Department of Computer Science and Engineering

Self-Organizing Radio Resource Management and Backhaul Dimensioning for Cellular Networks

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Parth Amin

Aalto University

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Self-Organizing Radio Resource Management and Backhaul Dimensioning for Cellular Networks

Parth Amin

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Aalto University
School of Science
Computer Science and Engineering
Data Communication Software

Supervising professor
Prof Jukka K. Nurminen

Thesis advisor
Prof Jukka K. Nurminen

Preliminary examiners
Prof Prashant Krishnamurthy, University of Pittsburgh, USA
Prof Ekram Hossain, University of Manitoba, Canada

Opponent
Dr. Rapeepat Ratasuk, Nokia Networks, USA

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Abstract

Author
Parth Amin

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Abstract

The huge appetite for mobile broadband has resulted to continuous and complementary improvement in both radio access technology and mobile backhaul of cellular networks, along with network densification. Femtocells are foreseen to complement traditional macro base stations (BSs) in Long Term Evolution (LTE) and future cellular networks.

Deployment of femtocells, introduce new requirements for distributing phase synchronization and interference management in heterogeneous network. Achieving phase synchronization for indoor femtocells will be beneficial for time division duplexing (TDD) operation and inter-cell interference cancellation and management techniques, but challenging to achieve as global positioning system does not work indoors. In this thesis, we propose coordinated transmission and reception algorithms to reduce interference across BSs, and thereby achieve better network-wide phase synchronization over the air. We also cover the problem of selecting component carriers for dense small cell network, by improving the throughput of cell-edge user equipment's (UEs). We propose three strategies: Selfish, Altruistic and Symmetric for primary carrier selection and remove the outage of the macro UEs near the closed subscriber group (CSG) femtocells. Further, we propose dynamic frequency selection algorithm for component carrier selection, where decisions to select or drop a carrier are based on gain/loss predictions made from UE handover measurements. Thereby, we maximize the sum utility of the dense femtocell network, which includes mean-rate, weighted fair-rate, proportional fair-rate and max-min utility.

Mobile backhaul dimensioning is studied to improve the handover and provide the cost-effective backhaul opportunity for femtocells deployed in emerging markets. In a packet-switched wireless system e.g. LTE, data packets are needed to be efficiently forwarded between BSs during handover over the backhaul. We improve the packet forwarding handover mechanism by reducing the amount of forwarded data between BSs. Another challenge lies in equipping the femtocells with backhaul, where copper cable, optical fiber or microwave radio links are expensive options for unplanned emerging market case. We consider leveraging macro LTE networks to backhaul High Speed Packet Access femtocells, thereby highlight the possibilities for cost-effective capacity upgrades of dense settlements.

Keywords self-organization, synchronization, interference, component carrier, handover, data forwarding, backhaul, heterogeneous network, femtocell, LTE, LTE-Advanced

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Dedicated to Amee

Preface

This dissertation represents the culmination of work and learnings gained, during four years from 2010 to 2014 at Nokia Devices R&D, Renesas Mobile (now part of Broadcom Corporation), Department of Communications and Networking and Data Communication Software Lab at Aalto University.

I owe my deepest gratitude to my supervisor, Prof Jukka K. Nurminen and Prof Antti Ylä-Jääski, for guiding me forward towards the PhD completion. Both of them were always there to support me in every possible ways towards the completion of this thesis. I would also like to thank Prof Olav Tirkkonen and Tero Henttonen, who actively guided me during my work at Nokia Devices R&D and later at Renesas Mobile.

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Thanks to all of my friends Nalin Gupta, Sachin Gaur, Anupam Arohi, Nilay Oza and Parag Thakore for being there with me on several occasions and making my life better.

Thanks to my mom and dad, who instilled the attitude of learning more and more in me and also cultivating the thoughts of believing in myself and being independent. Thanks to my grand-parents for caring for me and whose presence was fulfilling. I am also thankful to my parent-in-laws, who has shown confidence in me and made the journey towards PhD smooth. Last, but most importantly I would like to thank my beautiful wife Amee and cute little daughter Nyssa for inspiring me from the start of the PhD until the end. Thanks for dragging my mind out of thesis work when times have been tough! Amee, you were the greatest motivator, facilitator, and provider of comfort for me to finally get this work to an end. The extent of your endless patience, support, and understanding has been almost incomprehensible to me. I am also sorry for not being with both of you on several occasions, during the long working hours to make the completion of the PhD possible.

Helsinki, July 4, 2014,

Parth Amin

Contents

List of Publications and Author's Contribution

This thesis consists of an overview of the following original publications which are referred to in the text by their Roman numerals.

I Parth Amin; Olav Tirkkonen, "Network listening based synchronization techniques for femtocell systems," in *IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Toronto, Canada, 11-14 Sept, 2011, pp.1–5.

II Parth Amin; Vishnu Prasad Kaushik Ganesan; Olav Tirkkonen, "Bridging Interference Barriers in Self-Organized Synchronization," in *Self-Adaptive and Self-Organizing Systems (SASO), 2012 IEEE Sixth International Conference on*, Lyon, France, 10-14 Sept, 2012, pp.109–118.

III Parth Amin; Olav Tirkkonen; Tero Henttonen; Esa Pernila, "Primary component carrier selection for a heterogeneous network: A comparison of Selfish, Altruistic and Symmetric Strategies," in *IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, Paris, France, April 2012, pp.115–119.

IV Parth Amin; Olav Tirkkonen; Tero Henttonen; Esa Pernila, "Dynamic Frequency Selection based on Carrier Pricing between Cells," in *IEEE 77th Vehicular Technology Conference (VTC Spring)*, Dresden, Germany, 2-5 June, 2013, pp.1–5.

V Parth Amin; Antