{2}\Big(\frac{P_{k,d}^j\gamma_{k,d}^j}{1+\sum_k^K P_{k,d}^j\gamma_{k,d}}\Big)\Big).\end{aligned} \tag{17}$$

Optimal value of $\mathbf{P}$ are given in (14) and (15). Therefore, (17) can be viewed as multi-objective optimization problem, which aims at obtaining the trade-off of the first hop and second hop. Termination criteria for the whole RRA scheme is to find an optimal subcarrier set $\mathcal{K}^*$ that satisfies:

$$\begin{aligned}max\ &\Big(\min_{k\in\mathcal{K}^*}\Big\{\frac{(1-\mu^*)^2}{2}\Big(\frac{P_{s,k}^i\gamma_{s,k}^i}{1+P_{s,k}^i\gamma_{s,k}^i}\Big)\Big\}\\ &+\frac{(1+\mu^*)^2}{2}\Big(\frac{P_{k,d}^j\gamma_{k,d}^j}{1+\sum_k^K P_{k,d}^j\gamma_{k,d}}\Big)\Big).\end{aligned} \tag{18}$$

Therefore, the relay selection strategy can be chosen according to

$$\rho_k = \begin{cases} 1 & \text{, if } k\in\mathcal{K}^*,\\ 0 & \text{, otherwise.}\end{cases}$$

D. Optimal Subcarrier Allocation (OSA)

The goal of subcarrier allocation strategy is to assign subcarriers to given RNs that can obtain the best throughput performance. Following the same procedure as the relay selection, we can obtain the subcarrier allocation criteria as follows:

$$I^* = \arg\max\ \Big(\min_{k\in\mathcal{K}}\Big\{\frac{(1-\mu^*)^2}{2}\Big(\frac{P_{s,k}^i\gamma_{s,k}^i}{1+P_{s,k}^i\gamma_{s,k}^i}\Big)\Big\}\Big), \tag{19}$$

$$J^* = \arg\max\ \Big(\frac{(1+\mu^*)^2}{2}\Big(\frac{P_{k,d}^j\gamma_{k,d}^j}{1+\sum_k^K P_{k,d}^j\gamma_{k,d}^j}\Big)\Big). \tag{20}$$

If we denote the optimal subcarrier sets for the first and second hop as $\mathcal{I}^*$ and $\mathcal{J}^*$, respectively, the indicator for optimal subcarrier allocations can be expressed as

$$\omega_i = \begin{cases} 1 & \text{, if } i\in\mathcal{I}^*,\\ 0 & \text{, otherwise,}\end{cases}$$

$$\omega_j = \begin{cases} 1 & \text{, if } j\in\mathcal{J}^*,\\ 0 & \text{, otherwise.}\end{cases}$$

E. Joint Asymmetric Relay, Subcarrier and Power Allocation

We have described the algorithms for relay selection, subcarrier and power allocation in the previous subsections. Combining the above three procedures together with asymmetric time design, we can obtain optimal solution for (4). The flow chart of the whole algorithm is shown in Fig. 2. We can see that these three steps are conducted alternatively until the convergence is reached.

IV. Performance Evaluation

In this section we illustrate the performance of the RRA algorithm with couple of examples. We assume five RNs located between AP and MT, and MT is 1.8km away from AP. One example of RN distribution is shown in Fig. 3 when four RNs are selected for transmission. The Stanford University SUI-3 channel model is employed without considering multipath effect [16], in which the central frequency is 1.9GHz. A three-tap channel is invoked and signal fading follows Rician distribution. We choose the number of subcarriers N to be 32, so the duality gap can be ignored [9]. Flat quasi-static fading channels are considered, hence the channel coefficients are assumed to be constant during a complete frame, and can

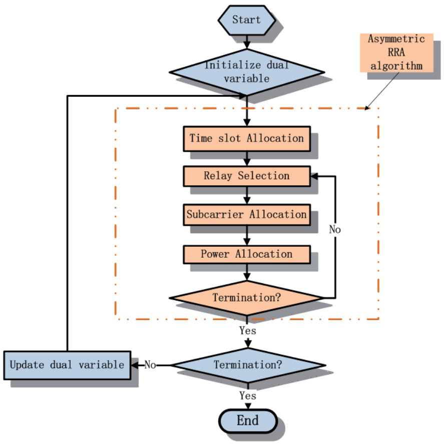


Figure 2. Algorithm flow chart

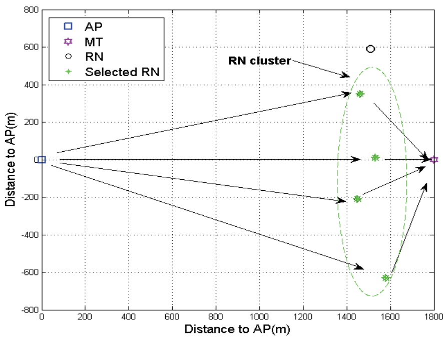


Figure 3. Relay node distribution and 4 RNs are selected

vary from a frame to another independently. The noise variance of the two hops are set to be 1 for simplicity. The path loss factor varies according to the different distances from RNs to AP and MT and the exponent is fixed to 3.5. The maximum transmit power of AP and RN are set to 40 dBm and 20 dBm, respectively.

We demonstrate our results compared with the performance of recently reported symmetric or asymmetric schemes:

1) Equal power allocation combined with proposed subcarrier allocation scheme and relay selection (EPA);

2) Waterfilling power allocation combined with proposed subcarrier allocation scheme and relay selection (Waterfilling);

3) Proportional Allocation scheme in [8] with fairness consideration (Fairness SA);

4) Asymmetric Resource Allocation scheme in [10] without cooperative relay assisted (ARA);

Fig. 4 demonstrates the impact of maximum transmit power

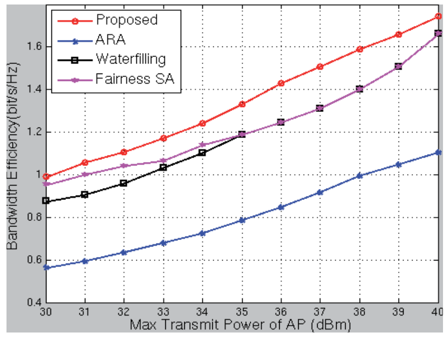


Figure 4. Impact of maximum transmit power $P_{s,max}$ on system bandwidth Efficiency

of AP on the system bandwidth efficiency. We denote $D_{s,d}$ as the distance between AP and MT, and $D_{s,k}$ as the distance between AP and RNs. In Fig. 4, we have $D_{s,d} = 1800\ m$ and $D_{s,k}$ from $1500\ m$ to $1600\ m$. The considered channel SNR at the RN k is varied from $\gamma_{s,k} = -20dB$ to $\gamma_{s,k} = -30dB$ and at MT d it is varied from $\gamma_{k,d} = -15dB$ to $\gamma_{k,d} = -25dB$. It can be seen that the proposed scheme achieves the best performance. The performance gain over other methods in comparison is up to 20%. It can also be noticed that if Waterfilling is used as the power allocation scheme (instead of our proposed scheme), the throughput performance is comparable with Fairness SA. Another performance gain can be seen in power consumption. We can see that with a fixed data rate requirement, our proposed scheme provides a clear power saving gain. For instance, at the level of 1.2 bit/s/Hz bandwidth efficiency our proposed scheme can reach a power saving around 2 dB compared to the other schemes.

Figs. 5 and 6 show the impact of distance between the AP and RNs on the system performance. The distances between AP and RNs are normalized to $D_{s,d}$ and varies from 0.1 to 0.9. In Fig. 5, we set the maximum AP power to $P_{s,max} = 35\ dBm$ and the maximum power of each RN to $P_{k,max} = 20\ dBm$, whereas we assume maximum power of each node to be $20\ dBm$ in Fig. 6. From Fig. 5, we can see that the proposed algorithm obtains the highest system capacity when the normalized distance is less than 0.9. When the average normalized distance between AP and RNs is around 0.9, we can find that the proposed scheme has comparable performance with the EPA algorithm. This results from the fact that some RNs are already very close to the MT so the achieved SNR is relatively high leaving less impact to power allocation schemes. The same situation can be observed in Fig. 6 where less AP power is considered. It can be concluded that the proposed algorithm can provide a noticeable performance gain over other existing algorithms even with rather low limits for AP maximum power.

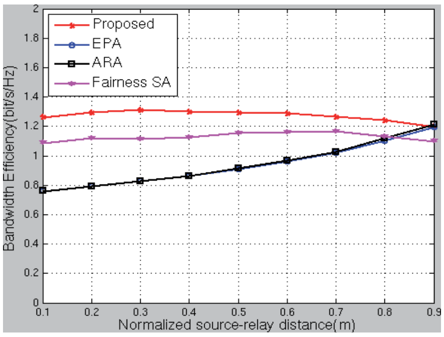


Figure 5. Impact of distance between AP and Relay on the system bandwidth efficiency, maximum AP power is 35 dBm, maximum RN power is 20 dBm

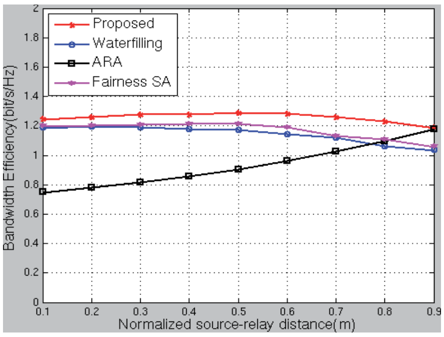


Figure 6. Impact of distance between AP and Relay on the system bandwidth efficiency, maximum power of each node is 20 dBm

V. Conclusion

In this paper we investigated the problem of asymmetric resource allocation for cooperative multi-relay assisted OFDMA networks. The joint optimization problem for radio resource allocation was solved by addressing three subproblems including optimal selection of collaborative relays, subcarriers and power with the objective of maximizing the system throughput. Theoretical expressions were derived for the optimal selections. It was shown that by designing asymmetric time slots for different hops, it is possible to reach a noticeable gain in the cell-edge throughput. This was also illustrated with simulation examples.

Acknowledgement

The authors would like to thank Graduate School in Computing and Mathematical Science (COMAS) and NOKIA foundation for the support.

References

[1] IEEE P802.11, [Online]. available: http://www.ieee802.org/11/Reports/

[2] *3rd Generation Partnership Project Specifications Home Pages.* [Online]. available: http://www.3gpp.org/specs/specs.htm

[3] *IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface*, IEEE std. 802.16-2011, Jun.1998

[4] G. Song and Y. Li, "Cross-layer Optimization for OFDM Wireless Networks-Part 1: Theoretical Framework," *IEEE Transaction on Wireless Communications*, Vol.4, No.2, pp.614-624, Mar. 2005.

[5] T.C-Y. Ng and W. Yu, "Joint Optimization of Relay Strategies and Resource Allocation in Cooperative Cellular Networks," *IEEE Journal on Selective Area in Communications*, Vol.25, No.2, pp.328-339 ,Feb. 2007.

[6] S-K. Kim, X. Wang, and M. Madihian, "Optimal Resource Allocation in Multi-hop OFDMA Wireless Networks with Cooperative Relay," *IEEE Transaction on Wireless Communications*, Vol.7, No.5, pp.1833-1838, May 2008.

[7] H. Jeong and J. H. Lee, "Adaptive Relay Selection for Regenerative OFDMA Relay Networks with Fairness Constraints," *Proc. of IEEE VTC 2008-fall*, Calgary, Canada, Sep. 2008.

[8] M. Tang, X. Wang, Y. Wang and J. Liao, "Dynamic Resource Allocation with Threshold in OFDMA-based Relay Networks," *Proc. of IEEE VTC 2010-Spring*, Taipei, Taiwan, May 2010.

[9] W. Dang, M.Tao, H. Mu and J. Huang, "Subcarrier-Pair Based Resource Allocation for Cooperative Multi-Relay OFDM systems," *IEEE Transaction on Wireless Communications*, Vol.9, No.5, pp. 1640-1649, May 2010.

[10] N. Zhou, X. Zhu and Y. Huang, "Optimal Asymmetric Resource Allocation and Analysis for OFDM-Based Multidestination Relay Systems in the Downlink," *IEEE Transaction on Vehicular Technology*, Vol.60, No.3, pp. 1307-1312, March 2011.

[11] D. Tse and P. Viswanath. *Fundamentals of Wireless Communications*, Cambridge UK: Cambridge University Press, 2005.

[12] Z. Chang and T. Ristaniemi, "Radio Reource Allocation for Cooperative Relay-assisted OFDMA Wireless Networks," *Proc. of 3rd Internatial Workshp on Cross-layer Desgin(IWCLD)*, Rennes, France, Nov. 2011.

[13] S. Boyd, and L. Vandenberghe, *Convex Optimization* , Cambridge UK: Cambridge University Press, 2004.

[14] W. Yu and R. Lui, "Dual Methods for Nonconvex Spectrum Optimization in Multicarrier System," *IEEE Transaction on Communications* , Vol.54, No.7, pp.1310-1322, Jul. 2006.

[15] A. S. Ibrahim, A. K. Sadek, W. Su, and K. J. R. Liu, "Cooperative Communications with Relay-Selection: When to Cooperate and Whom to Cooperate With," *IEEE Transaction on Communications*, Vol.7, No.7, pp.2814-2827, July 2008.

[16] R. Jain, *Channel Models A Tutoriall v1.0* , Feb. 2007.

PVI

EFFICIENT USE OF MULTICAST AND UNICAST IN COLLABORATIVE OFDMA MOBILE CLUSTER

by

Zheng Chang and Tapani Ristaniemi 2013

Proc. of 77th IEEE Vehicular Technology Conference (VTC'13-spring)

Efficient Use of Multicast and Unicast in Collaborative OFDMA Mobile Cluster

Zheng Chang*† and Tapani Ristaniemi†
*Magister Solutions Ltd, Hannikaisenkatu 41, FIN-40100 Jyväskylä, Finland
†Department of Mathematical Information Technology, University of Jyväskylä, P.O.Box 35, FIN-40014 Jyväskylä, Finland
Email: zheng.chang@magister.fi, tapani.ristaniemi@jyu.fi

***Abstract*—Future wireless services induces higher demands for the circuits of mobile terminals, which will subsequently increase energy usage and hence limit users' abilities to experience high quality of multimedia services offered by the high data rate wireless systems. In order to address this problem, we advocate a model called collaborative mobile cluster (CMC), that is foreseen as one of the potential solutions to reduce energy consumption per terminal in a network by enabling collaboration within a cluster of mobile terminals. We first compare the energy efficiency performance of unicast and multicast transmission strategies within the CMC. In addition, we propose an algorithm that can dynamically use unicast as an additional support for multicast, ultimately overcoming the inherent drawbacks of sole multicast. Analytical results are derived and illustrated by simulations. The analysis demonstrates that: i) CMC enables a great potential to reduce the per-terminal energy consumption; ii) unicast and multicast transmissions are two optional candidates, but a proper combination of them allows better energy saving gain while still fulfilling the minimum data rate requirement.**

***Index Terms*—OFDMA; energy consumption; energy efficiency; multicast; unicast; collaborative mobile cluster;**

I. Introduction

Due to the tremendous growth of the wireless market, the next-generation wireless communication systems are going toward offering broadband multimedia services. In order to accommodate such high-data traffic services, aggressive wireless techniques will be utilized to the mobile terminals (MTs), which consequently induce high energy consumption [1]. It is essential that MTs can fully exploit the high throughput gains offered by future wireless network whenever possible. However, the high energy consumption limits this due to the capacity limitation of battery and thus, the user experience of high-data rate multimedia services would be seriously impacted. Therefore, alleviating energy consumption of the MTs emerges as a critical issue to prolong the battery life in the future wireless networks.

For energy saving purpose, some research works have been done by improving transmission and receiving mechanism for a single receiver [1][2]. In [2], an overview of discontinuous reception (DRX) which is used in LTE to reduce receiver power consumption is presented. Authors in [1] introduced a resource allocation scheme which can dynamically allocate time and frequency to reduce the receiving energy consumption per single receiver. Meanwhile, [3] dedicated the work on the power saving schemes for wireless distributed computing networks. However, papers focused more on power saving performance of computing tasks rather than the one of wireless communications. In [4], short-range cooperation among MTs was proposed as a key idea to alleviate the transmit energy consumption for the data transfer from MTs to AP. Energy saving gains obtained by using different combination of technologies for short-range communications were also derived. However, they only considered transmit energy consumption excluding the studies on receiver side.

Regarding per-terminal energy consumption, we examined the energy efficiency performance of a collaborative mobile cluster (CMC) [5]. In CMC, several MTs can collaboratively receive the information data from access point (AP), and then exchange the received data with others. The CMC is also known as mobile cloud [6], whose operation mechanisms can ensure the model to has advantages on performing social interactions among numbers of users and improve the local services [7]. Although we assume the transmission scheme within CMC was unicast [5], the question of how to handle the inter-device transmissions is still under research. It is known that multicast transmission is an efficient method for group-data transmission [8]. Through broadcast in radio channels, a multicast transmission increases transmission efficiency due to reduction of transmitted redundant data. However, wireless multicast should be adapted according to the worst channel state user in a multicast group. Hence, the system capacity of multicast transmission is affected both by the number of users and the supportable data rate of MT with worst instantaneous channel condition. On the other hand, unicast transmission utilizes wireless channel variations and obtain the multiuser diversity gain [9]. Meanwhile, the unicast transmission can utilize the channel variation on the expense of introducing transmission overhead for same data. Therefore, unicast transmission is costly from the radio resources point of view.

As we can see, both of two strategies have their advantages and drawbacks. In light of reducing per-node energy consumption in the downlink while fulfilling the system requirements, we extend our previous research in [5] and provide detailed energy consumption analysis of the CMC using two different transmission strategies. Moreover, we propose a new algorithm, namely Unicast Supported Multicast (USM) scheme for CMC, which can dynamically use unicast as additional support multicast whenever seen advantageous

This work was partly supported by the Celtic-plus project Green-T(Project ID CP08-006).

from per-terminal energy saving purposes. The proposed USM scheme is designed to overcome the inherent drawback of multicast. By investigating analytical and numerical results, we discuss the benefits of exploiting two different transmission strategies as well as the significant improvements when using USM in CMC.

II. System Model and Problem Formulation

A. System Model

We consider an OFDMA network that consists of one AP and several MTs, where K MTs can form a CMC. All the MTs inside CMC are assumed to require the same data from AP, e.g. video. Each MT is assumed to be a dual-mode device, equipped with a short-range (e.g., WLAN) wireless communication technique for performing inter-terminal communications, and also equipped with broadband access technique(e.g., LTE/LTE-A) for receiving from AP. The channel information is assumed to be known for the considered scenario. The system model is as shown in Fig. 1, where $K = 3$.

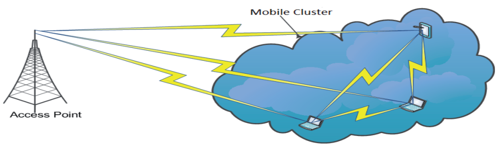


Figure 1. OFDMA network with Collaborative Mobile Cluster.

B. Problem Formulation

We first invoke the Resource Block Unit (RBU) as the elementary resource unit in our work. A RBU is defined as a certain frequency bandwidth W in one time slot. We assume that P_{AP} is the circuit power of MT that is used for receiving data in the bandwidth W of one RBU from AP. We also assume that there are total M RBUs that are invoked for transmission from AP to a single MT. Therefore, in case there is no collaboration between the terminals, the total per-terminal energy consumption E_{total} equals

$$E_{total} = MP_{AP}T_{AP}. \quad (1)$$

where T_{AP} is the duration of a time slot. Similarly, the total energy consumption per terminal in the case of CMC equals

$$E_{node} = E_{part} + E_{rx,node} + E_{tx,node}, \quad (2)$$

where E_{part} is the energy consumption of each MT which is used for receiving its assigned part of data from AP. Without any loss of generality, we assume $E_{part} = E_{total}/K$ meaning that each K MTs are assigned equal share of data. $E_{tx,node}$ and $E_{rx,node}$ are the transmit and receive energy consumption for data exchange inside the CMC, respectively. Examples of the CMC's unicast and multicast procedures are shown in Fig.

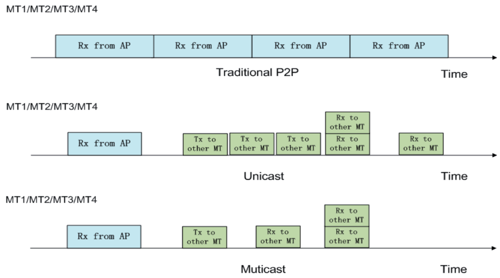


Figure 2. Traditional P2P vs. CMC unicast vs. CMC muticast

2 with comparison to traditional AP-MT (point-to-point) transmission. Regarding the terminals in CMC, denote $T_{tx,node}$ the transmit time, $I_{tx,node}$ the number of RBUs, P_E the baseband power consumption and $P_{rx,node}$ and $P_{tx,node}$ the transmit and receive RF power consumption for the terminal. The energy consumption per terminal for transmitting can be the expressed as

$$E_{tx,node} = I_{tx,node}(P_{tx,node} + P_E)T_{tx,node}. \quad (3)$$

With assumption of receive time duration $T_{rx,node}$ and number of RBUs $I_{rx,node}$, the energy consumption per terminal for receiving task is given as

$$E_{rx,node} = I_{rx,node}(P_{rx,node} + P_E)T_{rx,node} \quad (4)$$

Similarly, in case of no collaboration between the terminals the E_{total} is given as

$$E_{total} = M(P_{rx,AP} + P_E)T_{AP}. \quad (5)$$

where $R_{rx,AP}$ is the RF receive power for receiving from AP. The way to obtain RF power consumption can be found e.g. in [5].

III. Energy Saving of Using Unicast and Multicast

Since both unicast and multicast have their own advantages and drawbacks, how to choose one as the transmission strategy for the CMC is not obvious. Therefore, in this section, we first present the energy efficiency analysis for both strategies. For the sake of tractable analysis while not loosing any generality, we assume that every node inside CMC is assigned the same amount of resource for transmission. Thus, we have $I_{tx,node} = I_{rx,node} = I_{node}$, and $T_{tx,node} = T_{rx,node} = T_{node}$. Regarding unicast, the total energy consumption is as follows,

$$E_{node\_unicast}$$
$$=(K-1)(P_{rx,node}+P_{tx,node}+2P_E)I_{node}T_{node}+E_{total}/K$$
$$=\frac{MT_{AP}}{K}\big(P_{AP}+\frac{(K-1)(P_{tx_node}+P_{rx,node}+KP_E)}{\rho}\big) \quad (6)$$

Regarding multicast, the energy consumption is given as

$$E_{node\_multicast}$$
$$=((K-1)P_{rx,node}+P_{tx\_dist}+KP_E)I_{node}T_{node}+E_{total}/K$$
$$=\frac{MT_{AP}}{K}\big(P_{AP}+\frac{(K-1)P_{rx,node}+P_{tx\_dist}+KP_E}{\rho}\big) \quad (7)$$

where P_{tx_dist} is the RF transmit power to the receiver with worst channel quality and $I_{node}T_{node} = \frac{MT_{AP}}{K\rho}$. Here ρ is defined as the modulation radio, which depends on the amount of data that a subcarrier can carry, and in general, is decided by modulation and coding schemes (MCS). For example, if BPSK is used as modulation scheme from AP to MT and QPSK is used for inter-device communication inside MC, we have $\rho = 2$. Therefore, the energy saving ξ can be defined as

$$\xi = \begin{cases} E_{total} - E_{node\_unicast}, & \text{if unicast} \\ E_{total} - E_{node\_multicast}, & \text{if multicast.} \end{cases}$$

IV. Unicast Supported Multicast (USM)

In case of multicast transmission, the MT with worst inter-device channel quality requires higher transmit power in order to obtain the same data rate as others. Hence, the energy efficiency of multicast mode is deteriorated if the cluster of terminals in not compact but there exists one or more Mts having much worse inter-device channel conditions than the others. Therefore, in this section, we introduce a new transmission scheme, namely Unicast Supported Multicast (USM), which introduces the use of simultaneous unicast, as a support for multicast, in order to obtain better energy efficiency performance while meeting the system QoS requirement. One example of considered scenario for USM can be found in Fig. 3. We further refer the MTs in the CMC which do not require USM as 'multicast group', while the MT that needs additional unicast is called 'unicast MT'.

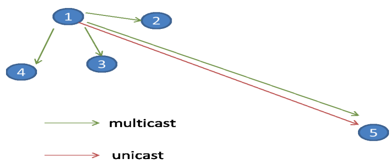


Figure 3. Considered Scenario with USM

The idea of the USM scheme is to allocate additional unicast channel to the specified MTs that can not obtain satisfied data rate as others when a fixed transmit power for multicast is used. How to perform USM is depicted in Algorithm 1.

Algorithm 1 Description of USM

1: Regarding the terminal who received data from AP, evaluate channel gains G_k between the other terminals k in CMC
2: Predefine channel gain G_T
3: Perform multicast transmission with power P_m, adjusted to worst G_k for which $\{G_k|G_k \geq G_T\}$
4: **if** $G_k < G_T$ **then**
5: perform USM using additional unicast transmit power P_u.
6: **end if**

A. Energy Efficiency of USM

USM aims to obtain better energy efficiency performance comparing with pure multicast transmission. From the previous description of USM, one may notice that the algorithm performance depends on the selection of P_m and P_u, i.e. the power of multicast group and additional power for unicast user. Hence, in this part, we will formulate the problem of power selection as well as examining the energy efficiency of the proposed USM scheme. In order to ensure the QoS, the inter-device transmission throughput for each MT in the CMC should fulfill the rate requirement of R_T,

$$R_T = log(1+\gamma_T) \quad (8)$$

where γ_T is the received Signal-to-Noise Ratio(SNR) of using multicast for all nodes and can provide data rate of R_T. Since inter-device distance is short, so it is reasonable to assume that channel gain is stable in a time slot and varying slowly. Due to the features of multicast transmission, if there exists a MT that has very bad channel condition, e.g., MT is far away from others, it requires higher power consumption for other inter-device source. So if there is a MT j that has very bad channel, the multicast data rate from MT i to MT j can be formulated as

$$R_{i,j} = log(1+\gamma_{i,j}) \quad (9)$$

where $\gamma_{i,j}$ is the received SNR of from MT i to MT j adopting multicast transmission. Meanwhile, we assume the SNR of unicast channel is as same as the one of multicast channel as well. Therefore, when a particular MT j needs additional unicast support, the needed additional data rate of it is given by

$$R_T - R_{i,j} = log\Big(\frac{1+\gamma_T}{1+\gamma_{i,j}}\Big) \quad (10)$$

Therefore, when using USM, MT j should has a unicast SNR γ_u

$$\gamma_u = \frac{\gamma_T - \gamma_{i,j}}{1+\gamma_{i,j}}. \quad (11)$$

Thus, we can see that the power saving obtained by using USM over multicast transmission depends on P_u, $\gamma_{i,j}$ and γ_T. Obviously, we have

$$\begin{cases} P_T = \gamma_T / G_{i,j}, \\ P_m = \gamma_{i,j} / G_{i,j}. \end{cases}$$

Hence, the power saving P_s obtained by using USM can be expressed as,

$$\begin{aligned} P_s &= P_T - P_m - P_u \\ &= \frac{\gamma_T}{G_{i,j}} - \frac{\gamma_{i,j}}{G_{i,j}} - \frac{\gamma_T - \gamma_{i,j}}{(1+\gamma_{i,j})G_{i,j}} \\ &= \frac{\gamma_{i,j}(\gamma_T - \gamma_{i,j})}{G_{i,j}(1+\gamma_{i,j})} = \frac{P_T - P_m}{\frac{1}{G_{i,j}P_m} + 1}. \end{aligned} \tag{12}$$

Since P_T and $G_{i,j}$ are fixed if we predefine the required QoS data rate and channel condition, our objective is to decide the value of P_m, which can maximize our power saving objective,

$$max\, P_s. \tag{13}$$

subject to

$$log(1 + P_m G_m) \geq R_T \tag{14}$$

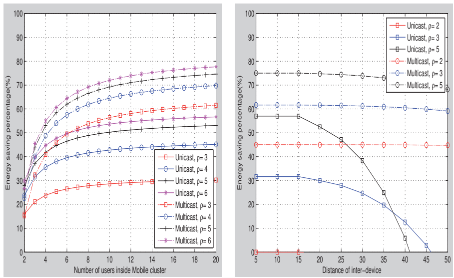
where G_m is the worst channel gain within the multicast group. We can notice that Eq. 13 is a convex optimization problem. Therefore, we can simply obtain the optimal value of P_m by applying the KKT conditions. Therefore, we could obtain the energy consumption for the MT that is close to others when using USM as follows,

$$\begin{aligned} &E_{node\_usm} \\ =&((K-2)P_{rx\_m} + P_{tx\_m} + (K-1)P_E)I_{node}T_{node} \\ &+ E_{total}/(K-1) + (P_{rx\_u} + P_{tx\_u} + 2P_E)I_{node}T_{node}. \end{aligned} \tag{15}$$

V. Numerical Results and Analysis

A. Unicast vs. Multicast

Results about impact of unicast and multicast transmission in a CMC are illustrated. Energy saving metric is defined as $\frac{\xi}{E_{total}} \times 100\%$. Parameters that are used here are the same as in [5]. The inter-device channel is defined in IEEE 802.11ac [10] with the assumption of indoor environment. The AP-MT channel is according to [11] with assumption around $1000m$ distance. Energy efficiency (EE) performance when considering different numbers of MTs inside MC and different values of ρ can be found in Fig. 4(a), where inter-device distance is assumed to be $20m$. From Fig. 4(a), we can see that as the number of MTs increases, energy saving gain obtained by using CMC arise as well. The energy saving percentage reach "almost" saturation when there are 20 MTs forming a CMC. It means that without any radio resource (e.g. RBUs) constraints, forming CMC can help MTs that are close to each other saving energy if proper MCS is used no matter which strategies are used. The performance of multicast is generally better than unicast when same scenario is assumed.



(a) Number of MTs vs. EE (b) inter-device dist vs. EE

Figure 4. Mutilcast vs. Unicast

If we fix the number of MTs inside MC to be 20, we could obtain the impact of inter-device distance and value of ρ in Fig. 4(b). We can observe that when the inter-device distance is shorter than $d_o = 15m$, the EE performance remains the same for same values of ρ in Fig. 4(b). Generally, we can see that lower order MCS should be used when inter-device distance is getting larger in order to achieve energy saving. For example, when inter-device distance is $20m$, we can obtain 55% when $\rho = 6$, which is the maximum energy saving percentage for that inter-device distance. However, $\rho = 5$ is the best choice when distance is $25m$. In this particular example, forming CMC will not result in any energy savings if the inter-device distance is longer than $45m$.

B. Performance of USM

From the previous subsection we can observe that if the distance among MTs inside CMC keeps the same, the EE of multicast transmission is superior to the one of unicast transmission. In this part, we analyze the energy efficiency of the proposed USM algorithm compared with sole multicast when there is a distant MT existing in the CMC as illustrated in Fig. 3.

First, we use the channel quality indicator that presents the difference of channel quality between unicast MT and multicast group, which is defined as $\chi = \frac{G_m - G_{i,j}}{G_m}$. The multicast group contains 20 MTs and has around 20m inter-device distance. χ is varied by changing the value of $G_{i,j}$, which by altering the position of unicast MT in practise. R_T is assumed to be 1 without loss of generality. The performance is measured by power saving, which is calculated as P_s/P_T. It is worth noticing that P_T is different for different $G_{i,j}$ so that QoS can be achieved. As we can observe from the Fig 5, our proposed USM scheme can achieve up to more than 50% power saving compared to the pure multicast transmission. It also worthy to remark that power saving gain obtained by USM arrives its maximum value when $\chi = 0.75$, which means

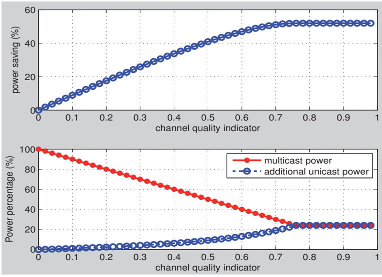


Figure 5. χ vs. power saving vs. multicast power

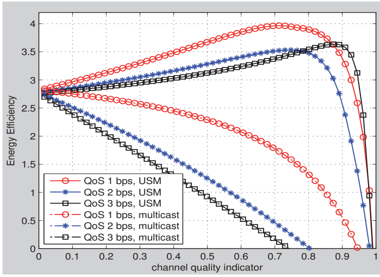


Figure 7. Energy Efficiency, USM vs. Multicast

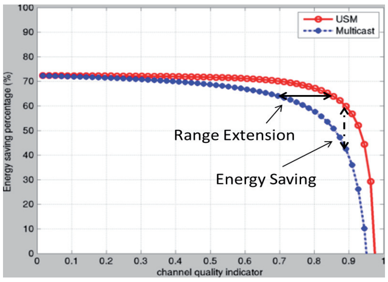


Figure 6. Energy Saving, USM vs. Multicast

that the use of USM is is beneficial when one node has much worse channel quality than the others.

The energy saving gain is illustrated in Fig. 6. One can observe that with USM, we can obtain range extension with same energy efficiency percentage. In other words, the CMC is able to host MTs that are further away from the others without any loss in energy savings. With the same channel quality, the USM can save more energy (e.g. 20% as we mark in the figure) than multicast. Therefore, the energy efficiency of USM over multicast for CMC can be easily noticed.

The EE in Fig. 7 is evaluated by $bits/Hz/J$, which is defined as the offered data rate divided by energy consumption. Here, EE is obtained by comparing to the traditional AP-MT network. It can be noticed that the EE of USM can be around 4 times than the traditional networks when $\chi \approx 0.75$ when $R_T = 1\ bps/Hz$. As the R_T increases, the value of χ at which we could obtain best EE is arisen as well. We can also observe that when the QoS data rate is getting higher, our proposed USM can achieve better EE performance comparing with multicast, especially when channel quality of the unicast user is worse. For example, we can see that USM can achieve 2 times better performance than multicast in light of $R_T = 2\ bps/Hz$ while the performance gain is about 1.5 times when $R_T = 1\ bps/Hz$ at $\chi = 0.4$. When $\chi = 0.7$, the performance gain is up tp 30 times when considering $R_T = 2\ bps/Hz$. However, when $R_T = 1$ bps/Hz, we only obtain 2 times energy efficiency when using USM over multicast at $\chi = 0.7$. Therefore, we can see that USM can achieve better EE performance than multicast scheme when higher data rate is required and bad channel quality is considered.

VI. Conclusion

In this work, we first exploited the energy efficiency benefits of using CMC in OFDMA networks. Moreover, we presented theoretical analysis on the energy consumption of MTs when multicast or unicast is used. Based on the analysis, we discussed the benefits of using multicast and unicast as transmission strategies for CMC. Furthermore, we proposed USM algorithm, that can compensate the inherent drawbacks of multicast transmission. Through simulation studies, we first observed that CMC shows great potential for obtaining energy saving for MTs. We also illustrated that the energy efficiency performance could be achieved by optionally choosing multicast and unicast as transmission scheme for CMC. With USM scheme, the energy efficiency performance can be improved compared to the case where only multicast is used for CMC.

References

[1] F-S. Chu, *et al*, "Green Resource Allocation to Minimize Receiving Energy in OFDMA Cellular Systems," *IEEE Comm. Lett.*, Vol.16, No. 30, pp.372-375, March 2012.

[2] C. Bontu and E.Illidge, "DRX mechanism for power saving in LTE," *IEEE Communication Magazine*, Vol. 47, No. 6, pp. 48-55, June 2009.

[3] D. Datla, *et al*, "Power Efficiency in Wireless Network Distributed Computing," *IEEE VTC-spring 2009*, 2009.

[4] A. Radwan and J. Rodriguez, "Energy Saving in Multi-standard Mobile Terminals through Short-range Cooperation," *EURASIP Journ. on Wirel. Comm. and Net.*, 2012:159, doi:10.1186/1687-1499-2012-159.

[5] Z. Chang and T. Ristaniemi, "Reducing Energy Consumption via Cooperative OFDMA Mobile Clusters," *Proceedings of IEEE CAMAD'12*, Bacelona, Spain, Sep. 2012.

[6] M. Hoyhtya, *et al*, "Cognitive engine: design aspects for mobile clouds, " Proceedings of CogART 2011, Barcelona, Spain, 26-29 October, 2011.

[7] M. V. Pederson and F. H. P. Fitzek, "Mobile Clouds: The New Content Sharing Platform," *Proceeding of IEEE*, Vol. 100, pp. 1400-1403, 2012.

[8] S. Y. Baek, *et al*, "Adaptive Transmission Scheme for Mixed Multicast and unicast Traffic in Cellular Systems", *IEEE Tran.on Veh. Tech.*, Vol. 58, No. 6, pp. 2899-2907, July 2009.

[9] S. J. Lee, *et al*, "Efficient Use of Multicast and Unicas Channels for Multicast Services Transmission", *IEEE Tran. on Comm.*, Vol. 59, No. 5, pp. 1264-1267, May 2011.

[10] IEEE P802.11ac. Specification Framework for TGac.

[11] J. Meinila, *et al*, "D5.3: WINNER+ Final Channel Models,".

PVII

ASYMMETRIC RADIO RESOURCE ALLOCATION SCHEME FOR OFDMA WIRELESS NETWORKS WITH COLLABORATIVE RELAYS

by

Zheng Chang and Tapani Ristaniemi 2013

Springer/ACM Wireless Networks, Volume 19, Issue 5, Page 619-627

Wireless Netw
DOI 10.1007/s11276-012-0490-8

Asymmetric radio resource allocation scheme for OFDMA wireless networks with collaborative relays

Zheng Chang · Tapani Ristaniemi

Abstract This work addresses the radio resource allocation problem for cooperative relay assisted OFDMA wireless network. The relays adopt the decode-and-forward protocol and can cooperatively assist the transmission from source to destination. Recent works on the subject have mainly considered symmetric source-to-relay and relay-to-destination resource allocations, which limits the achievable gains through relaying. In this paper we consider the problem of asymmetric radio resource allocation, where the objective is to maximize the system throughput of the source-to-destination link under various constraints. In particular, we consider optimization of the set of cooperative relays and link asymmetries together with subcarrier and power allocation. We derive theoretical expressions for the solutions and illustrate them through simulations. The results show clear additional performance gains through asymmetric cooperative scheme compared to the other recently proposed resource allocation schemes.

Keywords OFDMA · Relay selection · Subcarrier allocation · Asymmetric power allocation · Cooperative communications

Z. Chang (✉) · T. Ristaniemi
Department of Mathematical Information Technology,
University of Jyväskylä, P.O. Box 35, 40014 Jyväskylä, Finland
e-mail: zheng.chang@jyu.fi

T. Ristaniemi
e-mail: tapani.ristaniemi@jyu.fi

Z. Chang
Magister Solutions Ltd, Hannikaisenkatu 41, 40100 Jyväskylä, Finland

1 Introduction

As we know, Orthogonal Frequency Division Multiple Access (OFDMA) is an effective technique that exploits the benefits of Orthogonal Frequency Division Multiplexing (OFDM) for combating against channel noise and multipath effects and finally enables high data rate transmissions over fading channels. In addition, OFDMA is able to provide good bandwidth scalability as the number of subcarriers can be flexibly configured. Therefore, OFDMA is widely adopted in many standards of upcoming wireless communication systems, such as IEEE 802.11ac [1], LTE/LTE-A [2] and WiMAX [3].

Meanwhile, cooperative communication has emerged as one of the main trends to reach even better system performance in terms of throughput, energy efficiency or cell coverage. Therefore, the incorporation of OFDMA and cooperative relays is foreseen to result in a promising structure that offers a possibility to reach many desirable objectives for the future wireless networks. However, a combination of a conventional one-to-many (single hop) OFDMA system and a relay network calls for a careful design of the radio resource allocation (RRA) principles. This means a carefully design and coordination of the power and subcarrier allocation, selection of relay(s) across different hops and optimizing the resource asymmetries between the hops.

The resource allocation problem plays an important role in the development of both conventional and relay-aided OFDMA systems. Recently reported works in the field consider different aspects of the problem [4–10]. A cross-layer optimization algorithm for resource allocation in conventional network was presented in [4] without considering any relays and an iterative algorithm was proposed to solve the subcarrier assignment together with relay

Published online: 03 August 2012

selection in [5]. Then, the power allocation problem was assumed to be solved by another iterative method based on waterfilling algorithm. Authors in [6] introduced a closed-form solution for radio resource allocation for multihop cooperative relay network. However, the per-tone power constraint was assumed. The scheme used in [7] considered fairness constraints when selecting relays. In [8], a threshold method was proposed to solve two subproblems, subcarrier allocation and power allocation. Although the performance was shown to be improved, the total power constraint was considered instead of per-node power limitation. The work in [9] also proposed a subcarrier and relay pairing algorithm to solve the existing RRA problem but it resulted in higher computational complexity. Moreover, all the previous works assumed the transmission durations of base-to-relay and relay-to-source links to be equal, which may result in reduced achievable gains. Recently, a study on the asymmetric resource allocation was presented in [10]. However, that work considered single relay in the OFDMA networks without exploring cooperative diversity.

In this paper we take into consideration the shortcomings of the above mentioned approaches. In particular, we consider asymmetric link allocations meaning that the source-to-relay link duration (first hop) and relay-to-destination link duration (second hop) are not necessary equal. We then investigate the RRA problem in this setting and propose a method to solve the joint relay set selection for cooperation in addition to asymmetry, subcarrier and power allocations, and hence target to enhance the total system throughput. The use case selected in this paper is cell coverage extension, so we do not consider direct link from source to destination to be utilized. We propose a relay selection scheme, where the selected set of relays will obtain the best overall link data rate through collaboration. The sets of orthogonal frequency subcarriers are then assigned to the selected relays at each hop. Power allocation is performed to the source and relays under per-node constraints, which is more realistic than the scheme e.g. in [8] where only the whole system power sums are considered. We consider only downlink direction in this work, but it can be extended further to the uplink case as well. The key contributions of the paper can be divided into three parts:

(1) Problem formulation: Unlike many recent works mentioned above, we formulate a joint optimization problem for asymmetric two hop OFDMA networks including relay, subcarrier and power allocations.
(2) Resource allocation algorithm: We solve the optimization problem by using mathematical derivations. Theoretical expressions are provided to support the results.
(3) Iterative method: We furthermore divide the optimization problem into three subproblems including relay selection, and subcarrier and power allocations. This results in an iterative method for the problem.

The rest of this paper is organized as follows. Section 2 describes the relay-assisted OFDMA cooperative wireless networks and formulates the problem. We consider downlink only in this work, but it can be extended further to the uplink case. In Sect. 3, the proposed resource allocation schemes are presented. We demonstrate the benefits of our proposed algorithm in Sect. 4 and finally conclude the paper in Sect. 5.

2 Problem formulation

This paper investigates the RRA problem for OFDMA network with cooperative relays in the downlink. We consider a two-hop time-division duplex downlink relay system. The whole system consists of a source (i.e., access point, AP), a destination node (i.e., mobile terminal, MT) and several relays. The first hop is so called broadcast phase, where AP broadcasts information to a cluster of decode-and-forward (DF) relays. At second hop, relays cooperate to transmit the data to the MT, so that, e.g., spatial diversity gain can be achieved (relays are assumed to be far enough to each other). The channel state information (CSI) is assumed to be known at the receiver and then fed back to the transmitter perfectly. We assume a total of Z relays in the network, and the selected relay cluster $\mathcal{K}$ contains K potential half-duplex relays. The presented relay-assisted cooperative OFDMA network is depicted in Fig. 1, where $K = 2$.

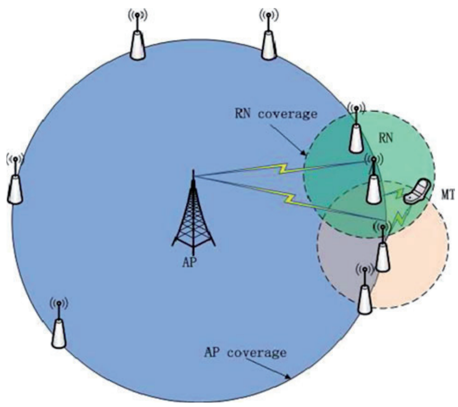


Fig. 1 Wireless cooperative relay-assisted network

Suppose h^i is the channel transfer function from transmitter to receiver and we assume the channel to be static within a time slot. For example, $h^i_{s,k}$ means the channel transfer function from AP s to relay node (RN) k over OFDM subcarrier i and $h^j_{k,d}$ means the channel transfer function from RN k to destination d over OFDM subcarrier j. Thus we have the channel gain of the first hop $G^i_{s,k} = | h^i_{s,k} |^2$ and the second hop $G^j_{k,d} = | h^j_{k,d} |^2$. L is the path loss factor and the noise variance for the first and second hops are σ_k^2 and σ_d^2, respectively. We denote the transmit power assigned to subcarrier i for transmitting data as P^i. In this work, we do not consider the direct link from AP to MT. This assumption is practical in the case that RNs are used for cell extension or cell edge optimization. One RN k occupies subcarrier i in the first hop and j in the second hop. In this work, we assume that the transmission durations for the first hop and second hop are allowed to differ. We denote these durations as T_1 and T_2, respectively. Therefore, in the first hop, the data rate of the broadcast phase is determined by the minimum rate of each link between AP and selected RNs. The achieved throughput of the first hop is as follows [10]:

$$R^{\mathcal{I}}_{s,\mathcal{K}} = \min_{k \in \mathcal{K}} \left\{ \frac{T_1}{T} log \left(1 + \sum_{i=1}^{M} \omega^i_{s,k} \rho_k P^i_{s,k} \gamma^i_{s,k} \right) \right\}, \tag{1}$$

where $\gamma^i_{s,k} = \frac{L_{s,k} G^i_{s,k}}{\sigma_k^2}$ is the channel SNR and $T = T_1 + T_2$. $\mathcal{M}$ is the subcarrier set of the system that contains M subcarriers. $\mathcal{I}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at the first hop. ρ_k indicates whether RN k is chosen for subcarrier allocation, that is,

$$\rho_k = \begin{cases} 1, & \text{if } k \text{ is chosen for relaying,} \\ 0, & \text{otherwise.} \end{cases}$$

We also define ω as the indicator whether certain subcarrier is assigned to RN k, i.e.,

$$\omega^i_{s,k} = \begin{cases} 1, & \text{if } i \text{ is assigned to } k \text{ at first hop,} \\ 0, & \text{otherwise.} \end{cases}$$

For the second hop, it is assumed that the RNs are perfectly synchronized. Therefore, the second hop can be viewed as a virtual MISO link and the throughput can be expressed as [11]

$$R^{\mathcal{J}}_{\mathcal{K},d} = \frac{T_2}{T} log \left(1 + \sum_{j=1}^{M} \sum_{k=1}^{K} \omega^j_{k,d} \rho_k P^j_{k,d} \gamma^j_{k,d} \right), \tag{2}$$

where $\gamma^j_{k,d} = \frac{L_{k,d} G^j_{k,d}}{\sigma_d^2}$. $\mathcal{J}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs. For indicator $\omega^j_{k,d}$, we also have

$$\omega^j_{k,d} = \begin{cases} 1, & \text{if } j \text{ is assigned to } k \text{ at second hop,} \\ 0, & \text{otherwise.} \end{cases}$$

Therefore, the total achieved end-to-end throughput of source s to destination d through RN set $\mathcal{K}$ is [12]

$$R_{sd} = min \left\{ R^{\mathcal{I}}_{s,\mathcal{K}}, R^{\mathcal{J}}_{\mathcal{K},d} \right\}. \tag{3}$$

Then, we can formulate the radio resource allocation problem as

$$max\, R_{sd}, \tag{4}$$

subject to

$$\begin{aligned} & T = T_1 + T_2, \\ & \sum_{i=1}^{M} \sum_{k=1}^{K} \omega^i_{s,k} P^i_{s,k} \le P_{s,max}, \\ & \sum_{j=1}^{M} \omega^j_{k,d} P^j_{k,d} \le P_{k,max}, \\ & \sum_{k=1}^{K} \omega^i_{s,k} = 1, \omega^i_{s,k} \in \{0,1\}, \\ & \sum_{k=1}^{K} \omega^j_{k,d} = 1, \omega^j_{k,d} \in \{0,1\}, \end{aligned} \tag{5}$$

where $P_{s,max}$ is the maximum transmit power of AP and $P_{k,max}$ is the maximum power of RN k. Therefore, our goal is to find the optimal solutions for relay set, link asymmetry, and subcarrier and power allocations which satisfy the problem (4).

It can be deduced that achieving maximum for (3) implies $R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}$. Thus, (4) can be modified as

$$\arg\max \left(R^{\mathcal{I}}_{s,\mathcal{K}} + R^{\mathcal{J}}_{\mathcal{K},d} \right), \tag{6}$$

subject to conditions in (5) and

$$R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}. \tag{7}$$

3 Resource allocation scheme

In this section, we introduce an adaptive RRA algorithm to solve the existing problems described in the previous section. Although the resource allocation problem is combinatorial in nature with a non-convex structure, it has been shown in [13] that the duality gap of the optimization problem becomes zero under the condition of time-sharing regardless of its convexity. For the general OFDM system, the condition of time-sharing is always fulfilled as the number of subcarriers is large enough. Therefore, the problem can be solved in the dual domain. The Lagrangian [14] of (6) is

$$\mathcal{L}(\mathbf{P}, T, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}) = \left(R^{\mathcal{I}}_{s,\mathcal{K}} + R^{\mathcal{J}}_{\mathcal{K},d}\right) - \lambda_s\left(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k} - P_{s,max}\right) - \sum_{k=1}^{K}\lambda_{k,d}\left(\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d} - P_{k,max}\right) - \mu\left(R^{\mathcal{I}}_{s,\mathcal{K}} - R^{\mathcal{J}}_{\mathcal{K},d}\right), \tag{8}$$

where $\mathbf{P} = \{P^i_{s,k}, P^j_{k,d}\}$ is the set of power allocation, $\boldsymbol{\omega} = \{\omega^i_{s,k}, \omega^j_{k,d}\}$ denotes the subcarrier allocation, and $\boldsymbol{\rho} = \{\rho_k\}$ is the relay assignment. The λ_s, $\lambda_{k,d}$ and μ are Lagrange multipliers. Then it can be derived that $\boldsymbol{\lambda} = \{\lambda_s, \lambda_{k,d}\} \geq 0$ and $\boldsymbol{\mu} = \{\mu\} \in (-1, 1)$ [10]. The Lagrange dual function can be written as

$$g(\boldsymbol{\lambda}, \boldsymbol{\mu}) = \max \mathcal{L}(\mathbf{P}, \boldsymbol{T}, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}). \tag{9}$$

We assume the number of subcarrier is sufficiently large, so that the duality gap between primal problem and dual function can be assumed negligible [13]. Consequently, we can solve the problem (4) by minimizing the dual function,

$$\min g(\boldsymbol{\lambda}, \boldsymbol{\mu}). \tag{10}$$

3.1 Evaluating dual variable

Since the dual function is always convex [14], we can choose e.g. sub-gradient or ellipsoid method [13] with guaranteed convergence to minimize $g(\boldsymbol{\lambda}, \boldsymbol{\mu})$. We follow the sub-gradient method in [13] to derive the subgradient $g(\boldsymbol{\lambda}, \boldsymbol{\mu})$ with the optimal power allocation p^* that will be presented in the following subsection.

In Algorithm 1, $\triangle\lambda = \{\triangle\lambda_s, \triangle\lambda_{1,d}, \ldots \triangle\lambda_{K,d}\}, \triangle\lambda_s$, $\triangle\lambda_{k,d}$ and $\triangle\mu$ can be expressed as

$$\begin{aligned} \triangle\lambda_s &= P_{s,max} - \sum_{i=1}^{M}\sum_{k=1}^{K}(P^i_{s,k})^* \\ \triangle\lambda_{k,d} &= P_{k,max} - \sum_{j=1}^{M}(P^j_{k,d})^* \\ \triangle\mu &= (R^{\mathcal{I}}_{s,\mathcal{K}})^* - (R^{\mathcal{J}}_{\mathcal{K},d})^*. \end{aligned} \tag{11}$$

Algorithm 1 Evaluating dual variable

1: Initialize $\boldsymbol{\lambda^0}$ and $\boldsymbol{\mu^0}$
2: **While**(!Convergence) **do**
3: Obtain $g(\boldsymbol{\lambda^a}, \boldsymbol{\mu^a})$ at the a th iteration;
4: Update a subgradient for $\boldsymbol{\lambda^{a+1}}$ and $\boldsymbol{\mu^{a+1}}$, by $\boldsymbol{\lambda^{a+1}} = \boldsymbol{\lambda^a} + \boldsymbol{\upsilon^a}\triangle\boldsymbol{\lambda}$ and $\boldsymbol{\mu^{a+1}} = \boldsymbol{\mu^a} + \boldsymbol{\upsilon^a}\triangle\boldsymbol{\mu}$;
5: **End while**

Here υ^a is the stepsize and a is the number of iterations. The sub-gradient algorithm (Algorithm 1) is guaranteed to converge to the optimal $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$. The computational complexity of Algorithm 1 is polynomial in the number of dual variable $K + 1$ [13]. Since (9) can be viewed as a nonlinear integer programming problem, its optimal solution requires high computational cost. Therefore, we are aiming to solve the optimization problem by solving three subproblems, which are relay selection, and subcarrier and power allocation. Firstly, we introduce asymmetric power allocation scheme.

3.2 Asymmetric power allocation

By assuming the relay selection and subcarrier allocation are done, the optimal time slot for each hop can be achieved by using Karush-Kuhn-Tucker (KKT) conditions [14]. This results in

$$T_1 = \frac{1-\mu^*}{2}T, \tag{12}$$

$$T_2 = \frac{1+\mu^*}{2}T. \tag{13}$$

The proof is given in Appendix 1. We assume subcarrier set $S_k(i,j)$ is assigned to RN k and recall the Lagrange dual function of (9). Then the optimal power allocation problem can be determined by solving problem (8) over variables $P^i_{s,k}$ and $P^j_{k,d}$. Applying Karush-Kuhn-Tucker (KKT) conditions [10], we obtain the optimal power allocation for the first hop:

$$(P^i_{s,k})^* = \left\{\frac{(1-\mu^*)^2}{2\lambda^*_s} - \frac{1}{\gamma^i_{s,k}}\right\}^+, \tag{14}$$

where $\{x\}^+ \triangleq max\{0, x\}$. Similarly, for the cooperation phase, the optimal RN power allocation is

$$(P^j_{k,d})^* = \left\{\frac{(1+\mu^*)^2}{2\lambda^*_{k,d}} - \frac{1}{\gamma^j_{k,d}} - \frac{\sum_{m=1,m\neq k}^{K} L_{m,d}G_{m,d}P_{m,d}}{G^j_{k,d}L_{k,d}}\right\}^+. \tag{15}$$

where $G_{m,d}$ denotes the channel gain from relay m to MT and $P_{m,d}$ is the power allocation of relay m. The proof of (14) and (15) can be found in Appendix 2.

3.3 Optimal relay selection (ORS)

We also consider relay selection in this work, unlike some traditional single relay selection algorithms in [9] and [15], as multiple RNs selection. The proposed algorithm is to select K RNs to form a cluster that can maximize the achieved throughput in (3). We can rewrite (8) as

$$\begin{aligned}\mathcal{L}(\mathbf{P},T,\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda}) = \min_{k\in\mathcal{K}}\left\{\frac{T_1}{T}log\left(1+\sum_{i=1}^{M}\omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k}\right)\right\}\\ +\frac{T_2}{T}log\left(1+\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d}\sigma^2_d\right)\\ -\mu\left(\min_{k\in\mathcal{K}}\left\{\frac{T_1}{T}log\left(1+\sum_{i=1}^{M}\omega^i_{s,k}\rho_k P^i_{s,k}\gamma_{s,k}\right)\right\}\right.\\ \left.-\frac{T_2}{T}log\left(1+\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d}\right)\right)\\ +\lambda_s\left(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k}-P_{s,max}\right)\\ -\sum_{k=1}^{K}\lambda_{k,d}\left(\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d}-P_{k,max}\right).\end{aligned} \tag{16}$$

By assuming the subcarrier and power allocations are done, and applying KKT condition, the RN is selected according to the following rule,

$$\begin{aligned}k^* = \arg\max_k\left(\min_{k\in\mathcal{K}}\left\{\frac{(1-\mu^*)^2}{2}\left(\frac{P^i_{s,k}\gamma^i_{s,k}}{1+P^i_{s,k}\gamma^i_{s,k}}\right)\right\}\right.\\ \left.+\frac{(1+\mu^*)^2}{2}\left(\frac{P^j_{k,d}\gamma^j_{k,d}}{1+\sum_k^K P^j_{k,d}\gamma_{k,d}}\right)\right).\end{aligned} \tag{17}$$

Optimal value of $\mathbf{P}$ can be given in (14) and (15). Therefore, (17) can be viewed as multi-objective optimization problem, which aims at obtaining the trade-off of the first hop and second hop. Termination criteria for the whole RRA scheme is to find an optimal subcarrier set $\mathcal{K}^*$ that satisfies:

$$\begin{aligned}max\left(\min_{k\in\mathcal{K}^*}\left\{\frac{(1-\mu^*)^2}{2}\left(\frac{P^i_{s,k}\gamma^i_{s,k}}{1+P^i_{s,k}\gamma^i_{s,k}}\right)\right\}\right.\\ \left.+\frac{(1+\mu^*)^2}{2}\left(\frac{P^j_{k,d}\gamma^j_{k,d}}{1+\sum_k^K P^j_{k,d}\gamma_{k,d}}\right)\right).\end{aligned} \tag{18}$$

Therefore, the relay selection strategy is

$$\rho_k = \begin{cases}1, & \text{if} k\in\mathcal{K}^*,\\ 0, & \text{otherwise.}\end{cases}$$

3.4 Optimal subcarrier allocation (OSA)

The goal of subcarrier allocation strategy is to assign subcarriers to given RNs that can obtain the best throughput performance. Following the same procedure as with the relay selection, we can obtain the subcarrier allocation criteria as follows:

Algorithm 2 ORS

1: **Definition**
2: $\mathcal{Z}$ is the set of all Z RNs.
3: $\mathcal{K}$ is the set of selected K RNs;
4: $C_{\mathcal{K}} = 0$ for $\forall k \in \mathcal{K}$;
5: sort the set of RN in the descending order according to its overall path loss;
6: while !satisfy (17) **do**
7: **for** $z = 1$ to Z **do**
8: add RN z to $\mathcal{K}$ according to its order;
9: do subcarrier and power allocation;
10: calculate value of $C_{\mathcal{K}}$ according to (18)
11: Find z satisfying (17),$\forall z \in \mathcal{Z}$;
12: **end for**
13: **end while**

$$i^* = \arg\max\left(\min_{k\in\mathcal{K}}\left\{\frac{(1-\mu^*)^2}{2}\left(\frac{P^i_{s,k}\gamma^i_{s,k}}{1+P^i_{s,k}\gamma^i_{s,k}}\right)\right\}\right), \tag{19}$$

$$j^* = \arg\max\left(\frac{(1+\mu^*)^2}{2}\left(\frac{P^j_{k,d}\gamma^j_{k,d}}{1+\sum_k^K P^j_{k,d}\gamma^j_{k,d}}\right)\right). \tag{20}$$

If we denote the optimal subcarrier set as $\mathcal{I}^*$ and $\mathcal{J}^*$ that contain all selected subcarrier for the first hop and second hop respectively, the OSA indicator for the first hop and second hop can be expressed as

$$\omega_i = \begin{cases}1, & \text{if} i\in\mathcal{I}^*,\\ 0, & \text{otherwise.}\end{cases}$$

$$\omega_j = \begin{cases}1, & \text{if} j\in\mathcal{J}^*,\\ 0, & \text{otherwise.}\end{cases}$$

3.5 Joint asymmetric relay, subcarrier and power allocation

We have described the algorithms for relay selection, and subcarrier and power allocation in the previous

Algorithm 3 OSA

1: **Definition**
2: c_1: the set of M subcarriers in the first hop;
3: c_2: the set of M subcarriers in the second hop;
4: while !satisfy (19) and (20) **do**
5: sort c_1 and c_2 in the descending order according to the channel gain.
6: **for** $m = 1$ to M **do**
7: find subcarrier set $\mathcal{I}$ for the first hop that satisfies (19);
8: find subcarrier set $\mathcal{J}$ for the first hop that satisfies (20);
9: **end for**
10: **end while**

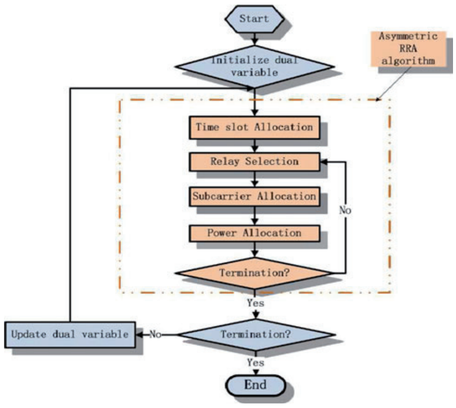


Fig. 2 Algorithm flow chart

subsections. Combining the above three phases together with asymmetric time design, we can obtain optimal solution for (4). The flow chart of the whole algorithm is shown in Fig. 2. We can see that these three steps are conducted alternatively until the convergence is reached.

4 Performance evaluation

In this section we illustrate the performance of the RRA algorithm with couple of examples. We assume five RNs located between AP and MT, and MT is 1.8 km away from AP. One example of RN distribution is shown in Fig. 3 when four RNs are selected for transmission. The Stanford University SUI-3 channel model is employed without considering multipath effect [16], in which the central frequency is 1.9 GHz. A three-tap channel is invoked and signal fading follows Rician distribution. We choose the number of subcarriers N to be 32, so the duality gap can be ignored [9]. Flat quasi-static fading channels are considered, hence the channel coefficients are assumed to be constant during a complete frame, and can vary from a frame to another independently. The noise variance of the two hops are set to be 1 for simplicity. The path loss factor varies according to the different distances from RNs to AP and MT and the exponent is fixed to 3.5. The maximum transmit power of AP and RN are set to 40 and 20 dBm, respectively.

We demonstrate our results compared with the performance of recently reported symmetric or asymmetric schemes:

(1) Equal power allocation combined with proposed subcarrier allocation scheme and relay selection (EPA);
(2) Waterfilling power allocation combined with proposed subcarrier allocation scheme and relay selection (Waterfilling);
(3) Proportional Allocation scheme in [8] with fairness consideration (Fairness SA);
(4) Asymmetric Resource Allocation scheme in [10] without cooperative relay assisted (ARA);

Figure 4 demonstrates the impact of maximum transmit power of AP on the system bandwidth efficiency. We denote $D_{s,d}$ as the distance between AP and MT, and $D_{s,k}$ as the distance between AP and RNs. In Fig. 4, we have $D_{s,d}$ = 1,800 m and $D_{s,k}$ from 1,500 to 1,600 m. The considered channel SNR at the RN k is varied from $\gamma_{s,k} = -20$ dB to $\gamma_{s,k} = -30$ dB and at MT d it is varied from $\gamma_{k,d} = -15$ dB to $\gamma_{k,d} = -25$ dB. It can be seen that the proposed scheme achieves the best performance. The performance

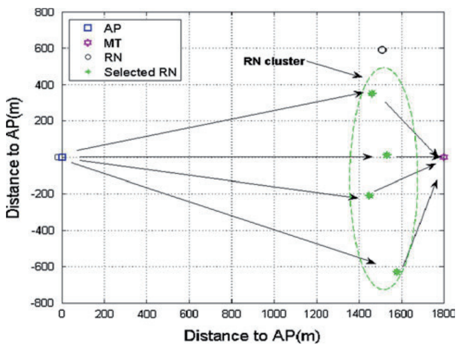


Fig. 3 Relay node distribution with 4 RNs selected for relaying

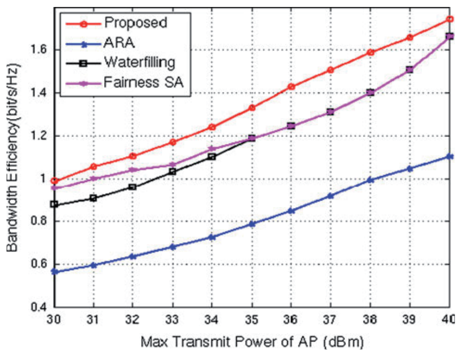


Fig. 4 Impact of maximum transmit power $P_{s,max}$ on the system bandwidth efficiency

gain over other methods in comparison is up to 20 %. It can also be noticed that if waterfilling is used as the power allocation scheme (instead of our proposed scheme), the throughput performance is comparable with Fairness SA. Another performance gain can be seen in the power consumption. We can see that with a fixed data rate requirement, our proposed scheme provides a clear power saving gain. For instance, at the level of 1.2 bit/s/Hz bandwidth efficiency our proposed scheme can reach a power saving around 2 dB compared to the other schemes.

Figures 5 and 6 show the impact of distance between the AP and RNs on the system performance. The distances between AP and RNs are normalized to $D_{s,d}$ and varies from 0.1 to 0.9. In Fig. 5, we set the maximum AP power to $P_{s,max} = 35$ dBm and the maximum power of each RN to $P_{k,max} = 20$ dBm, whereas we assume maximum power of each node to be 20 dBm in Fig. 6. From Fig. 5, we can see that the proposed algorithm obtains the highest system capacity when the normalized distance is less than 0.9. When the average normalized distance between AP and RNs is around 0.9, we can find that the proposed scheme has comparable performance with the EPA algorithm. This results from the fact that some RNs are already very close to the MT so the achieved SNR is relatively high leaving less impact to power allocation schemes. The same situation can be observed in Fig. 6 where less AP power is considered. It can be concluded that the proposed algorithm can provide a noticeable performance gain over other existing algorithms even with rather low limits for AP maximum power.

Figure 7 illustrates the convergence speed of the proposed algorithm and other two schemes. The proposed algorithm reaches the steady state after six iterations, which demonstrates a fast convergence speed. Although it

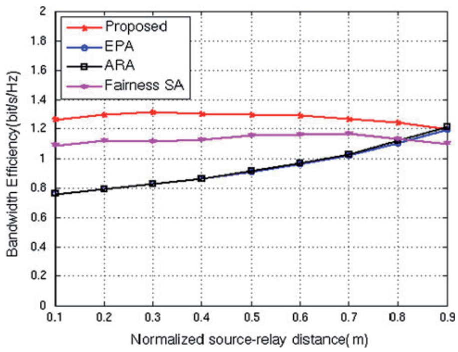


Fig. 5 Impact of the distance between AP and relay on the system bandwidth efficiency, when the maximum AP power is 35 dBm and maximum RN power is 20 dBm

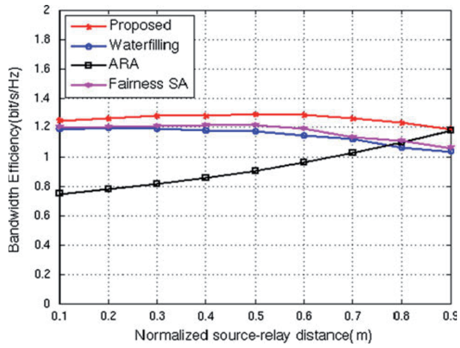


Fig. 6 Impact of the distance between AP and relay on the system bandwidth efficiency, when the maximum power of each node is 20 dBm

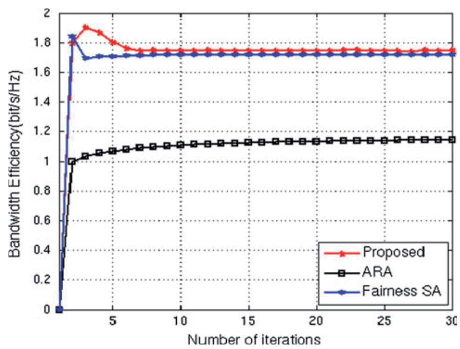


Fig. 7 Impact of the number of iteration on the system bandwidth efficiency

is slightly slower than the recently reported ARA algorithm, the achieved system capacity is much higher.

5 Conclusion

In this paper we investigated the problem of asymmetric resource allocation for cooperative multi-relay assisted OFDMA networks. The joint optimization problem for radio resource allocation was solved by addressing three subproblems including optimal selection of collaborative relays, subcarriers and power with the objective of maximizing the system throughput. Theoretical expressions were derived for the optimal selections. It was shown that by designing asymmetric time slots for different hops, it is possible to reach a noticeable gain in the cell-edge throughput. This was also illustrated with simulation examples.

Appendix 1

Derivation of optimal solution in (12) and (13).

For simplicity, we replace $log(1 + P^i_{s,k}\gamma^i_{s,k})$ with r_1 and $log(1 + \sum_{k=1}^{K} P^j_{k,d}\,\gamma^j_{k,d})$ with r_2. From (7), we have

$$\frac{T_1}{T_2} = \frac{r_2}{r_1}. \tag{21}$$

Then the derivative of $\mathcal{L}$ in (9) with respect to variable T_1 is given by

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial T_1} &= \frac{(T-T_1)r_1}{T^2} - \frac{(T_2)r_2}{T^2} - \mu\left(\frac{(T-T_1)r_1}{T^2} + \frac{(T_2)r_2}{T^2}\right)\\ &= \left(\frac{(T-T_1)T_2}{T^2T_1} - \frac{(T_2)}{T^2} - \mu\left(\frac{(T-T_1)T_2}{T^2T_1} + \frac{(T_2)}{T^2}\right)\right)r_2.\end{aligned} \tag{22}$$

Since we have $T = T_1 + T_2$ and $\frac{\partial \mathcal{L}}{\partial T_1} = 0$, the (22) can be converted to:

$$\frac{T_2}{T_1} = \frac{1+\mu}{1-\mu}, \tag{23}$$

and we have

$$T_1 = \frac{1-\mu}{2}T, \tag{24}$$

$$T_2 = \frac{1+\mu}{2}T. \tag{25}$$

Appendix 2

Derivation of optimal solution in (14) and (15).

For simplicity, we replace $P^i_{s,k}$ with P_1 and $P^j_{k,d}$ with $P_{2,k}$. Similarly, we use G_1 and L_1 to replace $G^i_{s,k}$ and $L_{s,k}$, $G_{2,k}$ and $L_{2,k}$ to replace $G^j_{k,d}$ and $L_{k,d}$. First, we solve the power allocation at the transmitter. When relay selection and subcarrier allocation are done, the derivative of $\mathcal{L}$ in (9) with respect to variable P_1 is given by

$$\frac{\partial \mathcal{L}}{\partial P_1} = (1-\mu)\frac{T_1}{T}\frac{1}{1+\frac{L_1P_1G_1}{\sigma_k^2}}\frac{L_1G_1}{\sigma_k^2} - \lambda_s. \tag{26}$$

Substituting (24) into (26) and applying KKT conditions, we obtain

$$P_1^* = \left\{\frac{(1-\mu)^2}{2\lambda_s} - \frac{\sigma_k^2}{G_1L_1}\right\}^+. \tag{27}$$

Then we discuss how to achieve optimal $P^*_{2,k}$. The derivative of $\mathcal{L}$ respect to $P_{2,k}$ is shown

$$\frac{\partial \mathcal{L}}{\partial P_{2,k}} = (1+\mu)\frac{T_2}{T}\frac{1}{1+\frac{\sum_{k=1}^{K} L_{2,k}P_{2,k}G_{2,k}}{\sigma_d^2}}\frac{L_{2,k}G_{2,k}}{\sigma_d^2} - \lambda_{k,d}. \tag{28}$$

By using the same scheme that shows above, we obtain

$$\begin{aligned}P^*_{2,k} = &\left\{\frac{(1+\mu)^2}{2\lambda_{k,d}} - \frac{\sigma_d^2}{G_{2,k}L_{2,k}}\right.\\ &\left.-\frac{\sum_{m=1,m\neq k}^{K} G_{2,m}L_{2,m}P_{2,m}}{G_{2,k}L_{2,k}}\right\}^+.\end{aligned} \tag{29}$$

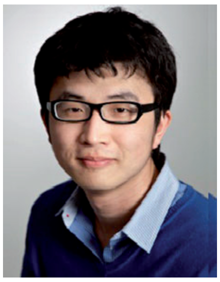
Thus, the optimality of solution P^* in (14) and (15) is proved.

References

1. IEEE-SA Standards Board. (1999). Wireless LAN medium access control and physical layer specifications: High-speed physical layer in the 5 GHz band, IEEE, New York.
2. 3rd Generation Partnership Project Specifications Home Pages. http://www.3gpp.org/specs/specs.htm. Accessed April 2011.
3. IEEE-SA Standards Board. (2006). IEEE standard for local and metropolitan area networks part 16: Air interface. New York, NY.
4. Song, G., & Li, Y. (2005). Cross-layer optimization for OFDM wireless networks-part 1: Theoretical framework. *IEEE Transaction on Wireless Communications*, *4*(2), 614–624.
5. Ng, T.C.-Y., & Yu, W. (2007). Joint optimization of relay strategies and resource allocation in cooperative cellular networks. *IEEE Journal on Selective Area in Communications*, *25*(2), 328–339.
6. Kim, S.-K., Wang, X., & Madihian, M. (2008). Optimal resource allocation in multi-hop OFDMA wireless networks with cooperative relay. *IEEE Transaction on Wireless Communications*, *7*(5), 1833–1838.
7. Jeong, H., & Lee, J. H. (2008). Adaptive relay selection for regenerative OFDMA relay networks with fairness constraints. *Proceedings of IEEE vehicular technology conference*, Calgary, Canada.
8. Tang, M., Wang, X., Wang, Y., & Liao, J. (2010). Dynamic resource allocation with threshold in OFDMA-based relay networks. *Proceedings of IEEE vehicular technology conference*.
9. Dang, W., Tao, M., Mu, H., & Huang, J. (2010). Subcarrier-pair based resource allocation for cooperative multi-relay OFDM systems. *IEEE Transaction on Wireless Communications*, *9*(5), 1640–1649.
10. Zhou, N., Zhu, X., & Huang, Y. (2011). Optimal asymmetric resource allocation and analysis for OFDM-based multidestination relay systems in the downlink. *IEEE Transaction on Vehicular Technology*, *60*(3), 1307–1312.
11. Tse, D., & Viswanath, P. (2005). *Fundamentals of wireless communications*. Cambridge: Cambridge University Press.
12. Chang, Z., & Ristaniemi, T. (2011). Radio resource allocation for cooperative relay-assisted OFDMA wireless networks. *Proceedings of 3rd international workshop on cross-layer design(IWCLD)*, Rennes, France.
13. Yu, W., & Lui, R. (2006). Dual methods for nonconvex spectrum optimization in multicarrier system. *IEEE Transaction on Communications*, *54*(7), 1310–1322.
14. Boyd, S., & Vandenberghe, L. (2004). *Convex optimization*, Cambridge: Cambridge University Press.

15. Ibrahim, A. S., Sadek, A. K., Su, W., & Liu, K. J. R. (2008). Cooperative communications with relay-selection: When to cooperate and whom to cooperate with. *IEEE Transaction on Communications*, *7*(7), 2814–2827.
16. Jain, R. (2007). Channel models a tutorial1 v1.0. http://www.cse.wustl.edu/jain/cse574-08/ftp/channel_model_tutorial.pdf. Accessed April 2011.

Author Biographies



Zheng Chang received the B.Eng. Degree from Jilin University, Changchun, China in 2007 and M.Sc. (Communications Engineering) from Helsinki University of Technology (Now Aalto University), Espoo, Finland in 2009. During 2008–2009, he was with the Department of Communications and Networking, Helsinki University of Technology. Since August 2010, he has been a Ph.D. student of University of Jyväskylä, Jyväskylä, Finland. Currently he is also working in Magister Solutions Ltd. His research interests include signal processing and radio resource allocation for wireless systems.

Tapani Ristaniemi received his M.Sc. in 1995 (mathematics), Ph.Lic. in 1997 (applied mathematics), and Ph.D. in 2000 (wireless communications), all from the University of Jyväskylä, Jyväskylä, Finland. During 2001–2003 he was a professor of wireless communications at the Department of Mathematical Information Technology, University of Jyvaskylä, and 2003-2006 a professor of wireless data communications, Institute of Communications Engineering, Tampere University of Technology, Tampere, Finland. In 2006 he joined the University of Jyvaskylä, where he holds a professorship of computer science. His research interests include signal processing, resource management and self-organization for wireless communication systems.

PVIII

ENERGY EFFICIENCY OF UNICAST SUPPORTED MULTICAST WITH QOS GUARANTEE

by

Zheng Chang and Tapani Ristaniemi 2013

Proc. of 2nd IEEE/CIC International Conference on Communications in China (ICCC'13)

Energy Efficiency of Unicast Support Multicast with QoS Guarantee

Zheng Chang*† and Tapani Ristaniemi*
*Department of Mathematical Information Technology, University of Jyväskylä, P.O.Box 35, FIN-40014 Jyväskylä, Finland
†Magister Solutions Ltd, Hannikaisenkatu 41, FIN-40100 Jyväskylä, Finland
Email: zheng.chang@magister.fi, tapani.ristaniemi@jyu.fi

***Abstract*—Multicast transmission is known as an efficient mechanism for offering the same services for different terminals. However, the power consumption is surprisingly arisen due to terminals with the worst channel quality while maintaining the Quality of Service (QoS) and data decoding requirements. In order to address this problem, we examine the energy saving performance of an efficient algorithm called Unicast Support Multicast (USM), which can dynamically and expeditiously use unicast transmission as an additional support for multicast transmission. The USM algorithm can overcome the inherent drawbacks of multicast transmission, and decrease the power consumption with QoS guarantee. Numerical results based on the conducted theoretical analysis demonstrate that power consumption is reduced with USM while fulfilling the data rate and decoding requirements. In addition, the energy efficiency of USM is superior compared to pure multicast transmission.**

***Index Terms*—power consumption; energy efficiency; multicast; unicast;**

I. Introduction

Due to the tremendous growth of the wireless market, popularity of mobile devices and motivated the development of different mobile applications and services are increased, which are having a profound effect on people's daily lifestyles. In recent years, mobile users have become increasingly addicted to multimedia applications, such as video streaming and IPTV. It can be anticipated that the next-generation wireless communication systems are going toward offering qualified broadband multimedia services for different users. Multicast is known as an efficient mechanism for operating such point-to-multipoint transmissions since it can simultaneously deliver the same information for many users [1]. However, in order to fulfill the Quality of Service (QoS) requirement for each user, in the light of multicast transmission, the transmitter has to increase the transmit power if there exists a user with much worse channel quality than the others. Such inherent drawback of multicast induces high power consumption and low energy efficiency for the transmitter. Since the future wireless communication systems are going towards undertaking much frequent internode communications, alleviating power consumption of the transmitters in the multicast transmission is a critical issue to prolong the battery life of different devices.

As we know, both multicast and unicast transmission mechanisms have their own advantages and drawbacks. Unicast transmission exploits multiuser diversity by utilizing independent variations of multiuser channels. Variable data rates according to users' demand and channel quality can be served by unicast transmission [2]. However, the utilization of channel variation is on the expense of introducing transmission overhead for same data. Therefore, unicast transmission is costly from the radio resources point of view. Through multicast in radio channels, a multicast transmission increases transmission efficiency without transmitting redundant data and using different transmit power for different users. Thus, the multicast transmission is used as an efficient method for delivering group-oriented wireless services. However, wireless multicast should be adapted according to the worst channel state user in a multicast group. Hence, the system capacity and energy efficiency of multicast transmission is affected both by the number of users and the supportable data rate of users with worst instantaneous channel condition.

Recent work on combining and utilizing advantages of both strategies can be found in [2]– [4], where the objectives are to maximize the total system throughput. In [2], a scheme using using multicast and unicast alternatively in different time slots was proposed. A scheme proposed in [3] targeted to efficient use of multicast and unicast transmissions to overcome the data rate limitation caused by the users with worst channel quality in multicast. The objective was to maximize the total throughput with power constraint. Authors in [4] utilized the subcarrier and power allocation schemes for OFDMA system to maximize the overall throughput when both multicast and unicast groups existed. Without considering any unicast transmission, [5] presented resource allocation scheme for multicast to minimize the power consumption. However, they did not consider QoS requirements for the users.

All the works mentioned above considered the use of unicast/multicast combinations for throughput maximization. In this work, however, our focus is to optimize the energy efficiency. Considering the similar idea reported in [3][6], Unicast Support Multicast (USM) is able to mitigate the inherent energy-efficiency problem related to pure multicast transmission. In light of reducing power consumption while maintaining the decoding requirement and service quality, the USM is going towards dynamically allocating unicast transmission as an additional support for multicast transmission. Considering there is a receiver with much worse channel quality than others, our prior target is to provide the receiver multicast service with better energy efficiency performance. Moreover, by extending the previous work presented in [6] and illustrating the numerical results based on the conducted theoretical analysis, we discuss the significant improvements gained by using USM in different aspects of energy efficiency.

This paper is organized as follows. The system model and assumptions are described in Section II. In Section III, the USM scheme is analytically derived by minimizing the power consumption while fulfilling the data rate requirement. In Section IV, numerical examples are presented to investigate the effect of using additional unicast on the performance gain. We finally conclude our work in Section II.

II. System Model

In multicast transmission, the receiver with worst channel quality requires higher transmit power than the others in order to successfully decode all data from transmitter and obtain same data rate. Hence, the power efficiency of using pure multicast will be deteriorated if one or more terminals have much worse channel conditions than the others. On the other hand, the use of unicast transmission can take advantage of channel variation and thus, variable data rates can be supported for a single user. In [3] the authors considered unicast as an additional support of multicast for the user who can not successfully decode the data on multicast channel, and optimized the scheme from the system throughput point-of-view. However, optimizing the scheme from energy-efficiency point-of-view results in different utilization of additional unicast and also affects to the utilization of multicast.

One simple example of the considered scenario for Unicast Supported Multicast (USM) can be found in Fig. 1. In that system model, several nodes that are close to each other form a group and one separate node is far away from the group. All nodes require the same data from node 1 so it transmits the same data to the others through multicast transmission. In light of QoS guarantee, the transmit power of node 1 will be arisen by the existence of node 5. Therefore, we expect the USM algorithm to decrease the power consumption of node 1 while still fulfilling the system requirement. In this work, we refer to the nodes that do not need USM as a multicast group, and the node which requires USM transmission is refereed to as the unicast node.

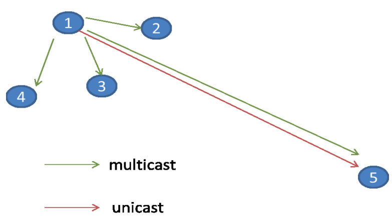


Figure 1. Considered scenario for USM.

III. Unicast Supported Multicast (USM)

A. Description of the USM Algorithm

The sole of the USM scheme is to allocate additional unicast channel for the specified node(s) that can not obtain required QoS (e.g., SNR or data rate) when a fixed transmit power for multicast is used. A user to which no additional unicast channel is allocated should have an SNR higher than G_T to successfully decode the data of the multicast channel. A user of SNR less than G_T cannot successfully decode the multicast service signal transmitted only through the multicast channel. Thus, in the proposed scheme, we utilize another unicast channel to assistant the multicast transmission, e.g., through carrying the lost data of multicast to receiver on demand. How to use the USM is depicted in Algorithm 1.

Algorithm 1 Description of USM

Evaluate channel gain (including noise) G_j of each node k
Predefine a channel gain threshold G_T
if $G_j \geq G_T$ **then**
    For these nodes j only multicast transmission is executed with power P_m;
else
    For these nodes j an additional unicast transmission is executed with power P_u.
end if

One may notice that the use of additional unicast channel involves combining the signals of both unicast and multicast channels at the receiver. Combining the signals is equivalent to combining the signals of the original transmission and the retransmission in a hybrid automatic repeat request (HARQ) system. According to [7], the capacity obtained by combining the signals of the original transmission and the retransmission equals the sum of the capacities of the original transmission and the retransmission for an optimal incremental redundancy scheme in the HARQ system. Therefore, for the user with worse channel gain $G_j \geq G_T$, the use of unicast channel can help to obtain data successfully.

B. Power Efficiency of USM

In this work, USM is aiming at obtaining better power saving performance compared to pure multicast transmission. From the previous description of USM, one may notice that the algorithm performance depends on the selection of P_m and P_u. Hence, in this part, we will formulate the problem of selection of powers P_m and P_u, as well as examining the energy-efficiency of the proposed USM scheme.

In order to ensure the QoS, the inter-node transmission for each node should fulfill the data rate requirement of, say, R_T. That is,

$$R_T = log(1 + \gamma_T), \tag{1}$$

where γ_T is the target Signal-to-Noise Ratio (SNR) of using pure multicast transmission from transmitter to all nodes. We assume that the channel gain remains the same during a time slot and varies slot by slot. Let us assume that there exists a node j that has a very bad channel quality and the transmitter using the multicast power is not able to offer the required data rate R_T. The multicast data rate from transmitter to node j can be formulated as

$$R_j = log(1 + \gamma_j), \tag{2}$$

where γ_j is the received SNR from transmitter to node j adopting multicast transmission and we have $\gamma_j < \gamma_T$ apparently. Meanwhile, we assume the channel gain of unicast channel is the same as the one of multicast channel. Therefore, when the particular node j needs additional unicast support, the required additional data rate is given by

$$R_T - R_j = log\Big(\frac{1 + \gamma_T}{1 + \gamma_j}\Big). \tag{3}$$

Therefore, when performing USM, node j needs the received SNR γ_u of unicast transmission to be equal to

$$\gamma_u = \frac{\gamma_T - \gamma_{i,j}}{1 + \gamma_j}. \tag{4}$$

Thus, we can see that the power saving obtained by using USM over multicast transmission depends on P_u, γ_j and γ_T. Obviously, we have

$$\begin{cases} P_T = \gamma_T / G_j, \\ P_m = \gamma_j / G_j, \\ P_u = \gamma_u / G_j. \end{cases}$$

Here P_T denotes the required hypothesis multicast power if fulfilling the QoS R_T for the distant user j. Hence, the power saving P_s obtained by using USM can be expressed as

$$\begin{aligned} P_s &= P_T - (P_m + P_u) \\ &= \frac{\gamma_T}{G_j} - \frac{\gamma_j}{G_j} - \frac{\gamma_T - \gamma_j}{(1 + \gamma_j)G_j} \\ &= \frac{\gamma_j(\gamma_T - \gamma_j)}{G_j(1 + \gamma_j)} \\ &= \frac{P_T - P_m}{\frac{1}{G_j P_m} + 1}. \end{aligned} \tag{5}$$

Hence, with predefining the required QoS and knowing the channel condition, that is, assuming P_T and G_j known, our goal is to decide the value of P_m that can maximize our power saving objective

$$\max_{P_m} P_s, \tag{6}$$

s.t.

$$log(1 + P_m G_m) \geq R_T, \tag{7}$$

where G_m is the worst channel gain in the multicast group and we interpret the QoS as data rate. One can notice that (6) is a convex optimization problem. Therefore, we can simply obtain the optimal value for P_m by using Lagrangian method and applying Karush-Kuhn-Turker (KKT) conditions [8]. By denoting λ as the Lagrangian multiplier, the lagrangian is

$$\mathcal{L}(P_m, \lambda) = P_s - \lambda(log(1 + P_m G_T) - R_T), \tag{8}$$

and the lagrange dual function is

$$g(\lambda) = max\, \mathcal{L}(P_m, \lambda). \tag{9}$$

Consequently we can solve the problem of (6) by minimizing the dual function $g(\lambda)$ and theoretical solutions can be reached easily. The optimal value of lagrangian multiplier λ can be obtained by using, e.g., subgradient algorithm [10] with guaranteed convergence [9]. The optimal solution of P_m^* can be found with optimal value of λ^* accordingly. After some calculations, we can arrive at the solution for P_m,

$$\begin{aligned} P_m^* =& \phi_1 + \frac{\phi_2}{[(J_1 + J_2)^{1/2} + J_3]^{1/3}} \\ &+ [(J_1 + J_2)^{1/2} + J_3]^{1/3} - \phi_2, \end{aligned} \tag{10}$$

where

$$\begin{cases} J_1 = (\phi_2^3 - \phi_3 + \phi_4)^2, \\ J_2 = (\phi_1 + \phi_2^2)^3, \\ J_3 = \phi_3 - \phi_2^3 - \phi_4. \end{cases}$$

and

$$\begin{cases} \phi_1 = G_j G_m P_T - 2G_{i,j} + 2G_j G m \lambda^*, \\ \phi_2 = G_j G_m, \\ \phi_3 = G_j^2 + 2G_j G_m - G_j G m \lambda^*, \\ \phi_4 = G_m \lambda^* + G_j P_T. \end{cases}$$

IV. Numerical Results

The power saving and energy efficiency performance are presented in this section. We assume 20 nodes in the multicast group and one unicast node in the network. The inter-node channel model is defined according to IEEE 802.11ac [11] with the assumption of indoor environment. The distance among nodes inside the multicast group is assumed to be 20m for simplicity. The QoS data rate requirements for Figs. 3 and 2 are assumed to be 1 without lost of generality and varies in Figs. 4 and 5 in order to examine the algorithm's ability to offer higher data rates. We invoke the term ξ as the channel indicator that presents the difference of channel quality between unicast node and multicast group. ξ is defined as

$$\xi = \frac{G_m - G_j}{G_m}. \tag{11}$$

Fig. 2 shows the power consumption ratios which are defined as P_m/P_T and P_u/P_T, which represent the power saving gains as well. One can observe that as the channel quality of unicast node is getting worse, the additional unicast power is increasing almost linearly. However, the multicast power of USM still maintains the same, which is in order to

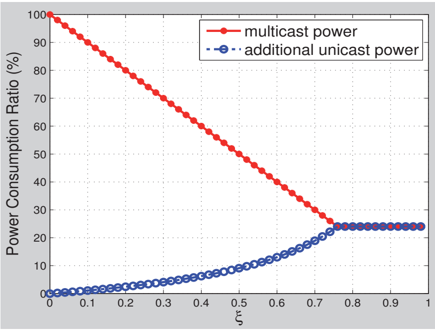


Figure 2. ξ vs. multicast power & unicast power

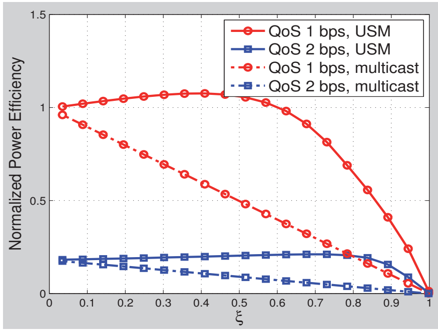


Figure 4. Normalized power efficiency, USM vs. Multicast

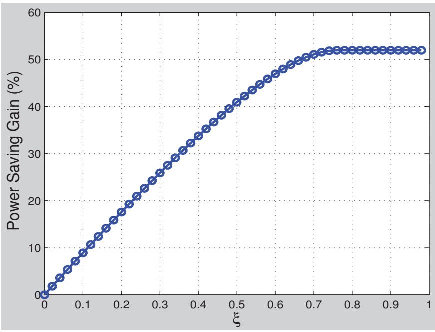


Figure 3. ξ vs. power saving gain

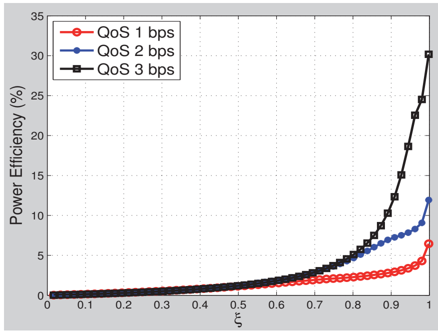


Figure 5. Energy efficiency of USM over multicast

support the QoS requirement for the nodes of the multicast group. When $\xi > 0,75$, in order to achieve maximum (optimal) power saving gain, both P_m and P_u are augmented based on the solution of (6) and (7).

In Fig. 3, the transmit power saving gain is presented by $P_s/P_T \times 100\%$. Since we assume the multicast group has around $20m$ inter-node distance, we vary the distance of unicast node in order to obtain different values for G_j. On y-axis we It is worth noticing that P_T is different for different G_j so that QoS can be achieved. As we can observe from the figure, our proposed USM scheme can achieve up to more than 50% power saving comparing with the pure multicast transmission.

The energy efficiency performance in Figs. 4 and 5 is evaluated by $bits/J$, which is defined as the offered data rate divided by energy consumption. Fig. 4 presents the normalized energy efficiency with respect to the case $R_T = 1$ bps and $\xi = 0$ for which the energy efficiency is set to 1. As can be seen the energy efficiency reach its maximum at $\xi = 0.45$ for $R_T = 1$ bps and at $\xi = 0.85$ for $R_T = 2$ bps, which means that USM is able to provide clear energy efficiency gains when the variability of channel gains get larger.

In Fig. 5 we present the energy efficiency gain of USM over the pure multicast. It can be clearly noticed that when the data rate requirement is getting higher, USM is able to provide energy efficiency gains in the sense that we can transmit the same amount of data with much less energy by invoking USM. For example, when $\xi = 0.9$ and $R_T = 3$, using USM can obtain more than 3 times energy efficiency than the one when $R_T = 1$. The performance gain is even higher (up to 4 times) when channel of unicast user getting worse. Therefore, together with the observation in Fig. 4, we can conclude that the USM scheme has superior energy efficiency performance compared to the conventional multicast for offering higher data rate services.

V. Conclusion

In this work, we considered a novel energy efficient variant for the conventional multicast transmission. The studied algorithm, namely Unicast Support Multicast (USM), when optimized from the energy efficiency point-of-view, was able to compensate the inherent drawbacks of multicast transmission and thus, obtain reductions in power consumption while still maintaining the same QoS requirement for the users in the considered scenario. Through numerical studies based on theoretical analysis, we observed that the energy efficiency performance can be significantly improved by utilizing USM when offering multicast service, especially when there exists nodes with much worse channel quality than the others.

ACKNOWLEDGEMENT

This work was partly supported by the Celtic-plus project Green-T (Project ID CP08-006). The authors also would like to thank NOKIA foundation for its funding.

REFERENCES

[1] C. Diot, W. Dabbous, and J. Crowcroft, "Multipoint Communication: A Survey of Protocols, Functions, and Mechanisms," *IEEE Journal on Selected Areas in Communications*, Vol. 15, No. 3, pp. 277-290, April 1997.

[2] S. Y. Baek, *et al*, "Adaptive Transmission Scheme for Mixed Multicast and unicast Traffic in Cellular Systems", *IEEE Transaction on Vehicular Technology*, Vol. 58, No. 6, pp. 2899-2907, July 2009.

[3] S. J. Lee, *et al*, "Efficient Use of Multicast and Unicast Channels for Multicast Services Transmission", *IEEE Transaction on Communications*, Vol. 59, No. 5, pp. 1264-1267, May 2011.

[4] H. Deng, X. Tao and J. Lu, "Qos-Aware Resource Allocation for Mixed Multicast and Unicast Traffic in OFDMA Networks," *EURASIP Journal on Wireless Communications and Networking*, 2012:195. , doi:10.1186/1687-1499-2012-195.

[5] J. Kim, T. Kwon and D. Cho, "Resource Allocation Scheme for Minimizing Power Consumption in OFDM Multicast Systems," *IEEE Communications Letters*, Vol. 11, No. 6, June 2007.

[6] Z. Chang and T. Ristaniemi, "Efficient Use of Multicast and Unicast in Collaborative OFDMA Mobile Cluster," *Proc. of IEEE VTC'13-spring*, Dresden, Germany, Jun. 2013.

[7] J.-F. Cheng, "Coding performance of hybrid ARQ schemes," IEEE Transaction on Communications, Vol. 54, No. 6, pp. 1017-1029, June 2006.

[8] S. Boyd, and L. Vandenberghe, *Convex Optimization* , Cambridge UK: Cambridge University Press, 2004.

[9] W. Yu and R. Lui, "Dual Methods for Nonconvex Spectrum Optimization in Multicarrier System," *IEEE Transactions on Communications*, Vol.54, No.7, pp.1310-1322, Jul. 2006.

[10] S. Boyd, and A. Mutapcic, *Subgradient Methods* , Lecture Notes of EE364b, Stanford University, 2006-2007.

[11] IEEE P802.11ac. Specification Framework for TGac.

PIX

ASYMMETRIC RESOURCE ALLOCATION FOR COLLABORATIVE RELAY OFDMA NETWORKS WITH IMPERFECT CSI

by

Zheng Chang, Tapani Ristaniemi and Zhisheng Niu 2013

Proc. of 2nd IEEE/CIC International Conference on Communications in China (ICCC'13)

Asymmetric Resource Allocation for Collaborative Relay OFDMA Networks with Imperfect CSI

Zheng Chang*†, Tapani Ristaniemi* and Zhisheng Niu ‡
*Department of Mathematical Information Technology, University of Jyväskylä,
P.O.Box 35, FIN-40014 Jyväskylä, Finland
† Magister Solutions Ltd, Hannikaisenkatu 41, FIN-40100 Jyväskylä, Finland
‡ Department of Electronic Engineering, Tsinghua National Laboratory for Information Science and Technology,
Tsinghua University, Beijing 100084, China
Email: zheng.chang@jyu.fi, tapani.ristaniemi@jyu.fi, niuzhs@tsinghua.edu.cn

***Abstract*—This paper addresses the resource allocation problem in collaborative relay-assisted OFDMA networks. Recent works on the subject have mainly considered symmetric source-to-relay and relay-to-destination resource allocations, which limits the achievable gains through relaying. In this paper our focus is two-fold. Firstly, we consider the problem of asymmetric radio resource allocation, where the objective is to maximize the system throughput of the source-to-destination link under various constraints. In particular, we consider optimization of the set of collaborative relays and link asymmetries together with subcarrier and power allocation. Secondly, we pay attention to the effects of imperfections in the channel-state information needed in the resource allocation decisions. We derive theoretical expressions for the solutions and illustrate them through simulations. The results validate clearly the additional performance gains through asymmetric cooperative scheme compared to the other recently proposed resource allocation schemes.**

***Index Terms*—OFDMA, relay selection, subcarrier allocation, asymmetric power allocation, imperfect CSI and cooperative communications**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is an effective technique that exploits the benefits of Orthogonal Frequency Division Multiplexing (OFDM) for combating against channel noise and multipath effects and finally enables high data rate transmissions over fading channels. Meanwhile, cooperative communication has emerged as one of the main trends to reach even better system performance in terms of throughput, energy efficiency or cell coverage. Therefore, the incorporation of OFDMA and cooperative relays is foreseen to result in a promising structure that offers a possibility to reach many desirable objectives for the future wireless networks. However, a combination of a conventional one-to-many (single hop) OFDMA system and a relay network calls for a careful design of the radio resource allocation (RRA) principles. This means a carefully design and coordination of the power and subcarrier allocation, selection of relay(s) across different hops and optimizing the resource asymmetries between the hops.

Radio resource allocation (RRA) plays an important role in wireless networks of any kind. Especially, incorporation of a set of collaborative relays into conventional one-to-many cellular system calls for a careful design of the RRA principles. This means a carefully design and coordination of the power and subcarrier allocation, selection of relay(s) across different hops and optimizing the resource asymmetries between the hops.

Related works on the subject (see. e.g. [1]-[6]) mostly assume perfect channel state information (CSI) to be available at the source. A cross-layer optimization algorithm for resource allocation in conventional OFDMA network was presented in [1] excluding any relays. An iterative algorithm was proposed to solve the subcarrier assignment together with relay selection in [2]. Then, the power allocation problem was solved by another iterative method based on waterfilling algorithm. The scheme used in [3] considered fairness constraints when selecting relays. In [4], a threshold method was used to solve two subproblems, subcarrier allocation and power allocation. Although the performance was improved comparing to some other algorithms, the total power constraint was considered, which is not a realistic case since each node has its own power limitation. The work in [5] also proposed a subcarrier and relay pairing algorithm to solve the existing RRA problem, but it is computationally quite complex. Moreover, all the previous works assumed the transmission durations for base station and relay link to be equal, which can result in a reduction of degree of freedom and system throughput [6]. In [6], a study on the asymmetric resource allocation was presented. However, this work considered only single relay in the OFDMA networks without exploring cooperative diversity. [7]-[8] presented the work about RRA with imperfect CSI. [7] considered the RRA algorithm for conventional OFDMA networks. The most recent work about RRA for OFDMA relay networks with imperfect CSI was introduced in [8], where only one relay is selected for assisting the transmission.

This paper extends the scope of the above-mentioned approaches by considering collaborative relays and asymmetric assignment for the source-to-relay (the first hop) and relay-to-destination (the second hop) links. We propose a new asymmetric resource allocation scheme for OFDMA networks with imperfect CSI, which can effectively solve the problems of joint relay selection, subcarrier and power allocation and thus, enhance the system throughput when only estimated CSI is available. Using a dual approach, we solve each sub-problem in an asymptotically optimal and alternating manner. In this work, relays are deployed for extending the cell coverage, so we do not consider the direct link from source to destination. Since the channel capacity in the presence of imperfect CSI is unknown, we use a capacity expectation as the performance metric. We propose a relay selection and subcarrier allocation schemes, where one set of relays that can obtain the best link data rate is selected. Power is allocated to the source and relays under per-node constraints, which is more realistic than the scheme, e.g., in [4] where only the sum of whole system power is considered.

The rest of this paper is organized as follows. Section II describes our relay-assisted OFDMA cooperative wireless networks and formulates the problem. We consider downlink only in this work, but it can be extended further to the uplink case. In Section III, the proposed resource allocation scheme is presented. We demonstrate the benefits of our proposed algorithm in section IV and finally conclude the paper in Section V.

II. System Model and Problem Formulation

A. System model and Assumptions

This paper investigates the problem of RRA in the cooperative relay OFDMA network. We consider our system as a two-hop (time slot) time-division duplex downlink relay system. The whole system consists of source(i.e. base station, AP), destination node(i.e. mobile station, MT) and several relays. The first hop is so called broadcast phase, where AP broadcasts information to a cluster of decode-and-forward (DF) relays. In the second hop, relays cooperate to transmit the information data to the MT, so that, i.e., spatial diversity gain can be achieved (relays are assumed to be far enough to each other). The estimated channel state information (CSI) is assumed to be known at receiver through estimator and then fed back to the transmitter perfectly. We also assume that channel estimation error pertains to the amplitude of the correct channel gain, while the phase of the channel gain can be perfectly obtained. As a result, CSI about the channel gain with an estimation error is available to both the transmitter and the receiver. The AP acts as a central controller to carry out all resource allocation related operations based on the CSI from the MT.

Assuming there are total Z relays in the networks, and the selected relay cluster $\mathcal{K}$ contains K potential half-duplex relays.

B. Problem Formulation

Let x be the transmit data from transmitter to receiver and P is the transmit power gain. So regardless of the path loss, the received data after estimator at receiver is

$$y = h\sqrt{P}x + n, \tag{1}$$

and we have

$$h = \hat{h} + \tilde{h}, \tag{2}$$

where $\hat{h}$ is the estimated channel function and $\tilde{h}$ is the independent estimation error which can be modeled as zero mean Gaussian random variable with variance $\sigma^2_{\tilde{h}}$. Thus, the imperfect CSI h is assumed to follow $\mathcal{CN}(\hat{h}, \sigma^2_{\tilde{h}})$. n is the additive noise which can be also modeled as complex Gaussian random variable with variance σ^2_n. Therefore, the square of imperfect CSI h follows a noncentral chi-square probability density function (PDF) given by [9]

$$f(G|\hat{G}) = \frac{1}{\sigma^2_{\tilde{h}}} e^{-\frac{\hat{G}+G}{\sigma^2_{\tilde{h}}}} \mathcal{J}_0\Big(2\sqrt{\frac{\hat{G}G}{\sigma^4_{\tilde{h}}}}\Big) \tag{3}$$

where we denote $G = |h|^2, \hat{G} = |\hat{h}|^2$. $\mathcal{J}_0$ is the 0th order modified Bessel Function of the first kind.

In our proposed system model, we suppose h^i is the channel transfer function from transmitter to receiver and we assume the channel is static in a time slot. For example, $\hat{h}^i_{s,k}$ means the channel estimate from AP s to relay node (RN) k over OFDM subcarrier i and $\hat{h}^j_{k,d}$ means the channel estimate from RN k to destination d over OFDM subcarrier j. We have channel gain of the first hop $\hat{G}^i_{s,k} = |\hat{h}^i_{s,k}|^2$ and second hop $\hat{G}^j_{k,d} = |\hat{h}^j_{k,d}|^2$. L is the path loss factor and the noise variance for two hops are σ^2_k and σ^2_d. The variance of related estimation error for two hops are $\sigma^2_{\tilde{h},k}$ and $\sigma^2_{\tilde{h},d}$ and we assume $\sigma^2_{\tilde{h}} = \sigma^2_{\tilde{h},k} = \sigma^2_{\tilde{h},d}$. We denote the transmit power assigned to subcarrier i for transmitting data as P^i. In this work, we do not consider the direct link from AP to MT, which is a practical assumption for the case where RNs are deployed for cell extension. One RN k occupies subcarrier i in the first hop and j in the second hop. In this work, we assume that the transmission durations for the first hop and second hop are allowed to differ. We denote these durations as T_1 and T_2. Therefore, at the first hop, the data rate of the broadcast phase is determined by the minimum rate of each link between AP and selected RNs. Since transmitter only knows the CSI conditioned on the feedback of receiver, we could obtain the expected achievable throughput of the first hop as follows:

$$R^{\mathcal{I}}_{s,\mathcal{K}} = \min_{k\in\mathcal{K}} \Big\{ \mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}} \Big[\frac{T_1}{T} log(1 + \sum_{i=1}^{M} \omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k}) \Big] \Big\}, \tag{4}$$

where $\gamma^i_{s,k} = \frac{L_{s,k}G^i_{s,k}}{\sigma^2_k}$ and $\hat{\gamma}^i_{s,k} = \frac{L_{s,k}\hat{G}^i_{s,k}}{\sigma^2_k}$. The notation $\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}$ means expectation with respect to $\gamma^2_{s,k}$ conditioned on $\hat{\gamma}^i_{s,k}$. $\mathcal{M}$ is the subcarrier set of the system that contains M subcarriers. $\mathcal{I}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at first hop. We further refer the link throughput and its expectation interchangeably for simplicity. ρ_k indicates that whether RN k is chosen for subcarrier allocation, so we obtain

$$\rho_k = \begin{cases} 1 & \text{if } k \text{ is chosen for relaying,} \\ 0 & \text{otherwise.} \end{cases}$$

We also define ω is the indicator whether certain subcarrier is assigned to RN k, which is,

$$\mathcal{L}(\mathbf{P},\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}) = \Big(R^{\mathcal{I}}_{s,\mathcal{K}}+R^{\mathcal{J}}_{\mathcal{K},d}\Big)-\lambda_s(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k}-P_{s,max})-\sum_{k=1}^{K}\lambda_{k,d}(\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d}-P_{k,max})-\mu(R^{\mathcal{I}}_{s,\mathcal{K}}-R^{\mathcal{J}}_{\mathcal{K},d}), \quad (11)$$

$$\omega^i_{s,k} = \begin{cases} 1 & \text{if } i \text{ is assigned to } k \text{ at first hop,} \\ 0 & \text{otherwise.} \end{cases}$$

For the second hop, it is assumed that the RNs are perfectly synchronized and transmitted at the same time. Therefore, the second hop can be viewed as a virtual MISO link. The expected throughput can be expressed as [10]

$$R^{\mathcal{J}}_{\mathcal{K},d} = \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}\Big[\frac{T_2}{T}log\big(1+\sum_{j=1}^{M}\sum_{k=1}^{K}\omega^j_{k,d}\rho_k P^j_{k,d}\gamma^j_{k,d}\big)\Big], \quad (5)$$

where $\gamma^j_{k,d} = \frac{L_{k,d}G^j_{k,d}}{\sigma^2_d}$ and $\hat{\gamma}^j_{k,d} = \frac{L_{k,d}\hat{G}^j_{k,d}}{\sigma^2_d}$. $\mathcal{J}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at second hop. For indicator $\omega^j_{k,d}$, we also have

$$\omega^j_{k,d} = \begin{cases} 1 & \text{if } j \text{ is assigned to } k \text{ at second hop,} \\ 0 & \text{otherwise.} \end{cases}$$

Therefore, the total achieved end-to-end throughput of source s to destination d through RN set $\mathcal{K}$ is [10]

$$R_{sd} = min \ \Big\{R^{\mathcal{I}}_{s,\mathcal{K}}, R^{\mathcal{J}}_{\mathcal{K},d}\Big\}. \quad (6)$$

To proceed, we can formulate our problem as

$$max \ \ R_{sd} \quad (7)$$

subject to

$$\begin{aligned} & T = T_1 + T_2 \\ & \sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k} \le P_{s,max} \\ & \sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d} \le P_{k,max} \\ & \sum_{k=1}^{K}\omega^i_{s,k} = 1, \omega^i_{s,k} \in \{0,1\} \\ & \sum_{k=1}^{K}\omega^j_{k,d} = 1, \omega^j_{k,d} \in \{0,1\} \end{aligned} \quad (8)$$

where $P_{s,max}$ is the maximum transmit power of AP and $P_{k,max}$ is the maximum power of RN k. Therefore, our goal is to find the optimal solutions for relay set, link asymmetry, and subcarrier and power allocations which satisfy the problem (7).

It can be deduced that achieving maximum for (6) implies $R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}$ [4]. Thus, (7) can be modified as

$$\arg\max \ \Big(R^{\mathcal{I}}_{s,\mathcal{K}} + R^{\mathcal{J}}_{\mathcal{K},d}\Big), \quad (9)$$

subject to conditions in (8) and

$$R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}. \quad (10)$$

III. Resource Allocation Scheme

In this section, we introduce an adaptive RRA algorithms to solve the existing problems described in the previous section. Although the resource allocation problem is combinatorial in nature with a non-convex structure, it has been shown in [12] that the duality gap of the optimization problem becomes zero under the condition of time-sharing regardless of its convexity. For the general OFDM system, the condition of time-sharing is always fulfilled as the number of subcarriers is large enough. As such, it can be solved in the dual domain and the solution is asymptotically optimal. The Lagrangian [11] of (9) is in (11), where $\mathbf{P} = \{P^i_{s,k}, P^j_{k,d}\}$ is the set of power allocation, $\boldsymbol{\omega} = \{\omega^i_{s,k}, \omega^j_{k,d}\}$ denotes the subcarrier allocation, and $\boldsymbol{\rho} = \{\rho_k\}$ is the relay assignment. The λ_s, $\lambda_{k,d}$ and μ are Lagrange multipliers. Then it can be derived that $\lambda_s, \lambda_{k,d} \ge 0$ and $\mu \in (-1,1)$ [6].

The Lagrange dual function can be written as:

$$g(\boldsymbol{\lambda},\boldsymbol{\mu}) = \max \mathcal{L}(\mathbf{P},T,\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}). \quad (12)$$

We assume the number of subcarrier is sufficiently large, so the duality gap between primal problem and dual function can be negligible [12]. Therefore, we can solve the problem (7) by minimizing the dual function:

$$\min \ g(\boldsymbol{\lambda},\boldsymbol{\mu}) \quad (13)$$

A. Evaluating Dual Variable

Since a dual function is always convex [11], we can choose e.g. sub-gradient algorithm [12] with guaranteed convergence to minimize $g(\boldsymbol{\lambda},\boldsymbol{\mu})$. We follow the sub-gradient method in [12] to derive the subgradient $g(\boldsymbol{\lambda},\boldsymbol{\mu})$ with the optimal power allocation p^* that will be presented in the following subsection.

Algorithm 1 Evaluating Dual Variable

1: Initialize $\boldsymbol{\lambda}^0$ and $\boldsymbol{\mu}^0$
2: **while** (!Convergance) **do**
3: Obtain $g(\boldsymbol{\lambda}^a,\boldsymbol{\mu}^a)$ at the ath iteration;
4: Update a subgradient for $\boldsymbol{\lambda}^{a+1}$ and $\boldsymbol{\mu}^{a+1}$, by $\boldsymbol{\lambda}^{a+1} = \boldsymbol{\lambda}^a + \upsilon^a\triangle\boldsymbol{\lambda}$ and $\boldsymbol{\mu}^{a+1} = \boldsymbol{\mu}^a + \upsilon^a\triangle\mu$;
5: **end while**

where $\triangle \boldsymbol{\lambda} = \{\triangle\lambda_s, \triangle\lambda_{1,d}, ...\triangle\lambda_{K,d}\}$, $\triangle\lambda_s$, $\triangle\lambda_{k,d}$ and $\triangle\mu$ can be expressed as

$$\begin{aligned} \triangle\lambda_s &= P_{s,max} - \sum_{i=1}^{M}\sum_{k=1}^{K}(P^i_{s,k})^* \\ \triangle\lambda_{k,d} &= P_{k,max} - \sum_{j=1}^{M}(P^j_{k,d})^* \\ \triangle\mu &= (R^{\mathcal{I}}_{s,\mathcal{K}})^* - (R^{\mathcal{J}}_{\mathcal{K},d})^*. \end{aligned} \tag{14}$$

Here, v^a is the stepsize and a is the number of iterations. The sub-gradient algorithm (Algorithm 1) is guaranteed to converge to the optimal $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$. The computational complexity of Algorithm 1 is polynomial in the number of dual variable $K+1$ [12]. Since (12) can be viewed as a nonlinear integer programming problem, its optimal solution requires high computational cost. Therefore, we are aiming to solve the optimization problem by solving three subproblems, which are relay selection, subcarriers and power allocation.

B. Asymmetric Power Allocation Scheme

By assuming the relay selection and subcarrier allocation are done, the optimal time slot for each hop can be achieved by using Karush-Kuhn-Tucker (KKT) conditions [11]. This results in

$$T_1 = \frac{1-\mu^*}{2}T \tag{20}$$

$$T_2 = \frac{1+\mu^*}{2}T \tag{21}$$

In order to obtain the optimal solution of power allocation, we are aiming to solve the problem solving problem (11) over variables $P^i_{s,k}$ and $P^j_{k,d}$. However, from (5) and (4), we see that problem (11) involves the conditional expectation of achievable throughput with respect to estimated CSI. Applying Karush-Kuhn-Tucker (KKT) conditions [11], we could obtain the optimal power allocation schemes by solving following equation numerically:

$$\frac{\alpha^i_{s,k}}{P^i_{s,k}}\big(\frac{\sigma^2_k\beta^i_{s,k}}{L_{s,k}P^i_{s,k}}\big)^{\alpha^i_{s,k}} e^{\frac{\sigma^2_k\beta^i_{s,k}}{L_{s,k}P^i_{s,k}}}\Gamma\big(-\alpha^i_{s,k}, \frac{\sigma^2_k\beta^i_{s,k}}{L_{s,k}P^i_{s,k}}\big) = \frac{2\lambda_s}{(1-\mu)^2}. \tag{22}$$

where $\Gamma(a,b)$ is the incomplete Gamma function. $\alpha^i_{s,k} = (\eta^i_{s,k}+1)^2/(2\eta^i_{s,k}+1)$ is the Gamma shape parameter with $\eta^i_{s,k} = \hat{G}^i_{s,k}/\sigma^2_{\tilde{h}}$ and $\beta^i_{s,k} = \alpha^i_{s,k}/(\hat{G}^i_{s,k}+\sigma^2_{\tilde{h}})$ is Gamma PDF rate parameter. Similarly, for the cooperation phase, the optimal RN power allocation is obtained by solving:

$$\frac{\alpha^j_{k,d}}{P^j_{k,d}}\big(c_1\beta^j_{k,d}\big)^{\alpha^j_{k,d}} e^{c_1\beta^j_{k,d}}\Gamma\big(-\alpha^j_{k,d}, c_1\beta^j_{k,d}\big) = \frac{2\lambda_{k,d}}{(1+\mu)^2}, \tag{23}$$

where $\alpha^j_{k,d} = (\eta^j_{k,d}+1)^2/(2\eta^j_{k,d}+1)$ with $\eta^j_{k,d} = \hat{G}^j_{k,d}/\sigma^2_{\tilde{h}}$ and $\beta^j_{k,d} = \alpha^j_{k,d}/(\hat{G}^j_{k,d}+\sigma^2_{\tilde{h}})$. We have $c_1 = \frac{\sigma^2_d + \sum_{m=1,m\neq k}^{K} P_{m,d}L_{m,d}G_{m,d}}{L_{k,d}P^j_{k,d}}$. $P_{m,d}$ and $G_{m,d}$ is the power allocation and channel gain from relay m to MT d. By using approximation method, e.g. , in [13], we are able to obtain the power allocation with imperfect CSI.

C. Opportunistic Relay Selection(ORS)

We consider ORS in this work, unlike some traditional single relay selection algorithms in [5], as the multiple RNs selection. The proposed algorithm is to select K RNs to form a cluster that can maximize the achieved throughput in (6) based on the imperfect CSI.

When assuming the subcarrier and power allocations are done, we can rewrite (11) as in (19).

By applying KKT condition, the RN is selected according to the following rule,

$$\begin{aligned} \mathcal{K}^* = \arg\max_k \ & \Bigg(\min_{k\in\mathcal{K}}\Big\{\frac{(1-\mu^*)^2}{2}\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}\Big[\frac{P_{s,k}\gamma_{s,k}}{1+P_{s,k}\gamma_{s,k}}\Big]\Big\} \\ & + \frac{(1+\mu^*)^2}{2}\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}\Big[\frac{P_{k,d}\gamma_{k,d}}{1+\sum_k^K P_{k,d}\gamma_{k,d}}\Big]\Bigg), \end{aligned} \tag{20}$$

Since we know that $\hat{\gamma}^i_{s,k} = \frac{L_{s,k}\hat{G}^i_{s,k}}{\sigma^2_k}$. The channel SNR $\gamma_{s,k}$ conditioned on $\hat{\gamma}^i_{s,k}$ is also a non-central Chi-squared distributed random variable with PDF:

$$f(\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}) = \frac{1}{\nu^i_{s,k}}e^{-\frac{\hat{\gamma}^i_{s,k}+\gamma^i_{s,k}}{\nu^i_{s,k}}}\mathcal{J}_0\Big(2\sqrt{\frac{\hat{\gamma}^i_{s,k}\gamma^i_{s,k}}{(\nu^i_{s,k})^2}}\Big) \tag{21}$$

$$f(\gamma^i_{s,k}|\hat{\gamma}^j_{k,d}) = \frac{1}{\nu^j_{k,d}}e^{-\frac{\hat{\gamma}^j_{k,d}+\gamma^j_{k,d}}{\nu^j_{k,d}}}\mathcal{J}_0\Big(2\sqrt{\frac{\hat{\gamma}^j_{k,d}\gamma^j_{k,d}}{(\nu^j_{k,d})^2}}\Big) \tag{22}$$

where $\nu^i_{s,k} = \sigma^2_k/\sigma^2_{\tilde{h}}$ and $\nu^j_{k,d} = \sigma^2_d/\sigma^2_{\tilde{h}}$. After some algebraic manipulation, we obtain

$$\begin{aligned} &\frac{(1-\mu^*)^2}{2}\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}\Big[\frac{P^i_{s,k}\gamma^i_{s,k}}{1+P^i_{s,k}\gamma^i_{s,k}}\Big] \\ =&\frac{(1-\mu^*)^2}{2}\psi^i_{s,k}\big(\frac{\theta^i_{s,k}}{P^i_{s,k}}\big)^{\psi^i_{s,k}}e^{\frac{\theta^i_{s,k}}{P^i_{s,k}}}\Gamma\big(-\psi^i_{s,k}, \frac{\sigma^2_k\theta^i_{s,k}}{L_{s,k}P^i_{s,k}}\big), \end{aligned} \tag{23}$$

$$\begin{aligned} &\frac{(1+\mu^*)^2}{2}\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}\Big[\frac{P^j_{k,d}\gamma^i_{k,d}}{1+\sum_k^K P^j_{k,d}\gamma^j_{k,d}}\Big] \\ =&\frac{(1-\mu^*)^2}{2}\psi^j_{k,d}\big(c_2\theta^j_{k,d}\big)^{\psi^j_{k,d}}e^{c_2\theta^j_{k,d}}\Gamma\big(-\psi^j_{k,d}, c_2\theta^j_{k,d}\big), \end{aligned} \tag{24}$$

where $\psi^i_{s,k} = (\zeta^i_{s,k}+1)^2/(2\zeta^i_{s,k}+1)$ with $\zeta^i_{s,k} = \hat{\gamma}^i_{s,k}/\nu^i_{s,k}$ and $\theta^i_{s,k} = \zeta^i_{s,k}/(\hat{\gamma}^i_{s,k}+\nu^i_{s,k})$. $\psi^j_{k,d} = (\zeta^j_{k,d}+1)^2/(2\zeta^j_{k,d}+1)$ with $\zeta^j_{k,d} = \hat{\gamma}^j_{k,d}/\nu^j_{k,d}$ and $\theta^j_{k,d} = \zeta^j_{k,d}/(\hat{\gamma}^j_{k,d}+\nu^j_{k,d})$. We have $c_2 = (1+\sum_{m=1,m\neq k}^{K} P_{m,d}\gamma_{m,d})/P^j_{k,d}$. $P_{m,d}$ and $\gamma_{m,d}$ are the power allocation and channel SNR from relay m to MT. Optimal value of $\mathbf{P}$ can be given in (22) and (23). Thus, (20) can be viewed as multi-objective optimization problem, which

$$\mathcal{L}(\mathbf{P},T,\boldsymbol{\omega},\boldsymbol{\rho},\boldsymbol{\lambda}) = \min_{k\in\mathcal{K}}\Big\{\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}[\frac{T_1}{T}log(1+\sum_{i=1}^{M}\omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k})]\Big\} + \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}[\frac{T_2}{T}log(1+\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d})]$$
$$-\mu\Big(\min_{k\in\mathcal{K}}\Big\{\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}[\frac{T_1}{T}log(1+\sum_{i=1}^{M}\omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k})]\Big\} - \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}[\frac{T_2}{T}log(1+\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d})]\Big)$$
$$+\lambda_s(\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k} - P_{s,max}) - \sum_{k=1}^{K}\lambda_{k,d}(\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d} - P_{k,max}). \quad (19)$$

aims at obtaining the trade-off of the throughput of first hop and second hop. (20) is also the termination criteria for the whole RRA scheme. Therefore, the relay selection strategy is

$$\rho_k = \begin{cases} 1 & \text{if } k \in \mathcal{K}^*, \\ 0 & \text{otherwise.} \end{cases}$$

D. Optimal Subcarrier Allocation (OSA)

The goal of subcarrier allocation strategy is to assign subcarriers to a given RN that can obtain best throughput performance. Following the same procedure as the relay selection, we could obtain subcarrier allocation criteria as follows,

$$\mathcal{I}^* = \arg\max \ \Big(\min_{k\in\mathcal{K}}\Big\{\frac{(1-\mu^*)^2}{2}\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}\Big[\frac{P^i_{s,k}\gamma^i_{s,k}}{1+P^i_{s,k}\gamma^i_{s,k}}\Big]\Big\} \quad (25)$$

$$\mathcal{J}^* = \arg\max\Big\{\frac{(1+\mu^*)^2}{2}\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}\Big[\frac{P^j_{k,d}\gamma^j_{k,d}}{1+\sum_k^K P^j_{k,d}\gamma^j_{k,d}}\Big]\Big\}\Big), \quad (26)$$

where channel SNR $\gamma^i_{s,k} = \frac{L_{s,k}G^i_{s,k}}{\sigma^2_k}$ and $\gamma^j_{k,d} = \frac{L_{k,d}G^j_{k,d}}{\sigma^2_d}$. Therefore, the OSA indicator for the first hop and second hop can be expressed as

$$\omega_i = \begin{cases} 1 & \text{if } i \in \mathcal{I}^*, \\ 0 & \text{otherwise.} \end{cases}$$

$$\omega_j = \begin{cases} 1 & \text{if } j \in \mathcal{J}^* , \\ 0 & \text{otherwise.} \end{cases}$$

IV. Performance Evaluation

Performance of the proposed algorithm is presented in this section. It is assumed that five RNs are located between AP and MT, and MT is 1.8km away from AP. The Stanford University SUI-3 channel model is employed [14], in which the central frequency is 1.9GHz. Channel is assumed to be 3-tap channel and signal fading follows Rician distribution. We choose number of subcarriers N to be 32, so the duality gap can be ignored [5]. Flat quasi-static fading channels are considered, hence the channel coefficients are assumed to be constant during a complete frame, and can vary from a frame to another independently. The noise variance of the two hops

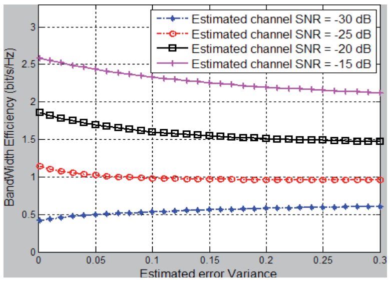


Figure 1. One example of impact of $\sigma^2_{\hat{h}}$ on the system bandwidth Efficiency

are set to be 1 for simplicity. The path loss factor varies according to the different distances from RNs to AP and MT and the exponent is fixed to 3.5. The maximum transmit power of AP and RN are 40 dBm and 20 dBm respectively.

We demonstrate our results compared with the performance of some other recently proposed symmetric or asymmetric schemes:

1) Equal power allocation combined with proposed subcarrier allocation scheme and relay selection(EPA);

2) Waterfilling power allocation and proposed subcarrier allocation scheme with relay selection (Waterfilling);

3) Proportional Allocation scheme in [4] with fairness consideration(Fairness SA);

4) Asymmetric Resource Allocation scheme in [6] without cooperative relay (ARA);

At first, the impact of value of $\sigma^2_{\hat{h}}$ on the system bandwidth efficiency is depicted in Fig. 1. We can notice that if we use an estimator with variance $\sigma^2_{\hat{h}} = 0.02$, it can result in around 5% difference on the system performance.

Fig. 2 demonstrates the impact of maximum transmit power of AP on the system throughput. We denote $d_{s,d}$ as the distance between AP and MT, and $d_{s,k}$ as the distance between AP and RNs. In Fig. 2, $d_{s,d} = 1800\ m$ and $d_{s,k} = 1500 - 1600\ m$. The maximum transmit power of RN is considered as half of the maximum transmit power of the AP. The considered channel SNR from AP to RN is $\gamma_{s,k} = -20\ dB\ \ -30\ dB$ and from RN to MT is $\gamma_{k,d} = -15\ dB\ \ -25\ dB$. We compare the performance of our proposed resource allocation

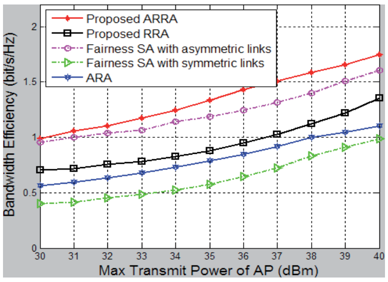


Figure 2. Impact of maximum transmit power $P_{s,max}$ on system bandwidth Efficiency

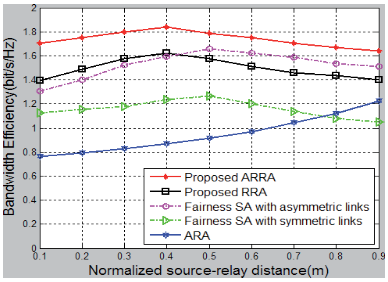


Figure 3. Impact of distance between AP and Relay on the system bandwidth efficiency, maximum AP power is 35 dBm, maximum RN power is 20 dBm

algorithm with two other recently proposed algorithms. The result of EPA scheme is also presented. The proposed scheme achieves the best performance, and the performance gain over other existed ARA methods is up to about 55%. Comparing to the Waterfilling and Fairness SA scheme, the bandwidth efficiency enhancement is around 20%. It can be noticed that if waterfilling is used as power allocation scheme instead of the proposed APA, the throughput performance is almost as same as the one of Fairness SA.

Fig. 3 shows the impact of distance between AP and RN on the system throughput. The distance between AP and RN is normalized to distance between AP and MT and vary from 0.1 to 0.9. In Fig. 3, we set maximum AP power $P_{s,max} = 40\ dBm$ and maximum RN power is $P_{k,max} = 20\ dBm$. From Fig. 3, we can see that the proposed algorithm obtains the highest system capacity when distance is less than 0.9. When the average normalized distance between AP and RN is around 0.9, we can find that the proposed scheme has the same capacity performance as the ARA algorithm. This may due to the fact the some RNs are very close to the MT so that the achieved SNR is rather high. Therefore, it can be concluded that the proposed algorithm can provide better performance gain over other existed algorithms even with small maximum AP power.

V. Conclusion

In this work, we considered the asymmetric resource allocation problem for cooperative multi-relay OFDMA networks. By designing asymmetric time slots for different hops, the proposed algorithm is able to increase the system throughput as well as the degrees of freedom. The optimization problem was divided into three subproblems including relay selection, subcarrier and power allocation with the objective of maximizing the transmission rate. At first relay and subcarrier is allocated according to the proposed criteria, respectively, which can provide better data rate. Then power allocation algorithm was proposed by solving the KKT condition. Therefore, a closed-form solution was achieved with a low computational cost. Simulation results illustrated that the achieved system performance of the proposed scheme was notably better than that of other exiting schemes.

Acknowledgement

This work is partly funded by Academy of Finland Project No. 265516. The authors also would like to thank NOKIA foundation for its generous support.

References

[1] G. Song and Y. Li, "Cross-layer Optimization for OFDM Wireless Networks-Part 1: Theoretical Framework," *IEEE Transaction on Wireless Communications*, Vol.4, No.2, pp.614-624, Mar. 2005.

[2] T.C-Y. Ng and W. Yu, "Joint Optimization of Relay Strategies and Resource Allocation in Cooperative Cellular Networks," *IEEE Journal on Selective Area in Communications*, Vol.25, No.2, pp.328-339 ,Feb. 2007.

[3] H. Jeong and J. H. Lee, "Adaptive Relay Selection for Regenerative OFDMA Relay Networks with Fairness Constraints," *Proc. of IEEE VTC 2008-fall*, Calgary, Canada, Sep. 2008.

[4] M. Tang, *et al*, "Dynamic Resource Allocation with Threshold in OFDMA-based Relay Networks," *Proc. of IEEE VTC 2010-Spring*, Taipei, Taiwan, May 2010.

[5] W. Dang, *et al*, "Subcarrier-Pair Based Resource Allocation for Cooperative Multi-Relay OFDM systems," *IEEE Transaction on Wireless Communications*, Vol.9, No.5, pp. 1640-1649, May 2010.

[6] N. Zhou, *et al*, "Optimal Asymmetric Resource Allocation and Analysis for OFDM-Based Multidestination Relay Systems in the Downlink," *IEEE Transaction on Vehicular Technology*, Vol.60, No.3, pp. 1307-1312, March 2011.

[7] M. K. Awad, *et al*, "A Dual-Decomposition-Based Resource Allocation OFDMA Networks with Impefect CSI," *IEEE Transaction on Vehicular Technology*, Vol.59, No.5, pp. 2394-2403, May 2010.

[8] J-H. Wang, *et al*, "Resource Allocation and Relay Selection for cooperative OFDMA Networks with Imperfect Channel Information," *Proc. of IEEE SPAWC 2011*, San Francisco, CA, June 2011.

[9] John G. Proakis and M. Salehi, *Digital Communications*,5th edition, McGraw-Hill Science, 2007.

[10] Z. Chang and T. Ristaniemi, "Radio Reource Allocation for Cooperative Relay-assisted OFDMA Wireless Networks," *Proc. of 3rd Internatial Workshp on Cross-layer Desgin(IWCLD)*, Rennes, France, Nov. 2011.

[11] S. Boyd, and L. Vandenberghe, *Convex Optimization* , Cambridge UK: Cambridge University Press, 2004.

[12] W. Yu and R. Lui, "Dual Methods for Nonconvex Spectrum Optimization in Multicarrier System," *IEEE Transaction on Communications* , Vol.54, No.7, pp.1310-1322, Jul. 2006.

[13] A. Lauschke, *Convergence Acceleration with Canonical Contractions of Continued Fractions: Incomplete Gamma Function* [Online]. available: http://216.80.120.13:8080/webMathematica/LC/gamma.jsp

[14] R. Jain, *Channel Models A Tutoriall v1.0* , Feb. 2007.

PX

POWER EFFICIENT MULTICAST TRANSMISSION FRAMEWORK WITH QOS AWARENESS

by

Zheng Chang and Tapani Ristaniemi 2013

Proc. of 2013 International Conference on Wireless Communications and Signal Processing (WCSP'13)

Power Efficient Multicast Transmission Framework with QoS Awareness

Zheng Chang*† and Tapani Ristaniemi*
*Department of Mathematical Information Technology, University of Jyväskylä, P.O.Box 35, FIN-40014 Jyväskylä, Finland
† Magister Solutions Ltd, Hannikaisenkatu 41, FIN-40100 Jyväskylä, Finland
Email: {zheng.chang, tapani.ristaniemi}@jyu.fi

***Abstract*—Multicast is recognized as an efficient transmission mechanism for delivering large number of common data to different mobile users. One inherent drawback of multicast transmission is that in order to guarantee the quality of service for each mobile user, the transmitter needs to adapt its data rate to the user(s) with worst channel condition in a multicast group. Therefore, power consumption could be seriously arisen. In order to address this problem, in this work we propose an energy efficient framework called Multicast Support Multicast (MSM) and examine its energy saving performance. The proposed MSM can dynamically use an extra channel as an additional support for traditional multicast transmission, by which power consumption of transmitter can be reduced. Moreover, through formulating optimization problem, we also discuss user grouping scheme that allows us to obtain the optimal energy saving gain. Numerical examples are presented to illustrate the proposed scheme and to show the performance gains obtained by employing additional multicast channel(s) and optimal user grouping.**

***Index Terms*—power consumption; energy efficiency; energy saving; multicast grouping;**

I. Introduction

The tremendous growth of wireless multimedia services have placed an exceptional demand on high data rate transmission for large number of users. It is worth noticing that, many emerging multimedia applications, such as IPTV, mobile TV, video conference and other group-oriented commence, aim to transmit large volume of data to multiple mobile users. Multicast/broadcast is recognized as an bandwidth efficient transmission mechanism for operating such point-to-multipoint (PMP) transmissions in order to provide such multimedia service since it can simultaneously deliver common information to many users [1] through same frequency channel. The PMP multicast transmission can noticeably increase the spectrum efficiency compared to the common unicast transmission. In fact, the multicast technique can be found in many systems, e.g., Digital Video Broadcasting-Terrestrial/Handheld (DVB-T/H). In 3GPP standardization, multimedia broadcast/multicast service (MBMS) was specified as well.

However, aiming to fulfill the Quality of Service (QoS) requirements (e.g., error rate/outage probability) of each user, in the light of multicast transmission, transmitter has to heavily increase transmit power if there exists a user with much worse channel quality than the others. Such inherent drawback of multicast induces high power consumption and low energy efficiency to the transmitter. To meet the challenges raised by high energy consumption and users' demands of wireless multimedia services, design of energy efficient multicast paradigm has become an urgent need for wireless networks today.

Wireless multicast has received much attention for enhancing its spectrum efficiency utilization and some work have been proposed to mitigate its inherent problems. As we know, in contrast to multicast, unicast has its own advantage in the context that unicast can exploit multiuser diversity by utilizing independent variations of multiuser channels. Variable data rates according to different channel conditions can be supported. Recent work on utilizing advantages of unicast to compensate the drawbacks of multicast can be found in [2] – [5], of which the objectives are to maximize the total system throughput with different constraints.

All the aforementioned work considered the use of unicast/multicast for throughput maximization. On another front, [6]–[8] endeavored to improve the spectrum efficiency by scheduling and grouping multiple multicast users. In [6], authors presented a comprehensive survey of different scheduling and resource allocation algorithms in multicast OFDM systems. [7] proposed to dynamically allocate the radio resource, i.e., subcarriers to the different multicast groups in order to increase their data rate. Although the throughput of the user with worst channel can be increased, high computational complexity is induced and this problem is even serious when number of users increase. In [8], authors introduced a utility maximization framework for efficient and fairness multicarrier multicast transmission. This work only investigated spectrum efficiency issue without touching power consumption related problems.

In this work, we further exploit the idea of supported multicast scheme and propose a novel Multicast Support Multicast (MSM) transmission method, which is a simple yet efficient scheme to enhance the energy saving performance. As observed from our previous work [9], the usage of additional unicast resulted in high power consumption as the number of users who need additional support became larger. Therefore, the energy saving performance could be limited if more users are with bad channel conditions. Such observation inspired us to employ the multicast, in stead of unicast, as the support for pure multicast transmission. In the proposed MSM scheme, we partition the users into to one Basic Multicast Group (BMG), and one Multicast Support Groups (MSG) so that energy efficiency can be maximized. Intuitively, grouping more users together results in a lower data rate at each channel simply because the data rate is determined by the worst user's channel, the gain of which degrades with the number of users. On the other hand, more users in a group yields an efficient utilization of spectrum since more users can be served. Therefore, we strike the optimal balance for this tradeoff by dynamically adjust the number of users in different multicast groups with objective of minimizing the energy consumption while still guaranteeing the QoS.

The reminder of this paper is organized as follows. The system model and assumptions are presented in Section II. In Section III, the MSM scheme is analytically derived following by the problem formulation of optimizing energy efficiency objective while fulfilling the data rate requirement in IV. Simulation results are presented to investigate the effect of using additional multicast on the performance gain in Section V. Section VI finally concludes our work.

II. System Model and Problem Formulation

The considered system is composed of one source node and multiple multicast destination nodes. We assume that K nodes divided into 2 groups, i.e., BSG $\mathcal{M}_b$ containing K_b nodes and MSG $\mathcal{M}_m$ including K_m nodes. K_b and K_m are denoting as group size in the following as well. We also define G_b as the channel gain threshold for using MSM scheme, that is, if one node k has channel gain $G_m \leq G_k < G_b$ who cannot successfully receive and decode the multicast service signals transmitted only through one pure multicast channel, it requires the MSM to support its transmission, where G_m is the worst channel gain in the overall multicast service group. Later we will discuss the optimized solution of G_b in the following sections. Note that channel gain in this work captures the path loss, fading effect and noise.

It is expected that the MSM algorithm is able to decrease the power consumption of transmit node while still fulfilling the QoS requirements, i.e., Signal-to-Noise Ratio (SNR) or data rate, of multicast receivers. For simplicity and properly expressing our method, we use basic multicast power and additional multicast power instead of BMG multicast power and additional multicast power for MSG respectively. Some key notations that are used through this paper are listed in Table I as well.

III. Multicast Supported Multicast (MSM)

A. Description of the MSM Algorithm

The soul of the MSM scheme is to allocate additional multicast channel(s) to the specified group of mobile user(s) that can not receive and decode successfully when a constant transmit power for multicast is employed. Therefore, for the user k with channel gain $G_m < G_k < G_b$, we use MSM as the transmission strategy, otherwise, pure multicast is applied for transmission.

One may notice that the use of additional multicast channel involves combining the signals of additional and basic multicast channels at the receiver. Combining the signals is equivalent to combining the signals of the original transmission and the retransmission in a hybrid automatic repeat request (HARQ) system. The capacity obtained by combining the signals of the original transmission and the retransmission equals the sum of the capacities of the original transmission and the retransmission for an optimal incremental redundancy scheme in the HARQ system. The system can also be interpreted as the additional channel carries the lost data to the users who can not successfully receive from the basic multicast channel. Therefore, for the user with worse channel gain $G_k \geq G_b$, the use of additional multicast channel can help to obtain data successfully.

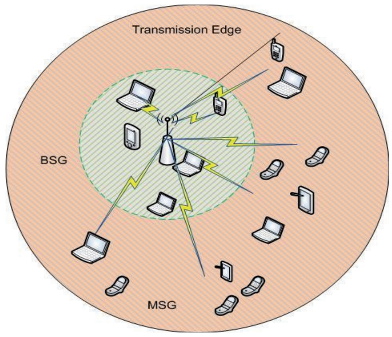


Figure 1. Considered scenario for MSM.

Table I
NOTATIONS

Parameter	Description
K	total number of served nodes
K_m	number of nodes in MSG
K_b	number of nodes in BMG
R_T	QoS data rate
G_m	minimum channel gain for multicast group
G_b	channel gain threshold for MSM
G_k	channel gain of k by using pure basic multicast transmission
γ_k	received SNR of k through basic multicast transmission
γ_m^a	received SNR for k in MSG through additional multicast transmission
P_b	basic multicast power
P_m	additional multicast power

B. Physical Layer Model of MSM

In order to ensure the QoS, the transmission quality of each transmitter-receiver pair should fulfill the data rate requirement of, say, R_T. That is,

$$R_T = Wlog(1 + \gamma_T), \tag{1}$$

where γ_T is the target SNR of using pure multicast transmission from transmitter to all nodes that can be successfully decoded by receiver and W is the allocated frequency bandwidth. Therefore, a user who does not need additional multicast support should have stronger SNR than γ^T. In this work, we assume that the channel gain remains stationary during a time slot and varies slot by slot. To express the idea of MSM, let us consider that there are K_m users in the MSG and the basic multicast power is not sufficient to offer the target SNR γ_T for these users. The multicast data rate from transmitter to MSG adopting basic multicast power can be formulated as

$$\begin{aligned} R_m^b &= \underset{k\in\mathcal{K}_m}{min} \left\{Wlog(1+\gamma_k)\right\} \\ &= \underset{k\in\mathcal{K}_m}{min} \left\{Wlog(1+P_bG_k)\right\} \\ &= \{Wlog(1+P_bG_m), \end{aligned} \tag{2}$$

where γ_k is the received SNR from transmitter to user k in $\mathcal{M}_m$ adopting multicast transmission and we have $\gamma_m \leq \gamma_k < \gamma_T, m \in \{1,2,...,M\}$ apparently. G_k is the channel gain of user k in group $\mathcal{M}_m$ and P_b is the basic transmit power. From (2) we can see that the data rate of MSG depends on the selection of P_b. Meanwhile, we consider the channel gain of additional channel is the same as the one of basic multicast channel for simplicity. Therefore, when the particular node k needs additional multicast support, the required additional data rate is given by

$$R_m^a = R_T - R_m^b = Wlog\Big(\frac{1+\gamma_T}{(1+P_bG_m)}\Big), \tag{3}$$

where we consider the additional multicast uses the same frequency bandwidth as the basic transmission. Thus, when conducting MSM, the effective received SNR γ_m^a that nodes in MSG $\mathcal{M}_m$ need for additional multicast transmission can be expressed as

$$\gamma_m^a = \frac{1+\gamma_T-(1+P_bG_m)}{(1+P_bG_m)}. \tag{4}$$

In this work, we focus on proposing an energy efficient optimization algorithm that can fulfill the data rate requirement of any node k by jointly optimizing over K_b/K_m and basic multicast power/additional multicast power for each $k \in \mathcal{K}_m$ so that the energy efficiency can be achieved.

C. Power Efficiency Optimization of MSM

MSM is proposed in order to achieve better energy saving performance comparing with conventional multicast transmission. Thus, the total power consumption of invoking MSM is given by

$$P_{msm} = P_b + P_m. \tag{5}$$

Thus, for $m \in \{0,1,\ldots,M\}$, the power efficiency optimization problem is expressed as

$$\mathbf{P0}\left\{\begin{array}{ll} min & P_{msm} \\ s.t. & log(1+P_bG_b) \geq R_T/W \\ & log[(1+P_bG_m)(1+P_mG_m)] \geq R_T/W \end{array}\right.$$

where $G_b = min_{k\in\mathcal{K}_b} G_k$.

Remark 1: For the users in $\mathcal{M}_m$, the allocated transmit power consists of P_B and P_m. We may also notice from (4) that P_m is also related to P_B. Thus, to solve the problem $\boldsymbol{P0}$, we aim to find optimal solution $\boldsymbol{\mathcal{X}^*} = \left(P_B^*, G_B^*\right)$ with respect to R^T.

IV. Proposed Solutions

A. Optimal Solution

From the previous description of MSM, one may notice that the algorithm performance depends on the selection of basic multicast power P_b, additional multicast power for MSG P_m, and P_T, which is the consumed power for offering γ_T for the worst channel gain user in a single multicast channel. Obviously, we have

$$\begin{aligned} P_T &= \gamma_T/G_m, \\ P_m &= \gamma_m^a/G_m. \end{aligned} \tag{6}$$

Therefore, we can see that the (5) can be reformed as

$$\begin{aligned} P_{msm} &= P_b + P_m \\ &= \frac{1/G_m + P_T}{1+P_bG_m} - \frac{1}{G_m} + P_b \end{aligned} \tag{7}$$

Remark 2: It is worth noticing that (7) is convex with respect to P_b. Therefore, $\boldsymbol{P0}$ can be viewed as a convex optimization problem. Since the P_m is derived by fulfilling the QoS rate according to the value of P_b. The second condition can be released.

We can then obtain the optimal value for P_b by using Lagrangian method and applying Karush-Kuhn-Turker (KKT) conditions [10]. By denoting λ as the Lagrangian multiplier, the lagrangian is

$$\begin{aligned} &\mathcal{L}(P_b,\lambda) \\ &= P_{msm} - \lambda\Big(log[1+P_bG_b] - R_T\Big) \end{aligned} \tag{8}$$

and the lagrange dual function is

$$g(\lambda) = min\,\mathcal{L}(P_b,\lambda). \tag{9}$$

Consequently we can solve the problem of ($bmP0$) by minimizing the dual function $g(\lambda)$ and theoretical solutions can be reached easily. The optimal value of lagrangian multiplier λ can be obtained by using subgradient algorithm [11]. The optimal solution of P_b^* can be found with optimal value of λ^* accordingly. The optimal solution can be given as follows

$$P_b^* = \phi_1 - \frac{2^{2/3}\phi_2}{\phi_3\phi_4} + \frac{\phi_3}{\phi_4} \tag{10}$$

where

$$
\begin{aligned}
\phi_1 &= -\frac{J_1}{J_2}, \\
\phi_2 &= -J_1^2 + J_1 J_2, \\
\phi_3 &= \left(J_3 + \sqrt{\left(J_3^2 + 4\left(-J_1^2 + J_1 J_2\right)^3\right)}\right)^{1/3}, \\
\phi_4 &= 2^{1/3} J_2,
\end{aligned} \tag{11}
$$

and

$$
\begin{aligned}
J_1 &= 2G_b G_m + G_m^2 - G_b G_m^2 \lambda^*, \\
J_2 &= 2G_b G_m^2, \\
J_3 &= J_1^3 G_b^3 G_m^3 - 3G_m^6 + 3J_2 G_m^4 \lambda^* - J_2^2 G_m^2 (\lambda^*)^2 \\
&+ \frac{J_2^3 (\lambda^*)^3}{9} - 2J_2^2 P_T (G_m + G_b) + J_2 P_T G_m G_b \lambda^*.
\end{aligned} \tag{12}
$$

B. Suboptimal Solution

One may notice that the optimal solution for P_b^* involving finding the proper value of G_b which is the worst channel gain of the BMG. Essentially, determining a G_b that can provide optimal P_b^* is a multicast grouping/clustering problem and the optimal solution in this system can be reached by exhausted searching. However, as we know the exhausted searching requires high computational complexity, and thus, we proposed a alternative suboptimal algorithm here.

Algorithm 1 Suboptimal Solution for MSM

1: Evaluate channel gain (including noise) G_k of each node k.
2: Sort G_k in an descending order.
3: Find the optimal P_b^* which can minimize (7).
4: **for** $k = 1 : K$ **do**
5: Find G_k that satisfies $1 + P_b^* G_k \geq \gamma_T$;
6: **if** $P_b^* G_k < \gamma_T$ **then**
7: $G_b = G_{k-1}$;
8: **end if**
9: **end for**

In the suboptimal, instead of exhausted searching over entire multicast group, we first calculate optimal P_b^* and use it to deliver the required data. By utilizing feedbacks from user, we can easily reach and find the corresponding G_b.

V. Performance Evaluation

The power saving performance of proposed scheme is presented in this section. To study the system performance in a small cell with multimedia services, we simply assume $N_{total} = 200$ and users are uniformly distributed in a cell with 200m radius. Path loss model follows IEEE 802.11ac standard with 5 GHz central frequency f_c. A -95 dBm noise is also assumed. The path loss function is

$$
L(r) = 20log(d_o) + 20log(f_c) - 147.55 + 35log(r/d_o), \tag{13}
$$

Table II
OPTIMAL VS. SUBOPTIMAL POWER CONSUMPTION RATIO (%)

QoS(bps)	1	2	3	4	5
suboptimal	49.15	18.21	6.10	1.98	0.67
optimal	48.05	18.18	6.07	1.95	0.65

where d_o is the break point distance and we use a typical value of $d_o = 15$m. The performance is measured by a power consumption ratio which is given as

$$
\xi = \frac{P_{msm}}{P_T}. \tag{14}
$$

and for illustration purpose, a user ratio is also defined as the number of users in different groups normalized by the total served users. Two user distribution cases are considered, one is that the user deployment follows uniform distribution and the other one is that there are one channel gain difference gap between two groups of users.

A. Uniformly Distributed Users

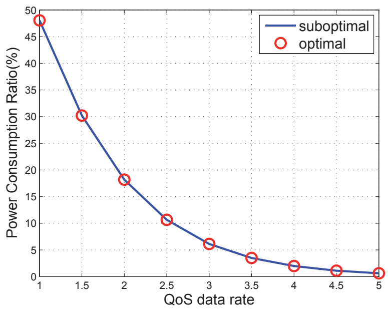


Figure 2. Optimal Power Consumption.

First we show the power saving performance of proposed optimal and suboptimal algorithms. Fig. 2 plots the power consumption for different QoS data rate obtained by two schemes. In general, the suboptimal solution can achieve almost the same performance as the optimal one. From Table II, one can observe that the performance gap is tiny, e.g., maximum gap is 1%, and most of differences are not even visible in the Fig. 2. From Fig. 2 we can conclude that using our proposed scheme, significant power saving can be achieved especially when QoS for multicast users is high. For example, when $R_T = 5$, in order to fulfill the multicast users' requirement, the power consumption P_T is rather high for the considered system. By using proposed scheme, we only need about 1% of P_T.

To further illustrate the advantages of our proposed scheme, we present the user ratios of different groups. By applying the optimization algorithm, we are able to obtain the optimal sizes of BMG and MSG. In Fig. 3, we show the BMG user ratio and MSG user ratio which are obtained by

$$U_{BMG} = \frac{K_b}{K}, U_{MSG} = \frac{K_m}{K}. \quad (15)$$

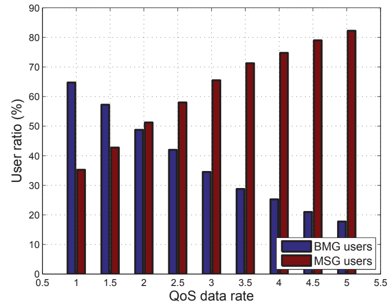


Figure 3. User Ratio of Different Groups.

From Fig. 3, we can see that as the increment of QoS data rate requirement result in the decrement of the number of users inside BMG. In other words, shrink of the BMG help to decrease the power consumption when QoS data rate is high. In the considered system, less number of users inside the BMG means better worst channel gain and smaller P_b of BMG. Due to the logarithmic nature of data rate equation of the second condition in $\boldsymbol{P0}$, when R_T is low, relative bigger P_b can demonstrate and minimize the P_{msm} whereas smaller P_b is preferred when R_T is getting higher. Therefore, a dynamic adaptive algorithm for finding P_b is introduced in this work.

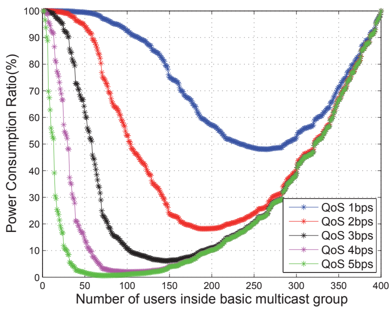


Figure 4. User Ratio vs. Power Consumption Ratio.

In Fig. 4 we clearly see the relations between U_{BMG} and ξ when considering different R_T. The trade-off between U_{BMG} and ξ is clearly existed. In general, we can achieve better power saving performance when QoS rate is high. For example, when there are about 270 users in BMG, ξ reaches its optimal (50%) for $R_T = 1$. However, for e.g. $R_T = 2$, although ξ is not optimal, it is still about 25% lower that the one when $R_T = 1$.

B. Two Group with Channel Quality Difference

In this part, we divide all users to two different groups in equal. The channel gain gap is defined as

$$\Delta G = \frac{min_{k \in \mathcal{K}_\infty} G_k - max_{k \in \mathcal{K}_\in} G_k}{min_{k \in \mathcal{K}_\infty} G_k}. \quad (16)$$

where $\mathcal{K}_\infty$ and $\mathcal{K}_\in$ are two groups and we assume that $\Delta G > 0$. We vary ΔG to see the impact of proposed scheme on the user grouping and power consumption.

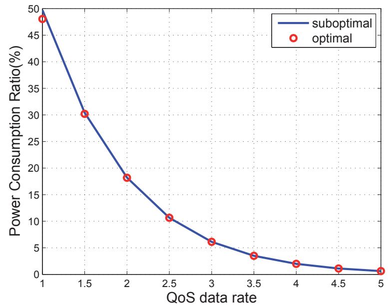


Figure 5. Power Consumption in Case 2.

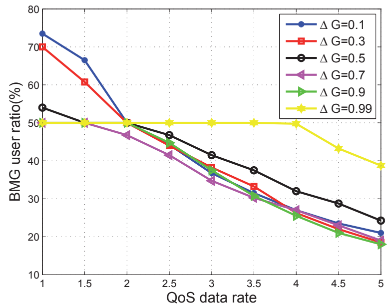


Figure 6. User Ratio of BMG in Case 2.

We may see that the different channel conditions of the users almost have no influence on the power consumption performance in Fig. 5. However, in Fig. 6 the user grouping performance is quite different from the one in Fig. 3. When $\Delta G = 0.99$, which means that the channel qualities of $\mathcal{K}_2$ are much worse than the ones of $\mathcal{K}_1$, one clearly notices that for QoS = $1-4$ bps,$|\mathcal{K}_b| = |\mathcal{K}_1|$. When $\Delta G = 0.1$, similar performance can be observed as shown in Fig. 3 with higher U_{BMG} at low QoS regime. The observations above leads to a conclusion that the proposed algorithm can dynamically optimize the power saving gain as well as the multicast group sizes and overcome the channel variations.

VI. Conclusion

In this work, we considered a novel energy efficient multicast transmission framework. The studied algorithm, namely Multicast Support Multicast (MSM), when optimized from the energy efficiency point-of-view, was able to compensate the inherent drawbacks of multicast transmission and thus, obtain reductions in power consumption while still maintaining the same QoS requirement for the users in the considered scenario. By using our proposed optimization algorithm, the multicast power and sizes of different groups are able to be optimized in order to provide maximum power saving gain. In the simulation study, we demonstrate our proposed scheme with two different user-location distributions. Through numerical results, we observed that the power consumption performance can be significantly improved by utilizing MSM when offering multicast service, especially when high QoS data rate is required.

Acknowledgement

This work was partly supported by the Celtic-plus project Green-T (Project ID CP08-006) and Academy of Finland (Project No. 265516).

References

[1] C. Diot, W. Dabbous, and J. Crowcroft, "Multipoint Communication: A Survey of Protocols, Functions, and Mechanisms," *IEEE Journal on Selected Areas in Communications*, Vol. 15, No. 3, pp. 277-290, April 1997.

[2] S. Y. Baek, *et al*, "Adaptive Transmission Scheme for Mixed Multicast and unicast Traffic in Cellular Systems", *IEEE Transaction on Vehicular Technology*, Vol. 58, No. 6, pp. 2899-2907, July 2009.

[3] S. J. Lee, *et al*, "Efficient Use of Multicast and Unicast Channels for Multicast Services Transmission", *IEEE Transaction on Communications*, Vol. 59, No. 5, pp. 1264-1267, May 2011.

[4] H. Deng, X. Tao, J. Lu, "Qos-Aware Resource Allocation for Mixed Multicast and Unicast Traffic in OFDMA Networks," *EURASIP Journal on Wireless Communications and Networking*, 2012:195, doi:10.1186/1687-1499-2012-195.

[5] D. Kim, Takeo Fujii, K. Lee, "A resource allocation algorithm for OFDM-based cellular system serving unicast and multicast services," *EURASIP Journal on Wireless Communications and Networking*, 2013:41 doi:10.1186/1687-1499-2013-41, Feb. 2013.

[6] R. O. Afolabi, A. Dadlani, K. Kim, "Multicast Scheduling and Resource Allocation Algorithms for OFDMA-Based Systems: A Survey," *IEEE Communications Surveys & Tutorials*, Vol. 15, No. 1, 2013.

[7] H. Won, H. Cai, D. Y. Eun, K. Guo, A. Netravali, I. Rhee, and K. Sabnani, "Multicast Scheduling in Cellular Data Networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4540-4549, Sep. 2009.

[8] J. Liu, W. Chen, Y. Zhang and Z. Cao, "A Utility Maximization Framework for Fair and Efficient Multicasting in Multicarrier Wireless Cellular Networks," *IEEE/ACM Transaction on Networking*, pp.110-120, Vol. 21, No. 1, Feb. 2013

[9] Z. Chang, and T. Ristaniemi, "Power Efficiency Optimization for Unicast Supported Multicast Transmission with QoS Provisioning," *submitted to IEEE TVT*.

[10] S. Boyd, and L. Vandenberghe, *Convex Optimization* , Cambridge UK: Cambridge University Press, 2004.

[11] S. Boyd, and A. Mutapcic, *Subgradient Methods* , Lecture Notes of EE364b, Stanford University, 2006-2007.

PXI

COLLABORATIVE MOBILE CLUSTERS: AN ENERGY-EFFICIENT EMERGING PARADIGM

by

Zheng Chang and Tapani Ristaniemi 2013

book chapter in "Broadband Wireless Access Networks for 4G: Theory, Application, and Experimentation" **(Invited)**

Collaborative Mobile Clusters: An Energy-Efficient Emerging Paradigm

Zheng Chang and Tapani Ristaniemi

Department of Mathematical Information Technology, University of Jyväskylä, FIN-40014 Jyväskylä, Finland

zheng.chang@jyu.fi, tapani.ristaniemi@jyu.fi

Abstract

Future wireless communication systems are expected to offer several gigabits data rate. It can be anticipated that the advanced communication techniques can enhance the capability of mobile terminals to support high data traffic. However, aggressive technique induces high energy consumption for the circuits of terminals, which drain the batteries fast and consequently limit user experience in the future wireless networks. In order to solve such a problem, a scheme called collaborative mobile cluster is foreseen as one of the potential solutions to reduce energy consumption per node in a network by exploiting collaboration within a cluster of nearby mobile terminals. This chapter provides a detailed analysis of the energy consumption of a terminal joining the cluster and also analyzes the conditions for energy savings opportunities.

Index: power consumption, energy consumption, energy efficient, mobile cloud, mobile cluster, cooperative communications, content sharing.

1. Introduction

By utilizing new technologies for cellular environments, such as Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink, Single-carrier Frequency-Division Multiple Access (SC-FDMA) in the uplink and multiple input multiple output (MIMO) schemes, the next generation wireless network is going towards offering high data rate multimedia services to the user. As the fast growth of wireless market, multicast/broadcast services, such as IPTV will become more popular. Meanwhile, the dramatic evolution of smart phones makes changes to how we use these mobile devices. For instance, the demand for sharing content among users, watching TV and other internet activities are surprisingly arisen. In this chapter, an emerging energy efficient paradigm, namely collaborative mobile cluster (CMC) is introduced to deal with such mobile evolution. The CMC model is foreseen as a potential platform to provide broadcast services and boost up sharing capabilities for mobile users with reduced energy consumption. In this section, next generation networks as well as some other background information are briefly overviewed.

1.1 Background

The wireless communications industry has witnessed tremendous growth in the past decade with over four billion wireless subscribers worldwide. The first generation analog cellular systems supported voice communication with limited roaming capability. Later on, the second generation digital systems brought higher data rate and better voice quality than did their analog counterparts. The current third generation (3G) cellular network is offering high-speed data transmissions, such as VoIP, etc, to the mobile subscribers. In order to ensure the competitiveness of Universal Mobile Telecommunications System (UMTS) for the coming 10 years and beyond, concepts for UMTS Long Term Evolution (LTE) have been investigated. The focus of LTE is to provide a high-data-rate, low-latency and packet-optimized radio access technology supporting flexible bandwidth deployments (3GPP TR 25.913).In parallel, a new network architecture is designed with the goal to support packet-switched traffic with seamless mobility, quality of service and minimal latency (3GPP TR 23.882, 2009).

In the physical layer (PHY) of LTE, according to the initial requirements defined by the 3rd Generation Partnership Project (3GPP), the network should support peak data rates of more than 100 Mb/s over the downlink and 50 Mb/s over the uplink. A flexible transmission bandwidth ranging from 1.25 to 20 MHz will provide support for users with different capabilities. These requirements will be fulfilled by employing new technologies for cellular environments, such as OFDMA in the downlink, SC-FDMA in the uplink and multi antenna (or MIMO) schemes. Additionally, channel variations in the time/frequency domain are exploited through link adaptation and frequency-domain scheduling, giving a substantial increase in spectral efficiency. In order to support transmission in paired and unpaired spectrum, frequency division duplex (FDD) as well as time division duplex (TDD) modes are supported by the LTE air interface.

In the past, cellular systems (e.g. 1G) have mostly focused on transmission of data intended for a single user and not on broadcast services. Broadcast networks, exemplified by the radio and TV broadcasting networks, have on the other hand focused on covering large areas and have offered no or limited possibilities for transmission of data intended for a single user. In the next generation (e.g. 4G) networks, the support of broadcast or multicast service can be expected as an essential part and it is important for offering multimedia services to different users. For example, support of MBMS (Multimedia Broadcast Multicast Services) is a requirement for LTE and will be an integral part of LTE (3GPP TR 36.440 ,2010).

1.2 Motivation

As expected, above mentioned future communication systems are going toward offering even gigabits data rate. In order to support such high data traffic, aggressive wireless technique will be utilized to the user equipments (UEs), which consequently induce high energy consumption (Chu, Chen & Fettweis, 2012). It is essential that these UEs can fully exploit the throughput gains offered by future communication systems whenever possible. Meanwhile, with the dramatic evaluations of smart phones, the way how people use cell phone is changing. Instead of simply making calls and sending short text messages, multimedia services are demonstrating the usage of cell phone. Moreover, due to the fact that the social medium and networks are becoming popular, the demand for sharing content among users is arisen as well.

On the other hand, the evaluation of wireless networks brings us facing many inherent problems. Telecommunications data volume increases approximately by an order of 10 every 5 years, which results in an increase of the associated energy consumption by approximately 16–20 percent per annum (3GPP TR 25.913, 2009). The escalation of energy consumption in wireless networks directly results in increased greenhouse gas emission, which has been recognized as a major threat to environmental protection and sustainable development. From the users' point of view, the high energy consumption restricts this due to the capacity limitation of battery and the user experience of high speed transmission would be seriously impacted. Therefore, reducing energy consumption emerges as a critical issue to prolong the battery life in the future wireless networks.

Motivated the aforementioned challenges, we introduce the CMC model, where a cluster of resource-constrained nodes that can perform receiving and decoding cooperatively and in a distributive manner. By utilizing such user-cooperation capability, the CMC is foreseen as energy efficient solutions for offering different services for users, such as broadcast services, content sharing, etc.

1.3 Related works

For energy saving purpose, some research works have been done by improving transmitting and receiving mechanisms for a single receiver (Gür & Alagöz, 2011; Bontu & Illidge, 2009). Gür & & Alagöz (2011) introduced a resource allocation scheme which can dynamically allocate time and frequency to reduce the receiving energy consumption per single receiver. In (Bontu & Illidge, 2009), an overview of discontinuous reception (DRX) which is used in LTE to reduce receiver power consumption was presented. Meanwhile Datla, et al (2009) and Datla, et al (2012) dedicated the work on the power saving schemes for wireless distributed computing networks. However, these contributions focus more on power saving performance of computing rather than the one of communication. In (Radwan & Rodriguez, 2012), short range cooperation among MTs was proposed as a key idea to reduce the transmit energy consumption for the transmission from MTs to AP. Energy saving gains obtained by using different combination of technologies for short range communication, such as WLAN and WiMAX, WLAN and WLAN were also derived in (Radwan & Rodriguez,2012). In order to improve the throughput, Alonso-Zarate, et al (2013) introduced Multi-Radio ARQ schemes for hybrid networks combining long-range and short-range communications. However, these studies consider transmit energy consumption only.

1.4 Notations

Some key notations are summarized in Table I.

2. Defining CMC: Concepts, Model and Applications

2.1 CMC Concepts

As stated in the last section, the related works mainly consider the transmit energy consumption in different kinds of wireless networks. In this chapter, we consider both transmit and receive energy consumptions. Scenario under consideration includes cooperation among UEs, which has previously been studied for enhancing single transmissions. This scenario also known as Mobile Cloud is modelled as a cluster of resource-constrained nodes that can perform receiving and decoding cooperatively and in a distributive manner (Hoyhtya, Palola, Matinmikko & Katz, 2011). One CMC contains several UEs that can cooperatively receive the information data from Base Station (BS), and then exchange the received data with others. By exploiting the benefits of CMC, we are able to obtain the receiver energy consumption reduction (Chang & Ristaniemi, 2013). Such model can potentially offer several advantages over traditional AP-to-UE (or Point-to-Point, P2P) networks, including reduction of energy and resource consumption per node. The links within the CMC is assumed to be device-to-device (D2D) links, where the MTs can share their received data and available resource. In this paper we provide detailed analysis of the energy consumption of a MT within the CMC and compare it with non-cooperative schemes

2.2CMC Model

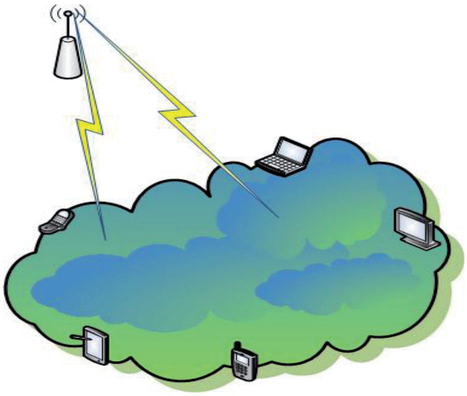


Fig.1 CMC model

Table I. NOTATIONS

Notations	Description
$E_{UE}^{tx/rx}$	UE total energy consumption for performing TX/RX in a CMC
$E_{BB}^{tx/rx}$	UE BB energy consumption for performing TX/RX in a CMC
$E_{RF}^{tx/rx}$	UE RF energy consumption for performing TX/RX in a CMC
P_E	UE BB power consumption for performing TX/RX in a CMC
$P_{tx/rx}$	UE RF power consumption for performing TX/RX in a CMC
$P_{tx,dist}$	UE RF power consumption for performing TX in a CMC by using unicast
$I_{tx/rx}$	Allocated number of RBUs per UE for performing TX/RX in a CMC
$T_{tx/rx}$	Time consumed performing TX/RX in a CMC
$\mathrm{E}_{\mathrm{UE}}^{\mathrm{BS}}$	UE total energy consumption for performing RX from BS
$\mathrm{E}_{\mathrm{UE}}^{\mathrm{unicsat}}$	UE total energy consumption for performing TX/RX in a CMC by using unicast
$\mathrm{E}_{\mathrm{UE}}^{\mathrm{unicsat}}$	UE total energy consumption for performing TX/RX in a CMC by using multicast
E_{part}	UE energy consumption for performing RX from BS in a CMC

We consider there are one Base Station (BS) and *Z* UEs in the system, where *K* UEs can form a CMC. All

UEs inside CMC require the same data from BS (e.g., through a video or television channel). Each UE can be dual-mode device, equipped with a short-range (e.g.,WLAN) wireless communication technique for information exchange between devices and equipped with broadband access technique(e.g. LTE/LTE-A) for receiving from BS. The scenario is depicted in Fig. 1, where K=5.

The transmission among different UEs inside a CMC can be modeled as unicast or multicast transmission. It is known that multicast transmission is an efficient method for group data transmission (Baek, Hong & Sung 2009). Through broadcast in radio channels, a multicast transmission increases transmission efficiency due to reduction of transmitted redundant data. However, wireless multicast should be adapted according to the worst channel state user in a multicast group. Hence, the system capacity of multicast transmission is affected both by the number of users and the supportable data rate of MT with worst instantaneous channel condition. On the other hand, unicast transmission utilizes wireless channel variations and obtains the multiuser diversity gain (Lee, Tcha, Seo & Lee, 2011). Meanwhile, the unicast transmission can utilize the channel variation on the expense of introducing transmission overhead for same data. Therefore, unicast transmission is costly from the radio resources point of view.

In the transmission, we invoke the Resource Block Unit (RBU) as the elementary resource unit in our work. A RBU is defined as a certain frequency bandwidth W (e.g. 12 subcarriers in LTE) in one time slot. One example of RBU concept can be found in Fig.2, in which the colored blocks represent the RBUs. By using this concept, we can express the unicast and multicast transmission inside a CMC as shown in Fig.3. In Fig.3, we assume there are 4 UEs forming a CMC and all of them require same information data from BS. Therefore, each of them can receive 1/4 part of the data and then share it with others. If unicast is considered as the transmission strategy, more time and frequency resource will be consumed comparing with using multicast inside CMC in this case. In general, we can observe that the receive time duration is reduced, which leads to potential energy saving gain for the UEs. We will discuss the energy efficiency related issue in next section.

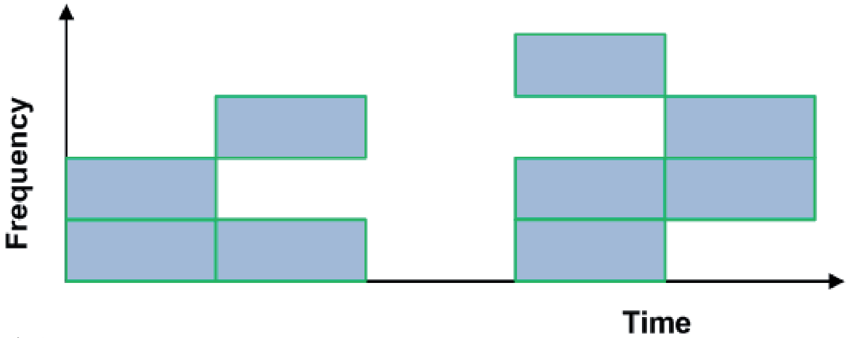


Fig.2 RBU concept

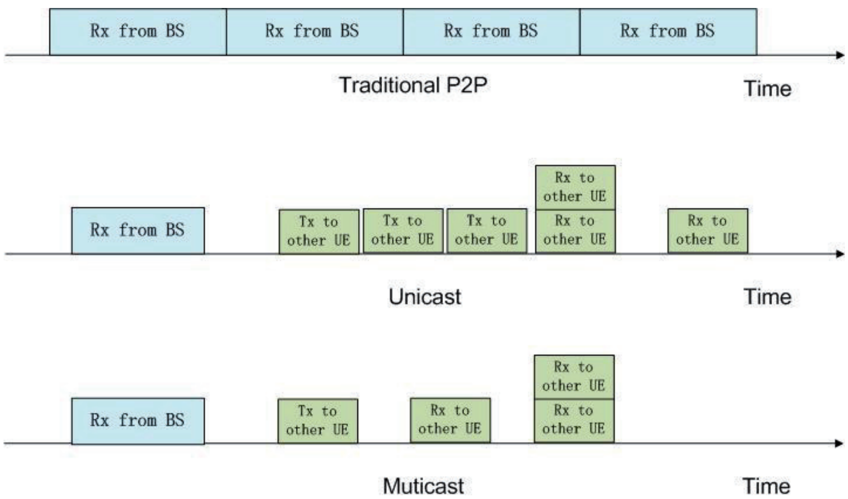


Fig. 3 Receive process and transmission inside CMC

2.3 CMC Applications in 4G

As we stated previously, CMC model has a great potential to achieve energy saving for the next generation wireless networks. In addition to obtain energy saving performance from technique side, CMC is also foreseeable to have advantages on performing social interactions among numbers of users and improve the local services. It can be a competitive candidate for content or resource sharing purpose as well (Pederson & Fitzek, 2012). Some of examples are broadband mobile system offering multimedia services, of which a typical application is for Multimedia Broadcast Multicast Service (MBMS) subscribers. Current networks, for example, have difficulties to support such kind of broadcast services for mass events, e.g. rock concerts or sport matches, especially when the receivers are spatially correlated. Furthermore, the social interaction over such content cannot be globalized, but is limited to people which are spatially or socially close to each other. Therefore, the trend tends to share the content in a more cooperative way in inter UE (or D2D) mode. Using CMC, the users closing to each other are able to watch same sport match in an energy efficient way. Also from network operator point of view, as the contents that have already been sent to UEs are not necessarily stored in the networks, resource of BS will be released. Therefore, both BS and UEs can exploit the benefits of using CMC in next generation wireless networks.

3. Energy Efficiency of CMC

The energy efficiency of CMC is examined in this section. As depicted in Fig. 3, for the energy consumption model, we consider both transmit (TX) and receive (RX) energy consumption. The overall TX/RX energy consumption can be categorized into baseband (BB) and RF energy consumption. The detailed models will be described in the following.

3.1 Power Consumption Model

We here model the energy consumption of the UE as the sum of BB power consumption and RF power consumption. In other words, the energy consumption of UE can be expressed as

$E_{UE} = E_{BB} + E_{RF}$,   (1)

where E_{BB} is the BB energy consumption and E_{RF} is the RF energy consumption. Therefore, when an UE is in the TX mode, the energy consumption is

$E_{UE}^{tx} = E_{BB}^{tx} + E_{RF}^{tx} = (P_E + P_{tx})\, T_{tx} I_{tx}$,   (2)

and for the UE in the RX mode, we have similar definition

$E_{UE}^{rx} = E_{BB}^{rx} + E_{RF}^{rx} = (P_E + P_{rx})\, T_{rx} I_{rx}$,   (3)

where P_E is the power consumption for BB in a RBU and P_{tx}/P_{rx} is the TX/RX power consumption. $\frac{T_{tx}}{T_{rx}}$ is the time duration that an UE perform TX/RX transmission inside CMC and I_{tx}/I_{rx} is the number of RBUs that are used for TX/RX.

3.1.1BB Power Consumption Model

The power dissipation for baseband signal processing can be modeled as (Schurgers, Aberthorne & Srivastava, 2011):

$P_E = \left(C_E + C_R \frac{R_{s,max}}{R_s}\right) R_s$,   (4)

where R_s is the symbol rate of the transmission, $R_{s,max}$ is the maximum symbol rate of the transmitter,C_E and C_R are related to system voltage level. The discussion of the BB power consumption may be out of scope of this chapter and more detailed explanations of baseband parameters are introduced in (Schurgers, et al, 2011).

3.1.2RF Power Consumption Model

For inter-UE communication inside DMC, the transmit power dissipation of RF front-end for one single RBU can be expressed as (Datla, et al, 2009; Datla, et al, 2012),

$P_{tx} = \beta_1 \gamma_{min} W L + \beta_2$,(5)

Where β_1 and $\beta_2$depend on the transceiver components and channel characteristics. In particular, $\beta_1$is related to transmitting actions on/after power amplifier (PA), such as antenna and channel gains. β_2 depends on transceiver RF circuit components, e.g., local oscillator and Digital-Analog Converter (DAC)/Analog-Digital Converter (ADC) for processing data on one subcarrier. L is the path loss and $W$is the frequency bandwidth of one RBU. γ_{min} is the minimum required Signal to- Noise Ratio (SNR) at the receiver, which is related to Bit- Error-Ratio (BER) requirement. Without loss of generality we can take QAM modulation as an example, which would result in (Chang & Ristaniemi, 2012)

$\gamma_{min} = \frac{2}{3}\left(2^b - 1\right) ln \frac{4(1-2^b)}{BER_{req}}$,   (6)

where $BER_{req}$is the BER requirement at receiver and b is the modulation order. Also, β_1 and β_2 can be expressed as (Chang & Ristaniemi, 2012)

$\beta_1 = \frac{\eta k_B T_o NF(\sigma_s)^{-Q^{-1}(1-P_{out})}(4\pi)^2}{G_t G_r \lambda^2 d_o^{-2}} LM$,   (7)

$\beta_2 = P_{DAC} + P_{RF} + \vartheta$,   (8) where $Q^{-1}$is inverse Q function. The explanation and possible values of parameters are shown in Table II (Datla, et al, 2009; Haloka, Chen, Lehtomaki, &Koskela, 2010).

3.1.3Total Energy Consumption Model

For simplicity, we assume that each node within DMC is assigned the same resource for transmission. Thus, for each UE inside CMC, we have equal I_{tx} and T_{tx} . In addition, it is easy to observe that $I_{tx} = I_{rx} = I_{UE}$ and $T_{tx} = T_{rx} = T_{UE}$ since all UEs have same amount of data.

Using unicast scheme, the overall energy consumption an UE with considering receiving certain amount of data from BS can be expressed as

$$E_{UE}^{unicast} = E_{UE}^{tx} + E_{UE}^{rx} + E_{part} = (K-1)(2P_E + P_{tx} + P_{rx})\, T_{UE} I_{UE} + E_{UE}^{BS}/K, \quad (9)$$

Similarly, using multicast scheme for transmission inside CMC, we have

$$E_{UE}^{multicast} = E_{UE}^{tx} + E_{UE}^{rx} + E_{part} = (KP_E + P_{tx,dist} + (K-1)P_{rx})\, T_{UE} I_{UE} + E_{UE}^{BS}/K, \quad (10)$$

where we assume there are K UEs inside a CMC and are assigned same amount of data. Due to the features of multicast transmission, $P_{tx,dist}$ is defined as the UE with worst channel gain. E_{UE}^{BS} is the UE energy consumption when performing receiving from BS without using CMC concept. E_{UE}^{BS} can be expressed as follows,

$$E_{UE}^{BS} = M P_{UE}^{BS} T_{UE}^{BS}, \quad (11)$$

where M is the number of RBUs. T_{UE}^{BS} is the time slot duration and We assume that P_{UE}^{BS} is the circuit power of UE that is used for receiving certain amount of data in one RBU from BS.

3.2 Energy Efficiency of Different Transmission Strategies

Based on the above analysis, we can define the energy saving gain of using unicast in CMC as

$$\xi_{unicast} = E_{UE}^{BS} - E_{UE}^{unicsat} = \frac{K-1}{K} M T_{UE}^{BS} (P_{UE}^{BS} - \frac{P_{tx}+P_{rx}}{\rho} + \frac{\rho-2}{\rho} P_E), \quad (12)$$

where we have $I_{UE} T_{UE} = MT_{UE}^{BS}/K\rho$, $\forall \rho > 0$. Since the amount of data carried by subcarrier increases, the air time and frequency bandwidth could be reduced. Here ρ depends on the amount of data that the subcarrier can carry, which in general, is decided by modulation and coding schemes. For example, if BPSK is invoked as modulation scheme from BS to UE and QPSK is used for inter UE communication inside DMC, we have $\rho = 2$. Similarly, we have the energy saving gain when using multicast transmission as (Chang & Ristaniemi, 2013)

$$\xi_{multicast} = E_{UE}^{BS} - E_{UE}^{multicast} = \frac{M}{K} T_{UE}^{BS} (P_{UE}^{BS} + \frac{(K-1)P_{rx}+P_{tx}}{\rho} + \frac{K}{\rho} P_E). \quad (13)$$

Table II. TX/RX POWER CONSUMPTION RELATED PARAMETERS

Parameters	Description	Value
η	Power amplifier Parameter	0.2
ϑ	Power amplifier Parameter	174 mW
k_B	Boltzmann Constant	1.3806×10^{-23} J/K
T_o	Temperature	300 K
NF	Noise Figure	9 dB
σ_s	Shadow fading standard deviation	12 dB
G_t	Tx antenna gain	2 dBi
G_r	Rx antenna gain	2 dBi
λ	Signal wavelength	0.15 (2 GHz)
LM	Link margin	15 dB
W	Bandwidth of RBU	0.2 MHz
d_o	Near field distance	15m
P_{out}	Channel outage probability	1%
P_{DAC}	Power of DAC	15.4 mW
P_{RF}	Power of other RF device	131.5 MW

Therefore, the energy efficiency performance can be denoted as

$EE = \frac{\xi}{E_{UE}^{BS}} \times 100\%$. (14)

4.Simulation Results

We present some simulation results here to illustrate the notable energy saving gain by using CMC model. EE in (13) is used as the performance metric. For baseband energy consumption, we have $R_{s,max} = 1\text{MHz}$ and $R_s = 250$ MHz. We also use the same $C_E = 8 \times 10^{-8} V^2$ and $C_R = 7 \times 10^{-7} V^2$ as in (Schurgers, et al, 2011), and $BER_{req} = 10^{-5}$. We examine the impact of size of the CMC in terms of number and distances of UEs within the cluster. Also, the effect of modulation order ρ to the EE performance is studied. The D2D channel is defined according to IEEE 802.11ac (2012), where inter-UE (or D2D) distance is assumed to be around 20m unless individually mentioned.

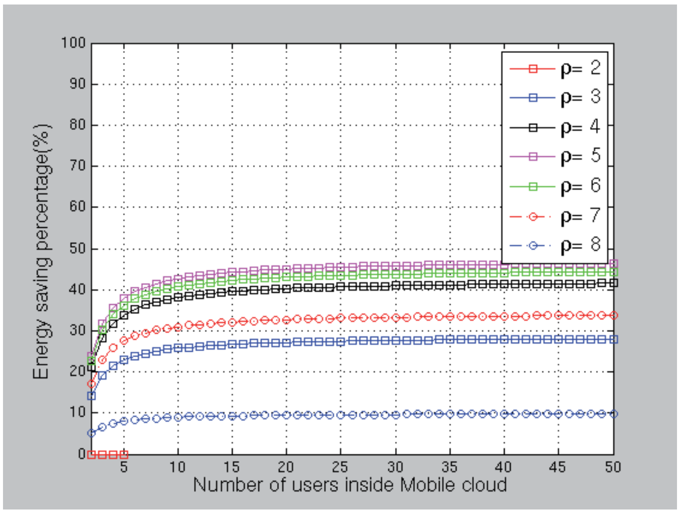


Fig. 4 Number of UEs vs. energy efficiency gain with fixed inter UE distance of 25m.

From Fig. 4, we can see that as the number of UEs increases, the energy saving gain obtained by using CMC arises as well. The energy saving percentage (or EE) reaches the 'almost' saturation level when there are 20 MTs forming a CMC. It means that without any radio resource (e.g. RBUs) constraints, forming DMC can help nearby MTs to save energy if proper modulation and coding schemes (MCS) are used. In Fig. 5, we notice that when $\rho = 5$, we reach the maximal energy saving gain for all cases in this setting. Due to shorter transmit times, the increase of the energy saving as a function of modulation order can be expected. However, there's also a need for higher transmit powers with higher modulation order so a trade-off clearly exists. As we see from the figure, when $\rho > 5$, the growth of transmit power appears to dominate the increase ofE_{UE}, and thus, energy saving percentage begins to decrease from its maximum.

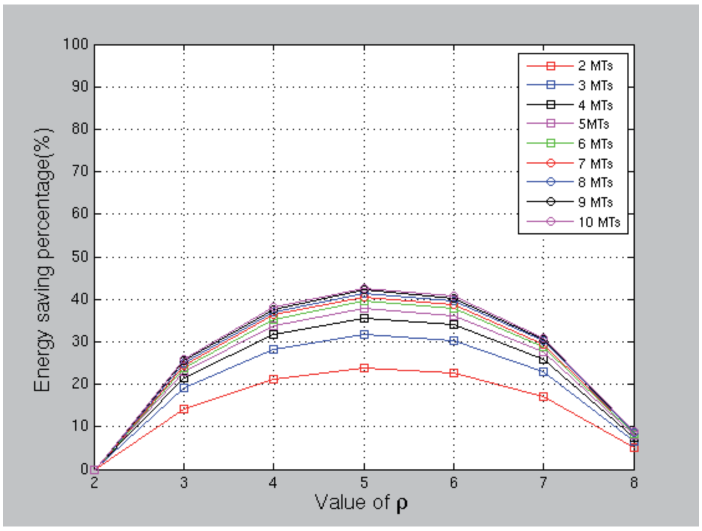


Fig. 5 ρ vs. energy efficiency gain with a fixed D2D distance of 25m.

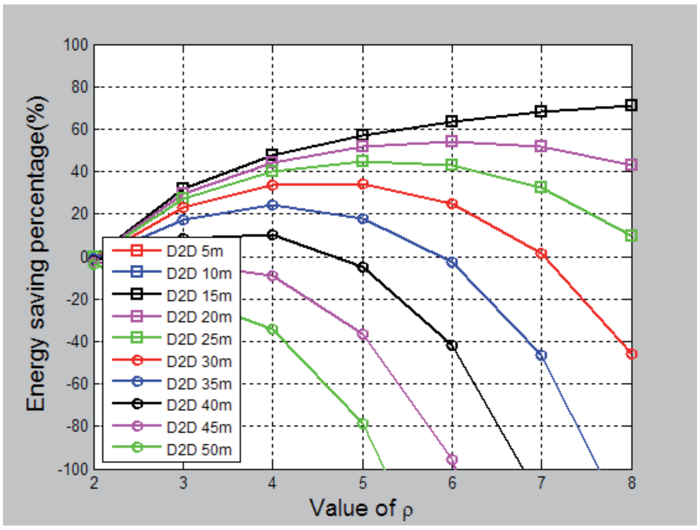


Fig.6 ρ vs. energy efficiency gain with a fixed number of UEs

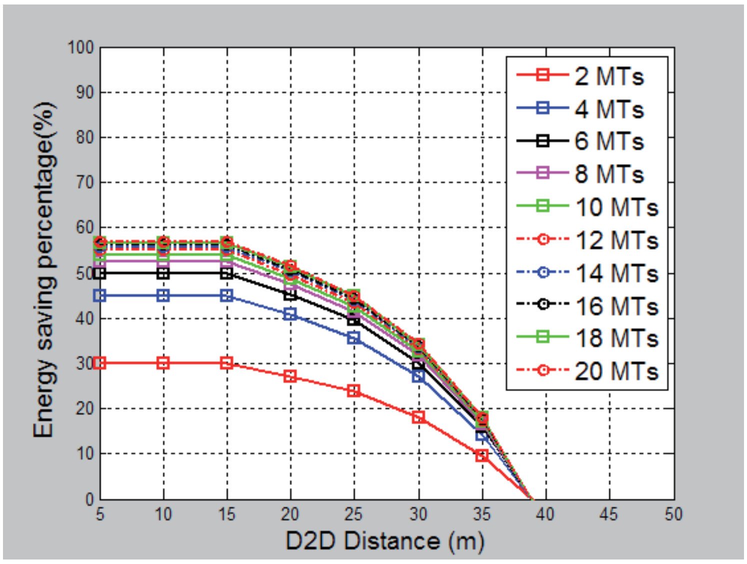


Fig. 7 D2D distance vs. energy efficiency gain with $\rho = 5$

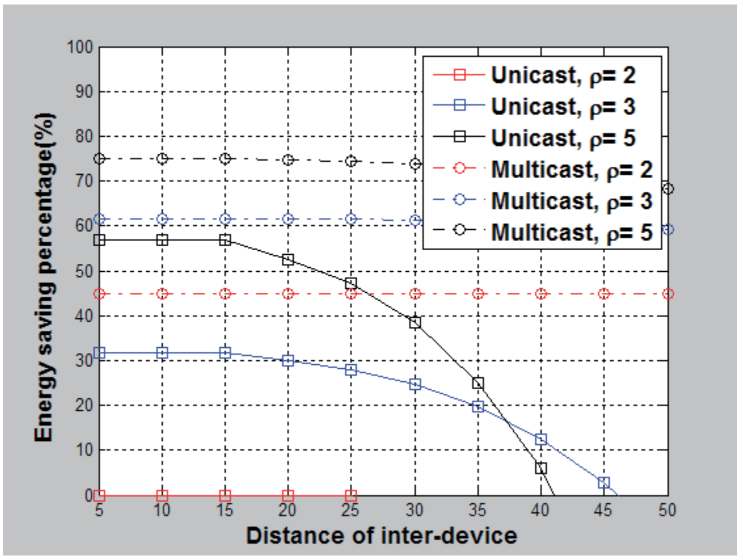


Fig. 8 D2D distance vs. energy efficiency, both multicast and unicast

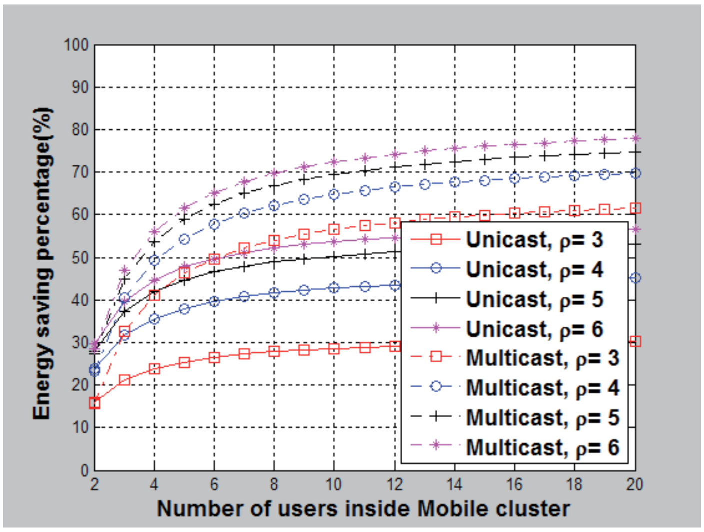


Fig.9 Number of UEs vs. energy efficiency, both multicast and unicast

If we fix the number of UEs inside CMC to be 20, we could obtain the impact of value of ρ in Fig.6. From Fig. 6, we can see that the energy efficiency can reach up to of 70% when D2D distance is shorter than break point distance d_o. In general, for same value of ρ, shorter D2D distance can obtain higher energy saving percentage. If we fix the value of ρ to be 5, we could obtain the impact of inter-UE distance in Fig. 7. When ρ = 5, we notice that the D2D distance should not be longer that 38m. The same situation as in Fig. 4 can be observed in Fig. 7, in other words, larger size of CMC results in higher energy saving gain. For instance, in Fig. 8, we see that a CMC with 4 UEs can obtain up to of 1.5 times energy saving gain that a CMC with 2 UEs. However, the difference is not so obvious when there are more UEs forming a CMC, e.g., a CMC with 20 UEs can only achieve a slight better (up to of around 4%) energy saving performance than that of a CMC formed by 10 UEs. From Figs. 8 and 9, we can see the comparison between multicast and unicast schemes. In general, we can observe that multicast has superior performance that unicast transmission in the considered scenario due to the fact that multicast transmission requires less transmitting times than unicast.

5. Conclusion and Future Directions

Targeting to decrease the total energy consumption of single UE, we studied a distributed mobile cloud model, which is formed by a number of collaborating UEs. The benefits achieved from CMC may be negated by the communication overhead inside it. Therefore, we presented a theoretical analysis on the energy consumption of UEs within the CMC. Moreover, we presented theoretical analysis on the energy consumption of UEs when multicast or unicast is used as well. Based on the analysis, we discussed the benefits of using multicast and unicast as transmission strategies for CMC. Through simulation studies, we first observed that CMC shows great potential for obtaining energy saving for UEs. We also discussed the great potential of CMC on the way to offer better broadcast services for future wireless networks.

CMC maps perfectly with the social need to share with people who are close to each other. The problem is, however, that the current mobile platforms are not, or even worse not anymore, ready for this. Besides some technique issues, such as ad hoc wireless access should be featured in the cellphone. Willingness of people for selfless sharing is hard to be motivated. Going towards solving the related obstacles in both technique and social domains will be the prior objectives for future work.

Reference

3GPP TR 25.913 (2009). Requirements for Evolved Universal Terrestrial RadioAccess (UTRA) and Universal Terrestrial Radio Access Network (UTRAN).

3GPP TR 23.882 (2009), 3GPP System Architecture Evolution: Report on Technical Options and Conclusions.

3GPP TR 36.440 (2010), Technical Specification Group Radio Access Network, EvolvedUniversal Terrestrial Radio Access Network (E-UTRAN); General aspects and principles for interfaces supporting Multimedia Broadcast Multicast Service (MBMS) within E-UTRAN, Release 9,.

Chu, F.-S., Chen, K.-C., & Fettweis, G. (2012). Green Resource Allocation toMinimize Receiving Energy in OFDMA Cellular Systems, *IEEE Communications Letters*, 16(3), 372-375.

Gür, G. & Alagöz, F. (2011). Green Wireless Communications via Cognitive Dimension: An Overview, "*IEEE Network*, 25(2), 50-56.

Bontu, C. & Illidge, E. (2009).DRX mechanism for power saving in LTE. *IEEE Communication Magazine*, 47(6), 48-55.

Datla, D., Chen, X., Newman, T. R., Reed, J. H. & Bose, T. (2009). Power Efficiency in Wireless Network Distributed Computing. *Proc. of 69th IEEE Vehicular Technology Conference*. Barcelona, Spain, April.

Datla, D., Volos, H. I. , Newman, T. R., Reed, J. H. & Bose, T. (2012). Wireless Distributed Computing in cognitive radio networks," *Ad Hoc Networks*, 10(5), 845-857.

Radwan A. & Rodriguez, J. (2012). Energy Saving in Multi-standard Mobile
Terminals through Short-range Cooperation. *EURASIP Journal on Wireless Communications and Networking*, 2012:159.

Alonso-Zarate, J. , Kartsakli, E., Katz, M., Alonso, L. & Verikoukis, C. (2013). Multi-Radio Cooperative ARQ in Wireless Cellular Networks: A MAC Layer Perspective. *Telecommunication Systems*, 52(3), 375-385.

Hoyhtya, M., Palola, M., Matinmikko, M. & Katz, M. (2011). Cognitive engine: design aspects for mobile clouds. Proceedings of CogART 2011.

Chang, Z. & Ristaniemi, T. (2013). Energy Efficiency of Collaborative OFDMA Mobile Clusters. *Proceedings of IEEE CCNC'13*.

Baek, S. Y., Hong Y.-J. & Sung, D. K. (2009). Adaptive Transmission Scheme for Mixed Multicast and unicast Traffic in Cellular Systems. *IEEE Transactions on Vehicular Technolog* , 58(6), 2899-2907.

Lee, S. J., Tcha Y., Seo, S.-Y. , Lee, S.-C. (2011). Efficient Use of Multicast and Unicast Channels for Multicast Services Transmission. *IEEE Transactions on Communications*, 59(5), 1264-1267.

Pederson, M. V. & Fitzek, F. H. P. (2012). Mobile Clouds: The New Content Sharing Platform", *Proceeding of IEEE*, 100, 1400-1403.

Schurgers, C., Aberthorne, O. & Srivastava, M. (2011). Modulation scaling for Energy Aware Communication Systems. *Proceedings of International Symposium on Low Power Electronics and Design*. Fukuoka, Japan, August.

Chang, Z. & Ristaniemi, T. (2012). Reducing Power Consumption via Collaborative OFDMA Mobile Clusters. *Proceedings of IEEE Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks(CAMAD'12)*. Barcelona, Spain, September.

Haloka, S., Chen, T., Lehtomaki, J. &Koskela, T. (2010). Device-to- Device(D2D) Communication in Cellular Network- Performance Analysis of Optimal and Practical Communication Mode Selection. *Proc. of 2010 IEEE Wireless Communications and Networking Conference*. Sydney, Australia, April.

Chang, Z. & Ristaniemi, T. (2013). Efficient Use of Multicast and Unicast in Collaborative OFDMA Mobile Clusters. *Proc. of 77th IEEE Vehicular Technology Conference.* Dresden, Germany, June.

IEEE 802.11ac specifications (2012)

PXII

ASYMMETRIC RELAY SELECTION AND RESOURCE ALLOCATION FOR OFDMA MULTI-RELAY NETWORKS WITH IMPERFECT CSI

by

Zheng Chang, Tapani Ristaniemi and Zhisheng Niu 2013

Department Report, Department of Mathematical Information Technology,
University of Jyväskylä, accepted by China Communication

Asymmetric Relay Selection and Resource Allocation for OFDMA Multi-Relay Networks with Imperfect CSI

Abstract

In this paper, the joint relay selection and resource allocation problem in cooperative relay-assisted OFDMA networks have been addressed. Recent works on the subject usually ignore either the selection of relays, asymmetry of the source-to-relay and relay-to-destination links or the imperfections of channel state information. In this article we take into account all these together and our focus is two-fold. Firstly, we consider optimization of the set of collaborative relays and link asymmetries together with subcarrier and power allocation. Using a dual approach, we solve each sub-problem in an asymptotically optimal and alternating manner. In addition, we pay attention to the effects of imperfect channel state information needed in resource allocation decisions. Theoretical expressions for solutions are derived and illustrated through simulations. The results validate clearly the additional performance gains through an asymmetric cooperative scheme compared to the other recently proposed resource allocation schemes.

1 Introduction

The demand for high-speed data transmission is significantly increased due to the fast-grow wireless multimedia services market in the last decade. Orthogonal Frequency Division Multiple Access (OFDMA) is known as an effective technique exploiting the benefits of OFDM for combating against channel fading and multipath effects and providing high speed data rate. Meanwhile, relay-assisted communication has became a promising technology to obtain better system performance in terms of spectrum and energy efficiency or cell coverage. Therefore, OFDMA wireless network with cooperative relays is foreseen as a promising structure that can offer a possibility to reach many desirable objectives in the context of future wireless networks development.

Nevertheless, due to the fact that there are many different radio resources available in the OFDMA relay networks, such as relays, subcarriers and transmit power, a cautious design of the radio resource allocation (RRA) principles is required when combining a conventional single hop OFDMA system with a relay network in order to fully realize aforementioned benefits. This calls for a careful design and coordination of the power and subcarrier allocation, selection of relay(s) across different hops and optimizing the resource asymmetries between the hops.

Related works on the subject (see. e.g. [1]-[7]) mostly assume perfect channel state information (CSI) to be available at the base station. Subcarrier assignments together with relay selection were solved by proposed iterative algorithm in [1]. Then, based on the waterfilling scheme, the power allocation problem was solved by another iterative method. The fairness constraints are considered in the proposed scheme of [4] when selecting relays. A threshold-based RRA method was used to solve problems of subcarrier and power allocations in [5]. Although comparing to some other algorithms the performance was improved, the total power limitation for all nodes was applied, which is a not practical case since each relay should have its own power constraint. Authors in [6] also proposed a relay and subcarrier pairing algorithm to address RRA problem, but it is computationally quite complex. Moreover, all the previous works assumed the transmission durations for base station and relay link to be equal, which may result in a reduction of degree of freedom and system throughput [7]. In [7], a study on the asymmetric resource allocation was presented. However, this work considered only single relay in the OFDMA networks without exploring cooperative diversity. [8]-[9] presented the work about RRA with imperfect CSI, where authors of [8] presented the RRA algorithm for conventional OFDMA networks when imperfect CSI is available. The recent work about RRA for OFDMA cooperative networks with imperfect CSI was introduced in [9], where the objective is to decide which single relay should be selected for assisting the transmission. Another work in this line [10] investigated the issue of joint RRA and relay selection with imperfect CSI. The authors, however, focused on power minimization and mean rate to characterize the CSI uncertainty. We have proposed RRA scheme in the context of imperfect CSI available at BS in [11]. However, symmetric source-to-relay and relay-to-destination scenario is considered without exploring the link asymmetry.

The essence of this paper is to consider all the above-mentioned fundamental properties jointly: the selection of the relay(s), resource allocation for the relays (subcarriers and power), link asymmetry and imperfection in CSI. All the previous studies lack in including one of those properties. Here we consider them all jointly. Namely, we propose a new asymmetric resource allocation scheme for OFDMA networks with imperfect CSI, which can effectively solve the problems of joint relay selection, subcarrier and power allocation and thus, enhance the system throughput when only estimated CSI is available. Through a dual approach, we solve each sub-problem in an asymptotically optimal and alternating manner. In this work, relays are deployed for extending the cell coverage, so the direct link from base station to destination node is not taken into consideration. As the actual channel throughput in the presence of imperfect CSI is unknown, we employ the capacity expectation as the performance metric. We propose a relay selection and subcarrier allocation schemes, where one set of relays that can obtain the best throughput is selected. Power allocation is done in the way that under per-node constraint is considered, which is more realistic than the scheme, e.g., in [5] where only the sum of whole system power is taken into consideration.

The reminder of this paper is organized as follows. Section II describes our relay-assisted OFDMA wireless networks in the downlink and formulates the problem. In Section III, the proposed relay selection and resource allocation scheme is presented. Through simulations, the benefits of our proposed algorithm are demonstrated in section IV and finally we conclude the paper in Section V.

2 System Model and Problem Formulation

2.1 System Model and Assumptions

System model in this work is considered as a two-hop time-division duplex downlink Decode-and-Forward (DF) relay wireless network. The whole system consists of a transmitter, e.g., Base Station (BS)/ Access Point (AP), a receiver, e.g., mobile terminal (MT) , and several relays. The first hop is the broadcast phase, where BS is able to broadcast information data to a selected group of DF relays. At the second hop, the selected relays cooperate to forward the decoded data to the MT, so the spatial diversity gain can be achieved (relays are assumed to be far enough to each other). In this work, only the estimated CSI is assumed to be known at the receiver by using the estimator and the feedback of the estimate is instantaneous and perfect to the BS. It is assumed that channel estimation error pertains to the amplitude of the correct channel gain, while the phase of the channel gain can be perfectly obtained. As a result, only estimated channel information with estimation error is available to both BS and MT. All relay selection, subcarrier assignment and power allocation related operations are carried out at BS based on the imperfect CSI from the MT.

Assuming there are total Z relays in the networks, and the selected relay cluster $\mathcal{K}$ contains K potential half-duplex relays. In this work we do not consider direct BS-MT transmission link since we tackle the problem in the context of that relays are deployed for extending the cell coverage. An example can be found in Fig. 1.

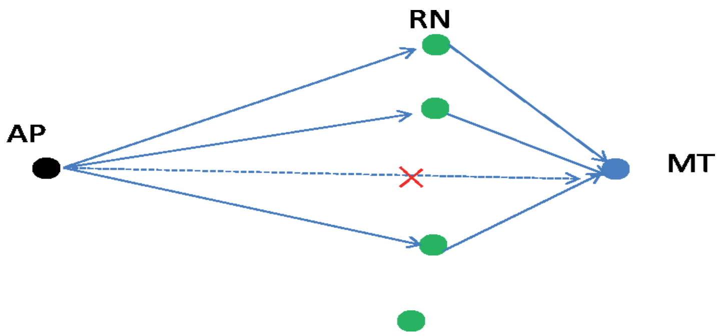


Figure 1: OFDMA Multi- Relay Networks

2.2 Problem Formulation

Denoting x as the transmit data from BS to MT. After data passing through the wireless channel, the output after estimator at the receiver regardless of the path loss can be expressed as,

$$y = (\hat{h} + \tilde{h})\sqrt{P}x + n, \tag{1}$$

where P is the transmit power gain. $\hat{h}$ is the channel estimated function and $\tilde{h}$ is the independent estimation error which is modeled as a zero mean Gaussian random variable with variance $\sigma^2_{\tilde{h}}$. Thus, the imperfect CSI h follows $\mathcal{CN}(\hat{h}, \sigma^2_{\tilde{h}})$. n is the additive noise which can be also modeled as a complex Gaussian random variable with variance σ^2_n. If we use $h = \hat{h}+\tilde{h}$ and denote $G = |h|^2$, $\hat{G} = |\hat{h}|^2$, channel gain G follows a noncentral chi-square probability density function (PDF) given by [12]

$$f(G|\hat{G}) = \frac{1}{\sigma^2_{\tilde{h}}} e^{-\frac{\hat{G}+G}{\sigma^2_{\tilde{h}}}} \mathcal{J}_0\Big(2\sqrt{\frac{\hat{G}G}{\sigma^4_{\tilde{h}}}}\Big) \tag{2}$$

where $\mathcal{J}_0$ is the 0th order modified Bessel Function of the first kind.

In this work, h^i is denoted as the channel transfer function from transmitter to receiver. For instance, $\hat{h}^i_{s,k}$ means the channel estimate from BS s to relay node (RN) k over OFDM subcarrier i and $\hat{h}^j_{k,d}$ means the channel estimation from RN k to destination d over OFDM subcarrier j. Thus, we obtain channel gain of the first hop $\hat{G}^i_{s,k} = |\hat{h}^i_{s,k}|^2$ and second hop $\hat{G}^j_{k,d} = |\hat{h}^j_{k,d}|^2$. L is the path loss and σ^2_k and σ^2_d are the noise variance for two hops respectively.$\sigma^2_{\tilde{h},k}$ and $\sigma^2_{\tilde{h},d}$ are the variance of related estimation error for two hops. We have $\sigma^2_{\tilde{h}} = \sigma^2_{\tilde{h},k} = \sigma^2_{\tilde{h},d}$. We use P^i as the transmit power assigned to subcarrier i for delivering data to RN. One RN k occupies subcarrier i in the first hop and j in the second hop. In this work, we assume that the transmission durations for the first hop and second hop are allowed to differ in the context of asymmetric link. We denote these durations as T_1 and T_2. Therefore, at the first hop, the transmission rate is determined by the minimum rate of each link between BS and selected RNs since broadcasting is assumed. As BS only knows the CSI conditioned on the feedback of MT, we thus can obtain the expected achievable throughput of the first hop as follows:

$$R^{\mathcal{I}}_{s,\mathcal{K}} = \min_{k\in\mathcal{K}} \Big\{ \mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}} \Big[\frac{T_1}{T} log(1 + \sum_{i=1}^{M} \omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k}) \Big] \Big\}, \tag{3}$$

where $\gamma^i_{s,k} = \frac{L_{s,k}G^i_{s,k}}{\sigma^2_k}$ and $\hat{\gamma}^i_{s,k} = \frac{L_{s,k}\hat{G}^i_{s,k}}{\sigma^2_k}$. The notation $\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}$ means expectation with respect to $\gamma^2_{s,k}$ conditioned on $\hat{\gamma}^i_{s,k}$. $\mathcal{M}$ is the subcarrier set of the system that contains M subcarriers and $\mathcal{I}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at first hop. We further refer the link throughput and its expectation interchangeably for simplicity. ρ_k indicates that whether RN k is chosen for subcarrier allocation, so we obtain

$$\rho_k = \begin{cases} 1 & \text{if } k \text{ is chosen for relaying,} \\ 0 & \text{otherwise.} \end{cases}$$

ω is the indicator whether certain subcarrier is assigned to RN k, which can be expressed as,

$$\omega^i_{s,k} = \begin{cases} 1 & \text{if } i \text{ is assigned to } k \text{ at first hop,} \\ 0 & \text{otherwise.} \end{cases}$$

For the second hop, it is assumed that the RNs are perfectly synchronized and transmitted at the same time. Therefore, the second hop can be viewed as a virtual MISO link. The expected throughput can be expressed as [13]

$$R^{\mathcal{J}}_{\mathcal{K},d} = \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}} \Big[\frac{T_2}{T} log\big(1 + \sum_{j=1}^{M}\sum_{k=1}^{K} \omega^j_{k,d}\rho_k P^j_{k,d}\gamma^j_{k,d}\big) \Big], \tag{4}$$

where $\gamma^j_{k,d} = \frac{L_{k,d}G^j_{k,d}}{\sigma^2_d}$ and $\hat{\gamma}^j_{k,d} = \frac{L_{k,d}\hat{G}^j_{k,d}}{\sigma^2_d}$. $\mathcal{J}$ is the subcarrier set which contains the subcarriers that are allocated to the selected RNs at second hop. For indicator $\omega^j_{k,d}$, we also have

$$\omega^j_{k,d} = \begin{cases} 1 & \text{if } j \text{ is assigned to } k \text{ at second hop,} \\ 0 & \text{otherwise.} \end{cases}$$

Therefore, the total achieved end-to-end throughput of source s to destination d through RN set $\mathcal{K}$ is [13]

$$R_{sd} = min\ \left\{R^{\mathcal{I}}_{s,\mathcal{K}}, R^{\mathcal{J}}_{\mathcal{K},d}\right\}. \tag{5}$$

To proceed, our problem is then formulated as

$$max\ \ R_{sd} \tag{6}$$

subject to

$$\begin{aligned}
&T = T_1 + T_2\\
&\sum_{i=1}^{M}\sum_{k=1}^{K}\omega^i_{s,k}P^i_{s,k} \leq P_{s,max}\\
&\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d} \leq P_{k,max}\\
&\sum_{k=1}^{K}\omega^i_{s,k} = 1, \omega^i_{s,k} \in \{0,1\}\\
&\sum_{k=1}^{K}\omega^j_{k,d} = 1, \omega^j_{k,d} \in \{0,1\}
\end{aligned} \tag{7}$$

where $P_{s,max}$ is the maximum transmit power of BS and $P_{k,max}$ is the maximum power of RN k. Therefore, the objective is to find the optimal solutions for relay set selection, link asymmetry, and subcarrier and power allocations which satisfy the problem (6).

Remark 1: It can be noticed that when $T_1 = T_2 = \frac{T}{2}$, the source-relay and relay-destination links are symmetric.

It can be noticed that achieving maximum for (5) implies $R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}$ [5]. Therefore, (6) can be modified as [14]

$$\arg\max\ \left(R^{\mathcal{I}}_{s,\mathcal{K}} + R^{\mathcal{J}}_{\mathcal{K},d}\right), \tag{8}$$

subject to presented conditions in (7) and

$$R^{\mathcal{I}}_{s,\mathcal{K}} = R^{\mathcal{J}}_{\mathcal{K},d}. \tag{9}$$

3 Radio Resource Allocation Scheme

An adaptive ARRA algorithm is presented to solve the described problems in this section. Although the formulated resource allocation problem is combinatorial in nature with a non-convex structure, it has been shown in [17] that the duality gap of the optimization problem becomes zero under the condition of time-sharing regardless of its convexity. For the general OFDM system, the condition of time-sharing is always fulfilled as the number of subcarriers is large enough. As such, it can be solved in the dual domain and the solution is asymptotically optimal. The Lagrangian [15] of (8) is in (10), where $\mathbf{P} = \{P^i_{s,k}, P^j_{k,d}\}$ is the set of power allocation, $\boldsymbol{\omega} = \{\omega^i_{s,k}, \omega^j_{k,d}\}$ denotes the subcarrier allocation, and $\boldsymbol{\rho} = \{\rho_k\}$ is the relay assignment. The λ_s, $\lambda_{k,d}$ and μ are Lagrange multipliers. Then it can be derived that $\lambda_s, \lambda_{k,d} \geq 0$ and $\mu \in (-1, 1)$ [7].

$$\begin{aligned}\mathcal{L}(\mathbf{P}, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}) =& \Big(R^{\mathcal{I}}_{s,\mathcal{K}} + R^{\mathcal{J}}_{\mathcal{K},d}\Big) - \lambda_s\Big(\sum_{i=1}^{M}\sum_{k=1}^{K} \omega^i_{s,k} P^i_{s,k} - P_{s,max}\Big) \\ & - \sum_{k=1}^{K} \lambda_{k,d}\Big(\sum_{j=1}^{M} \omega^j_{k,d} P^j_{k,d} - P_{k,max}\Big) - \mu\big(R^{\mathcal{I}}_{s,\mathcal{K}} - R^{\mathcal{J}}_{\mathcal{K},d}\big),\end{aligned} \tag{10}$$

We could obtain Lagrange dual function as follows,

$$g(\boldsymbol{\lambda}, \boldsymbol{\mu}) = \max \mathcal{L}(\mathbf{P}, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}). \tag{11}$$

With the assumption that the number of subcarrier is sufficiently large, thus, the duality gap between primal and dual functions can be assumed negligible [17]. Therefore, we can solve the problem (6) by minimizing the dual function:

$$\min \; g(\boldsymbol{\lambda}, \boldsymbol{\mu}) \tag{12}$$

3.1 Dual Variable Evaluation

Since a dual function is always convex [15], many methods can be used to minimize dual function and find the dual point with guaranteed convergence. In this work, we follow the subgradient method in [17] to derive the subgradient Lagrange dual function with the optimal power allocation p^* which is presented in the following subsection.

Algorithm 1 Evaluating Dual Variable

Initialize $\boldsymbol{\lambda}^0$ and $\boldsymbol{\mu}^0$

while (!Convergence) **do**

  Obtain $g(\boldsymbol{\lambda}^l, \boldsymbol{\mu}^l)$ at the lth iteration;

  Update a subgradient for $\boldsymbol{\lambda}^{l+1}$ and $\boldsymbol{\mu}^{l+1}$, by $\boldsymbol{\lambda}^{l+1} = \boldsymbol{\lambda}^l + \upsilon^l \triangle\boldsymbol{\lambda}$ and $\boldsymbol{\mu}^{l+1} = \boldsymbol{\mu}^l + \upsilon^l \triangle\mu$;

end while

where $\triangle\boldsymbol{\lambda} = \{\triangle\lambda_s, \triangle\lambda_{1,d}, ...\triangle\lambda_{K,d}\}$, $\triangle\lambda_s$, $\triangle\lambda_{k,d}$ and $\triangle\mu$ can be expressed as

$$\begin{aligned} \triangle\lambda_s &= P_{s,max} - \sum_{i=1}^{M}\sum_{k=1}^{K}(P_{s,k}^i)^* \\ \triangle\lambda_{k,d} &= P_{k,max} - \sum_{j=1}^{M}(P_{k,d}^j)^* \\ \triangle\mu &= (R_{s,\mathcal{K}}^{\mathcal{I}})^* - (R_{\mathcal{K},d}^{\mathcal{J}})^*. \end{aligned} \tag{13}$$

Here, υ^l is the stepsize and the number of iterations is denoted as l. The sub-gradient based Algorithm 1 can reach the optimal $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ with guaranteed convergence. The computational complexity of Algorithm 1 is polynomial in the number of dual variable $K+1$ [17]. Since (11) can be viewed as a nonlinear integer programming problem, its optimal solution requires high computational cost. Therefore, we decompose the optimization problem to three subproblems, which are relay selection, subcarriers and power allocation under link asymmetry and aim to solve the original problem by addressing three subproblems.

3.2 Power Allocation Scheme

With the assumption that relay selection and subcarrier allocation are done, the optimal time slot for each hop can be achieved by using Karush-Kuhn-Tucker (KKT) conditions [15]. This results in

$$T_1 = \frac{1-\mu^*}{2}T \tag{14}$$

$$T_2 = \frac{1+\mu^*}{2}T \tag{15}$$

In order to obtain the optimal solution of power allocation, we are aiming to solve the problem (10) over variables $P_{s,k}^i$ and $P_{k,d}^j$. However, from (4) and (3), we see that problem (10) involves the conditional expectation of achievable throughput with respect to estimated CSI. Applying Karush-

Kuhn-Tucker (KKT) conditions [15], we could obtain the optimal power allocation schemes by solving following equation numerically:

$$\frac{\alpha_{s,k}^{i}}{P_{s,k}^{i}}\Big(\frac{\sigma_k^2\beta_{s,k}^{i}}{L_{s,k}P_{s,k}^{i}}\Big)^{\alpha_{s,k}^{i}} e^{\frac{\sigma_k^2\beta_{s,k}^{i}}{L_{s,k}P_{s,k}^{i}}}\Gamma\Big(-\alpha_{s,k}^{i},\frac{\sigma_k^2\beta_{s,k}^{i}}{L_{s,k}P_{s,k}^{i}}\Big)=\frac{2\lambda_s}{(1-\mu)^2}. \tag{16}$$

where $\Gamma(a,b)$ is the incomplete Gamma function. $\alpha_{s,k}^{i}=(\eta_{s,k}^{i}+1)^2/(2\eta_{s,k}^{i}+1)$ is the Gamma shape parameter with $\eta_{s,k}^{i}=\hat{G}_{s,k}^{i}/\sigma_{\tilde{h}}^2$ and $\beta_{s,k}^{i}=\alpha_{s,k}^{i}/(\hat{G}_{s,k}^{i}+\sigma_{\tilde{h}}^2)$ is Gamma PDF rate parameter. Similarly, for the cooperation phase, the optimal RN power allocation is obtained by solving:

$$\frac{\alpha_{k,d}^{j}}{P_{k,d}^{j}}\big(c_1\beta_{k,d}^{j}\big)^{\alpha_{k,d}^{j}} e^{c_1\beta_{k,d}^{j}}\Gamma\big(-\alpha_{k,d}^{j},c_1\beta_{k,d}^{j}\big)=\frac{2\lambda_{k,d}}{(1+\mu)^2}, \tag{17}$$

where $\alpha_{k,d}^{j}=(\eta_{k,d}^{j}+1)^2/(2\eta_{k,d}^{j}+1)$ with $\eta_{k,d}^{j}=\hat{G}_{k,d}^{j}/\sigma_{\tilde{h}}^2$ and $\beta_{k,d}^{j}=\alpha_{k,d}^{j}/(\hat{G}_{k,d}^{j}+\sigma_{\tilde{h}}^2)$. We have $c_1=\frac{\sigma_d^2+\sum_{m=1,m\neq k}^{K}P_{m,d}L_{m,d}G_{m,d}}{L_{k,d}P_{k,d}^{j}}$. $P_{m,d}$ and $G_{m,d}$ is the power allocation and channel gain from relay m to MT d. Through approximation method in [20], we are able to obtain the power allocation with imperfect CSI.

The proof can be found in Appendix A. One example is shown in Fig. 2 where different value of $\sigma_{\tilde{h}}^2$ are considered. We can see that when the estimation error is relatively small, the result of power allocation in the presence of imperfect CSI (red curve with circles) is very close to the one when perfect CSI can be obtained by BS. It is also worth noticing that when the channel SNR is low (e.g. -18 dB in Fig. 2), the power allocation performance when estimation error is large (e.g. variance is 0.1) is quite close to the one while CSI perfection is assumed.

3.3 Opportunistic Relay Selection (ORS)

Most of the previous work concerning about the relay selection problem was single relay selection [6][7]. However, the opportunistic relay selection scheme proposed in this work, unlike some traditional single relay selection algorithms, is multiple RNs selection. K RNs will be selected in the proposed scheme to form a group that can maximize the achieved throughput in (5) based on the imperfect CSI.

When assuming the subcarrier and power allocations are done, (10) can be rewrite as in (18). Simliar to the power allocation and by invoking KKT condition, the RN can be performed according to the rule expressed in (19).

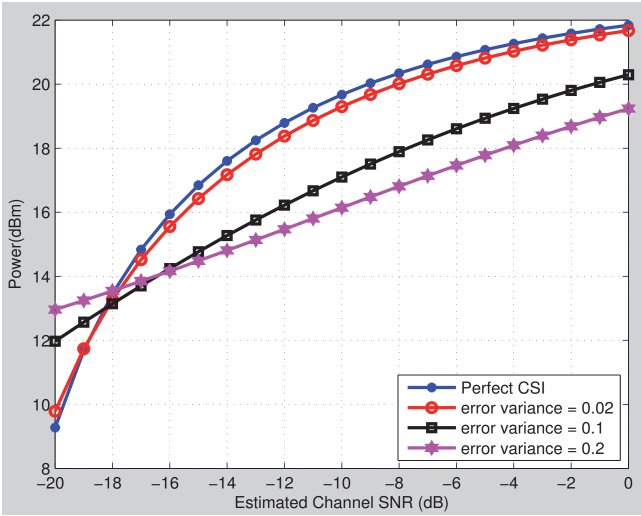


Figure 2: Results of power allocation when different value of $\sigma^2_{\tilde{h}}$ is used.

$$
\begin{aligned}
&\mathcal{L}(\mathbf{P}, T, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\lambda}) \\
&= \min_{k\in\mathcal{K}} \Big\{ \mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}} [\frac{T_1}{T} log(1 + \sum_{i=1}^{M} \omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k})] \Big\} + \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}} [\frac{T_2}{T} log(1 + \sum_{i=1}^{M}\sum_{k=1}^{K} \omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d})] \\
&-\mu\Big(\min_{k\in\mathcal{K}} \Big\{ \mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}} [\frac{T_1}{T} log(1 + \sum_{i=1}^{M} \omega^i_{s,k}\rho_k P^i_{s,k}\gamma^i_{s,k})] \Big\} - \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}} [\frac{T_2}{T} log(1 + \sum_{i=1}^{M}\sum_{k=1}^{K} \omega^i_{s,k}\rho_k P^j_{k,d}\gamma^j_{k,d})] \Big) \\
&+\lambda_s(\sum_{i=1}^{M}\sum_{k=1}^{K} \omega^i_{s,k}P^i_{s,k} - P_{s,max}) - \sum_{k=1}^{K}\lambda_{k,d}(\sum_{j=1}^{M}\omega^j_{k,d}P^j_{k,d} - P_{k,max}).
\end{aligned}
\tag{18}
$$

$$
\mathcal{K}^* = \arg\max_{k} \ \Big(\min_{k\in\mathcal{K}} \Big\{ \frac{(1-\mu^*)^2}{2} \mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}} [\frac{P_{s,k}\gamma_{s,k}}{1 + P_{s,k}\gamma_{s,k}}] \Big\} + \frac{(1+\mu^*)^2}{2} \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}} \Big[\frac{P_{k,d}\gamma_{k,d}}{1 + \sum_k^K P_{k,d}\gamma_{k,d}}\Big] \Big), \tag{19}
$$

Since we know that $\hat{\gamma}^i_{s,k} = \frac{L_{s,k}\hat{G}^i_{s,k}}{\sigma^2_k}$, the channel SNR $\gamma_{s,k}$ conditioned on $\hat{\gamma}^i_{s,k}$ is also a non-central Chi-squared distributed random variable with PDF

$$
f(\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}) = \frac{1}{\nu^i_{s,k}} e^{-\frac{\hat{\gamma}^i_{s,k} + \gamma^i_{s,k}}{\nu^i_{s,k}}} \mathcal{J}_0\Big(2\sqrt{\frac{\hat{\gamma}^i_{s,k}\gamma^i_{s,k}}{(\nu^i_{s,k})^2}}\Big) \tag{20}
$$

$$f(\gamma^i_{s,k}|\hat{\gamma}^j_{k,d}) = \frac{1}{\nu^j_{k,d}} e^{-\frac{\hat{\gamma}^j_{k,d}+\gamma^j_{k,d}}{\nu^j_{k,d}} \mathcal{J}_0\Big(2\sqrt{\frac{\hat{\gamma}^j_{k,d}\gamma^j_{k,d}}{(\nu^j_{k,d})^2}}\Big)} \tag{21}$$

where $\nu^i_{s,k} = \sigma^2_k/\sigma^2_{\hat{h}}$ and $\nu^j_{k,d} = \sigma^2_d/\sigma^2_{\hat{h}}$. Consequently, following the same procedure as in Appendix A, one can arrive at

$$\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}\Big[\frac{P^i_{s,k}\gamma^i_{s,k}}{1+P^i_{s,k}\gamma^i_{s,k}}\Big] = \psi^i_{s,k}\Big(\frac{\theta^i_{s,k}}{P^i_{s,k}}\Big)^{\psi^i_{s,k}} e^{\frac{\theta^i_{s,k}}{P^i_{s,k}}}\Gamma\Big(-\psi^i_{s,k}, \frac{\sigma^2_k\theta^i_{s,k}}{L_{s,k}P^i_{s,k}}\Big), \tag{22}$$

$$\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}\Big[\frac{P^j_{k,d}\gamma^i_{k,d}}{1+\sum_k^K P^j_{k,d}\gamma^j_{k,d}}\Big] = \psi^j_{k,d}\big(c_2\theta^j_{k,d}\big)^{\psi^j_{k,d}} e^{c_2\theta^j_{k,d}}\Gamma\big(-\psi^j_{k,d}, c_2\theta^j_{k,d}\big), \tag{23}$$

where $\psi^i_{s,k} = (\zeta^i_{s,k}+1)^2/(2\zeta^i_{s,k}+1)$ with $\zeta^i_{s,k} = \hat{\gamma}^i_{s,k}/\nu^i_{s,k}$ and $\theta^i_{s,k} = \zeta^i_{s,k}/(\hat{\gamma}^i_{s,k}+\nu^i_{s,k})$. Similarly, $\psi^j_{k,d} = (\zeta^j_{k,d}+1)^2/(2\zeta^j_{k,d}+1)$ with $\zeta^j_{k,d} = \hat{\gamma}^j_{k,d}/\nu^j_{k,d}$ and $\theta^j_{k,d} = \zeta^j_{k,d}/(\hat{\gamma}^j_{k,d}+\nu^j_{k,d})$. Also we have $c_2 = (1+\sum_{m=1,m\neq k}^K P_{m,d}\gamma_{m,d})/P^j_{k,d}$, and $P_{m,d}$ and $\gamma_{m,d}$ are the power allocation and channel SNR from relay m to MT. The optimal value of $\mathbf{P}$ can be expressed as in (16) and (17). Thus, (19) can be considered as a multi-objective optimization problem, which aims to obtain a trade-off between the throughput of two hops. (19) also acts as the termination criteria for the whole RRA scheme. The ORS scheme is depicted in Algorithm 2. Therefore, the relay selection strategy can be expressed as,

$$\rho_k = \begin{cases} 1 & \text{if } k \in \mathcal{K}^*, \\ 0 & \text{otherwise.} \end{cases}$$

Algorithm 2 ORS

```
Definition
𝒵 is the set of all Z RNs.
𝒦 is the set of selected K RNs;
C_𝒦 = 0 for ∀k ∈ 𝒦;
sort the set of RN in the descending order according to its overall path loss;
while !satisfy (19) do
  for z = 1 to Z do
    add RN z to 𝒦 according to its order;
    do subcarrier and power allocation;
    calculates the value of C_𝒦 according to the right-hand side of (19)
    find z satisfying (19),∀ z ∈ 𝒵;
  end for
end while
```

3.4 Optimal Subcarrier Allocation (OSA)

The goal of the subcarrier allocation strategy is to assign subcarriers to a selected RN that can obtain best system throughput performance. Following the same procedure as the relay selection, we can obtain the subcarrier allocation criteria as follows:

$$\mathcal{I}^* = \arg\max \; \Big(\min_{k\in\mathcal{K}} \Big\{ \frac{(1-\mu^*)^2}{2} \mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}} \Big[\frac{P^i_{s,k}\gamma^i_{s,k}}{1+P^i_{s,k}\gamma^i_{s,k}} \Big] \Big\} \Big) \tag{24}$$

$$\mathcal{J}^* = \arg\max \Big\{ \frac{(1+\mu^*)^2}{2} \mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}} \Big[\frac{P^j_{k,d}\gamma^j_{k,d}}{1+\sum_k^K P^j_{k,d}\gamma^j_{k,d}} \Big] \Big\} . \tag{25}$$

where channel SNR $\gamma^i_{s,k} = \frac{L_{s,k}G^i_{s,k}}{\sigma^2_k}$ and $\gamma^j_{k,d} = \frac{L_{k,d}G^j_{k,d}}{\sigma^2_d}$. The detailed procedure of OSA is shown in Alg. 3. Therefore, the OSA indicator for the first hop and second hop can be expressed as

$$\omega_i = \begin{cases} 1 & \text{if } i \in \mathcal{I}^*, \\ 0 & \text{otherwise.} \end{cases}$$

$$\omega_j = \begin{cases} 1 & \text{if } j \in \mathcal{J}^* \;, \\ 0 & \text{otherwise.} \end{cases}$$

Algorithm 3 OSA

```
Definition
c1: the set of M subcarriers at first hop;
c2: the set of M subcarriers at second hop;
while !satisfy (24) and (25) do
    sort c1 and c2 in the descending order according to the channel gain.
    for m = 1 to M do
        find subcarrier set I for the first hop that satisfy (24);
        find subcarrier set J for the first hop that satisfy (25);
    end for
end while
```

3.5 Joint Relay, Subcarrier and Power Allocation

We have described the algorithms for relay selection, subcarrier and power allocation in the previous section. The two subproblems presented are interconnected hierarchically. Combining the above three phases together with asymmetric time design, we can obtain suboptimal solution for (6) when number of subcarriers is sufficiently large. The flow chart of the whole algorithm is shown in Fig. 3. We can see these four steps are conducted in alternating fashion until the convergence is reached.

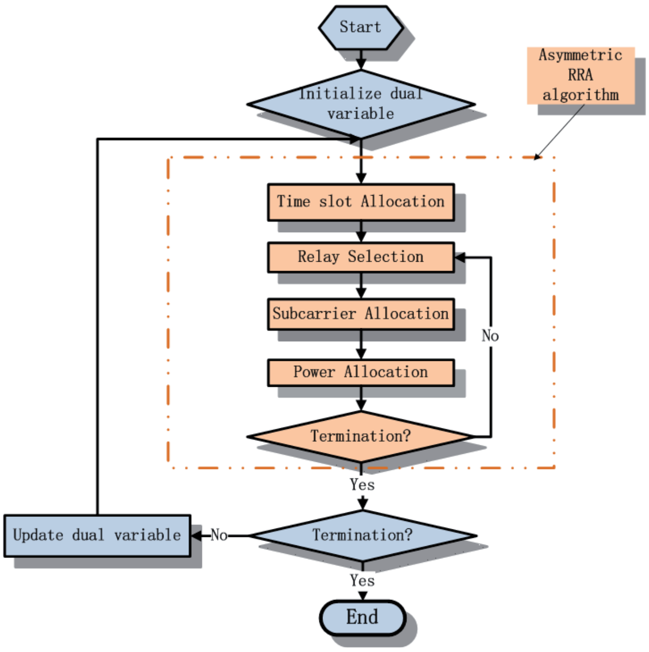


Figure 3: Algorithm flow chart.

4 Performance Evaluation

Performance of the proposed algorithm is presented in this section. It is assumed that five RNs are located between BS and MT, and the distance between BS and MT is 1.8km. The Stanford University SUI-3 channel model is employed [21], in which the central frequency is 1.9GHz. 3-tap channel and signal fading follows Rician distribution is applied in the simulations. We choose the number of subcarriers to be 32, so the duality gap can be ignored [6]. Flat quasi-static fading channels are adopted, hence the channel coefficients are assumed to remain constant during one transmission frame, and can vary from one frame to another independently. The path loss gain is varied according to the distances from RNs to BS and MT and path loss exponent is fixed to 3.5. The maximum transmit power of BS and RN are 40 dBm and 20 dBm respectively. If not otherwise stated, the channel estimator with an error variance $\sigma_{\tilde{h}}^2 = 0.02$ is assumed at the receiver. There are 1000 trials simulations and the average performance is presented.

We compare our simulation results with the performance of other selected recently proposed symmetric or asymmetric schemes:

- Proposed relay selection and subcarrier allocation scheme together with Waterfilling power allocation(Waterfilling);
- Proportional Allocation scheme in [5] with fairness consideration(Fairness SA);
- Asymmetric Resource Allocation scheme in [7] without multiple relay selection(ARA);

At first, the impact of CSI error variance $\sigma^2_{\tilde{h}}$ to the system spectral efficiency is depicted in Fig. 4. We can notice that the accuracy of the estimator can lead to up to 20% differences on the spectral efficiency when the estimated channel SNR is 20 dB. If we use an estimator with variance $\sigma^2_{\tilde{h}} = 0.02$, it can result in around 5% difference on the systems performance.

Fig. 5 demonstrates the impact of maximum transmit power of BS on the system throughput. We denote $d_{s,d}$ as the distance between BS and MT, and $d_{s,k}$ as the distance between BS and RNs. In Fig. 5, $d_{s,d} = 1800\ m$ and $d_{s,k} = 1500 - 1600\ m$. The maximum transmit power of RN is considered as half of the maximum transmit power of the BS. The considered channel SNR from BS to RN is $\gamma_{s,k} = -20\ dB\ -30\ dB$ and from RN to MT is $\gamma_{k,d} = -15\ dB\ -25\ dB$. We compare the performance of our proposed resource allocation algorithm with two other recently proposed algorithms. The proposed ARRA scheme achieves the best performance, and the performance gain over other existed ARA methods is up to about 55%. Comparing to the Fairness SA scheme, the bandwidth efficiency enhancement is around 20%.

Fig. 6 shows the impact of distance between BS and RN on the system throughput. The distance between BS and RN is normalized to distance between BS and MT and vary from 0.1 to 0.9. In Fig. 6, we set maximum BS power $P_{s,max} = 40\ dBm$ and maximum RN power is $P_{k,max} = 20\ dBm$. From Fig. 6, when distance is less than 0.4 one can observe that the proposed ARRA obtains the highest system throughput. When the normalized distance between BS and RN is increasing to 0.9, it can be seen that the spectral efficiency difference between proposed ARRA scheme and Fairness SA is less than the one when distance is smaller than 0.4. Moreover, the ARA algorithm can reach higher throughput when the normalized distance between BS and RN increases. This may due to the fact the some RNs are very close to the MT so that the achieved SNR is rather high for all schemes. Therefore, it can be concluded that the proposed algorithm can provide better performance gain over other existed algorithms even with small maximum BS power.

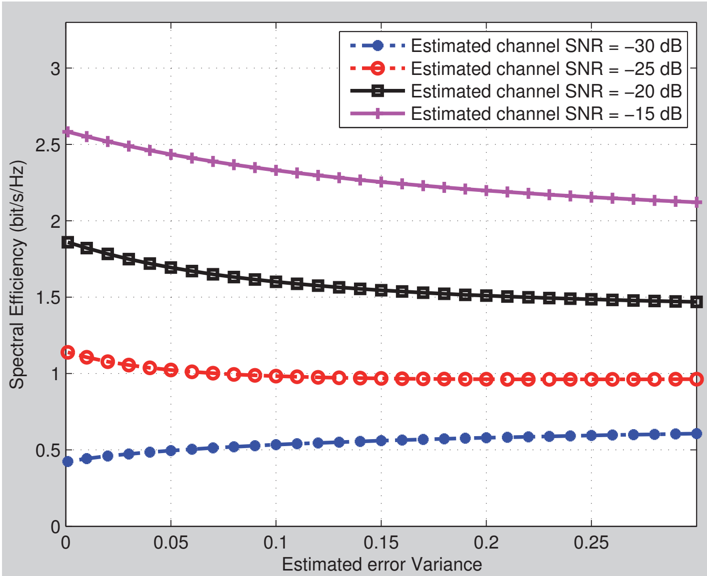


Figure 4: Impact of $\sigma_{\tilde{h}}^2$ on the system spectral efficiency.

Fig. 7 presents the convergence speed of the proposed ARRA, Waterfilling and ARA algorithms. The considered $P_{s,max}$ is fixed to 35 dB and$P_{r,max}$ is 18 dB. The throughput performance of the proposed algorithm becomes stable after several iterations, which demonstrates fast convergence speed.

5 Conclusion

In this work, we considered the asymmetric relay selection and resource allocation problem for cooperative multi-relay OFDMA networks. By designing asymmetric time slots for different hops, the proposed algorithm is able to increase the system throughput as well as the degrees of freedom. The optimization problem was divided into three subproblems including relay selection, subcarrier and power allocations with the objective of transmission rate maximization under link asymmetry. At first relay was selected and subcarriers were allocated according to the proposed criteria, respectively, which can provide better data rate. Then the power allocation algorithm was proposed by solving the KKT condition. Therefore, a closed-form solution was achieved with a low computational cost. Performance evaluation illustrated that the achieved system performance of the proposed scheme was notably better than that of other recent proposed algorithms.

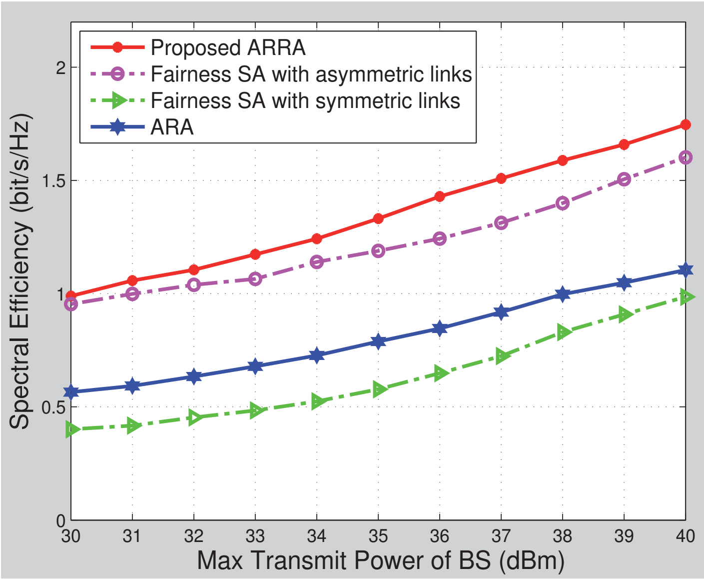


Figure 5: Impact of maximum transmit power $P_{s,max}$ on system spectral efficiency.

Appendix A

Derivation of optimal solution in (16) and (17)

For simplicity, we replace $P^i_{s,k}$ with P_1 and $P^j_{k,d}$ with $P_{2,k}$. Similarly, we use G_1 and L_1 to replace $G^i_{s,k}$ and $L_{s,k}$,$G_{2,k}$ and $L_{2,k}$ to replace $G^j_{k,d}$ and $L_{k,d}$. We also replace $\mathbb{E}_{\gamma^i_{s,k}|\hat{\gamma}^i_{s,k}}$ and $\mathbb{E}_{\gamma^j_{k,d}|\hat{\gamma}^j_{k,d}}$ with $\mathbb{E}_{G_1|\hat{G}_1}$ and $\mathbb{E}_{G_{2,k}|\hat{G}_{2,k}}$ respectively. First, we solve the power allocation at the transmitter. When the relay selection and subcarrier allocation are done, the derivative of $\mathcal{L}$ in (11) with respect to variable P_1 is given by

$$\frac{\partial \mathcal{L}}{\partial P_1} = (1-\mu)\frac{T_1}{T}\mathbb{E}_{G_1|\hat{G}_1}[\frac{1}{1+\frac{L_1P_1G_1}{\sigma_k^2}}\frac{L_1G_1}{\sigma_k^2}] - \lambda_s. \tag{26}$$

Applying KKT conditions, we obtain

$$\mathbb{E}_{G_1|\hat{G}_1}\Big[\frac{1}{1+\frac{L_1P_1G_1}{\sigma_k^2}}\frac{L_1G_1}{\sigma_k^2}\Big] = \frac{2\lambda_s}{(1-\mu)^2}. \tag{27}$$

We could approximate the PDF in (2) using Gamma distribution that is known to approximate

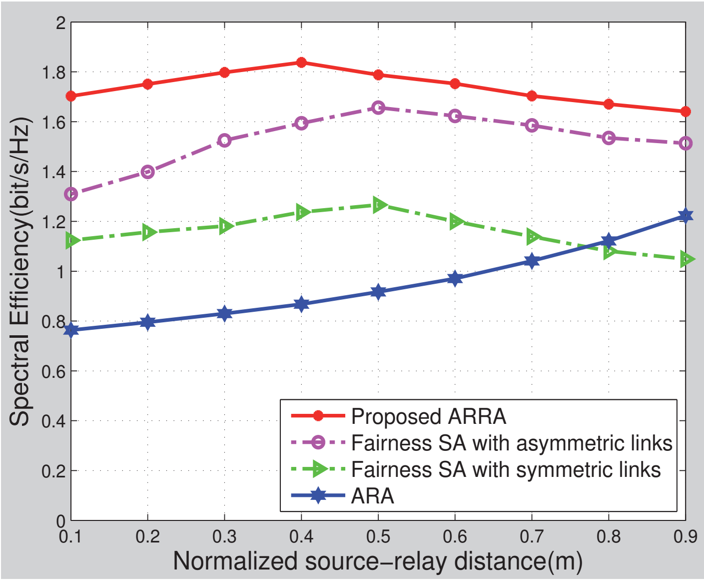


Figure 6: Impact of distance between BS and RN on the system spectral efficiency. Maximum BS power is 40 dBm and maximum RN power is 20 dBm.

the non-central Chi-squared distribution quite well [18]. We can obtain

$$f(G_1|\hat{G}_1) \approx \frac{\beta_1^{\alpha_1}}{\Gamma(\alpha_1)} G_1^{\alpha_1 - 1} e^{-\beta_1 G_1}, \tag{28}$$

where $\alpha_1 = (\eta_1 + 1)^2/(2\eta_1 + 1)$ is the Gamma shape parameter with $\eta_1 = \hat{G}_1/\sigma_{\tilde{h}}^2$ and $\beta = \alpha_1/(\hat{G}_1 + \sigma_{\tilde{h}}^2)$ is Gamma PDF rate parameter. Hence, by using (28), we simplify the expectation in (27) as follows

$$\begin{aligned}
(27) &= \int_0^\infty \frac{1}{1 + \frac{L_1 P_1 G_1}{\sigma_k^2}} \frac{L_1 G_1}{\sigma_k^2} f(G_1|\hat{G}_1) dG_1 \\
&= \int_0^\infty \frac{1}{1 + \frac{L_1 P_1 G_1}{\sigma_k^2}} \frac{L_1 G_1}{\sigma_k^2} \frac{\beta_1^{\alpha_1}}{\Gamma_1(\alpha_1)} G_1^{\alpha_1 - 1} e^{-\beta_1 G_1} dG_1 \\
&\approx \frac{\beta_1^{\alpha_1}}{P_1 \Gamma(\alpha_1)} \int_0^\infty \frac{G_1^{\alpha_1}}{\sigma_k^2 / L_1 P_1 + G_1} e^{-\beta_1 G_1} dG_1 \\
&= \frac{\alpha_1}{P_1} \Big(\frac{\sigma_k^2 \beta_1}{L_1 P_1}\Big)^{\alpha_1} e^{\frac{\sigma_k^2 \beta_1}{L_1 P_1}} \Gamma\Big(-\alpha_1, \frac{\sigma_k^2 \beta_1}{L_1 P_1}\Big),
\end{aligned} \tag{29}$$

where the closed form of the integral is obtained by using [19, page 348, Section 3.383.10] and

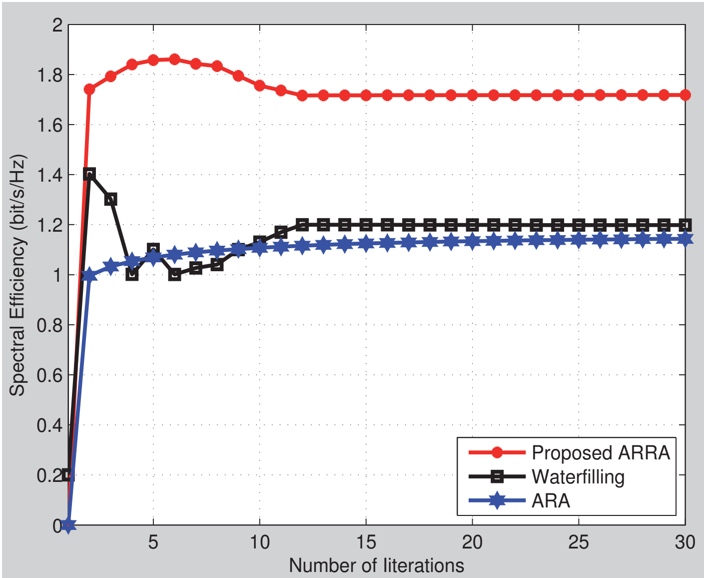


Figure 7: Convergence speed.

$\Gamma(a,b) = \int_b^{\infty} e^{-t} t^{a-1} dt$ is the incomplete Gamma Function. Therefore, using (29) in (27), we could arrive at the approximation of power allocation of the first hop numerically. Similarly, for the second hop, using KKT conditions we arrive at

$$\mathbb{E}_{G_{2,k}|\hat{G}_{2,k}}\Big[\frac{1}{1+\frac{\sum_k^K L_{2,k}P_{2,k}G_{2,k}}{\sigma_d^2}}\frac{L_{2,k}G_{2,k}}{\sigma_d^2}\Big] = \frac{2\lambda_{k,d}}{(1+\mu)^2}. \tag{30}$$

We can see that for $G_{k,d}$, the PDF can be expressed as

$$f(G_{2,k}|\hat{G}_{2,k}) \approx \frac{\beta_{2,k}^{\alpha_{2,k}}}{\Gamma(\alpha_{2,k})} G_{2,k}^{\alpha_{2,k}-1} e^{-\beta_{2,k}G_{2,k}}, \tag{31}$$

where $\alpha_{2,k} = (\eta_{2,k}+1)^2/(2\eta_{2,k}+1)$ with $\eta_{2,k} = \hat{G}_{2,k}/\sigma_{\tilde{h}}^2$ and $\beta_{2,k} = \alpha_{2,k}/(\hat{G}_{2,k}+\sigma_{\tilde{h}}^2)$ is Gamma

PDF rate parameter. Hence, by using (31), we obtain the expectation in (30)

$$
\begin{aligned}
(30) &= \int_0^{\infty} \frac{1}{1+\frac{\sum_k^K L_{2,k}P_{2,k}G_{2,k}}{\sigma_d^2}} \frac{L_{2,k}G_{2,k}}{\sigma_d^2} f(G_{2,k}|\hat{G}_{2,k}) dG_{2,k} \\
&= \int_0^{\infty} \frac{L_{2,k}G_{2,k}}{\sigma_d^2+\sum_k^K L_{2,k}P_{2,k}G_{2,k}} \frac{\beta_{2,k}^{\alpha_{2,k}}}{\Gamma_{2,k}(\alpha_{2,k})} G_{2,k}^{\alpha_{2,k}-1} \\
&\quad e^{-\beta_{2,k}G_{2,k}} dG_{2,k} \\
&\approx \frac{\alpha_{2,k}}{P_{2,k}} \big(c\beta_{2,k}\big)^{\alpha_{2,k}} e^{c\beta_{2,k}} \Gamma\big(-\alpha_{2,k}, c\beta_{2,k}\big),
\end{aligned}
\tag{32}
$$

where we have $c=\frac{\sigma_d^2+\sum_{m=1,m\neq k}^K P_{2,m}L_{2,m}G_{2,m}}{L_{2,m}P_{2,m}}$. Then approximation of power allocation $P_{2,k}$ can be achieved by substituting (32) into (30).

References

[1] NG C Y, YU W, Joint Optimization of Relay Strategies and Resource Allocation in Cooperative Cellular Networks[J], IEEE Journal on Selective Area in Communications, 2007, 25(2), 328-339.

[2] JEONG C, KIM H, Radio Resource Allocation in OFDMA Multihop Cellular Cooperative Networks, Proc. of IEEE PIMRC 2008, Cannes, France, Sep. 2008.

[3] KIM S K, Wang X, MADIHIAN M, Optimal Resource Allocation in Multi-hop OFDMA Wireless Networks with Cooperative Relay[J], IEEE Transaction on Wireless Communications, 2008, 7(5), 1833-1838.

[4] JEONG H, LEE J H, Adaptive Relay Selection for Regenerative OFDMA Relay Networks with Fairness Constraints, Proc. of IEEE VTC 2008-fall, Calgary, Canada, Sep. 2008.

[5] TANG M, WANG X, WANG Y, LIAO J, Dynamic Resource Allocation with Threshold in OFDMA-based Relay Networks, Proc. of IEEE VTC 2010-Spring, Taipei, Taiwan, May 2010.

[6] DANG W, Tao M, MU H, HUANG J, Subcarrier-Pair Based Resource Allocation for Cooperative Multi-Relay OFDM systems[J], IEEE Transaction on Wireless Communications, 2010, 9(5), 1640-1649.

[7] ZHOU N, ZHU X, HUANG Y, Optimal Asymmetric Resource Allocation and Analysis for OFDM-Based Multidestination Relay Systems in the Downlink[J], IEEE Transaction on Vehicular Technology, 2011, 60(3), 1307-1312.

[8] AWAD M K, MAHINTHAN V, MEHRJOO M, SHEN X, MARK J W, A Dual-Decomposition-Based Resource Allocation OFDMA Networks with Impefect CSI[J], IEEE Transaction on Vehicular Technology, 2010, 59(5), 2394-2403.

[9] WANG J H, LIN Y B, SU Y T, Resource Allocation and Relay Selection for cooperative OFDMA Networks with Imperfect Channel Information, Proc. of IEEE SPAWC 2011, San Francisco, CA, June 2011.

[10] AHMAD M, "Joint Resource Optimization and Relay Selection for cooperative Cellular Networks with Imperfect Channel Knowledge," *Proc. of IEEE SPAWC 2010*, Marrakech, Morocco, June 2010.

[11] CHANG Z, RISTANIEMI T, Resource Allocation for Cooperative Relay-assisted OFDMA Networks with Imperfect CSI, Proc. of 2012 IEEE Military Communications Conference (MILCOM'12), Orlando, FL, Nov. 2012.

[12] PROAKIS J, SALEHI M, Digital Communications,5th edition, McGraw-Hill Science, 2007.

[13] CHANG Z, RISTANIEMI T, NIU Z, Asymmetric Resource Allocation for Collaborative Relay OFDMA Networks with Imperfect CSI, Proc. of 2nd IEEE/CIC International Conference on Communications in China (ICCC'13), Xi'an, China, Aug. 2013.

[14] CHANG Z, RISTANIEMI T, Asymmetric Radio Resource Allocation Scheme for OFDMA Wireless Networks with Collaborative Relays[J], Wireless Networks, 2013, 19(5), 619-627.

[15] BOYD S, VANDENBERGHE A, Convex Optimization , Cambridge UK: Cambridge University Press, 2004.

[16] BOYD S, and MUTAPCIC A, Lecture Notes for EE364b , Standford University , 2006–2007.

[17] YU W, LUI R, Dual Methods for Nonconvex Spectrum Optimization in Multicarrier System[J], IEEE Transaction on Communications, 2006, 54(7), 1310-1322.

[18] STÜBER G, Principles of Mobile Communication, Kluwer Academic, 2001.

[19] GRADSHYEIN I, RYZHIK I, ZWILLINGER D, JEFFREY A, Table of Intergrals, Serie, and Products. New York: Academic, 2007.

[20] LAUSCHKE A, Convergence Acceleration with Canonical Contractions of Continued Fractions: Incomplete Gamma Function [Online]. available: http://216.80.120.13:8080/webMathematica/LC/gamma.jsp

[21] JAIN R, Channel Models A Tutorial1 v1.0 , Feb. 2007.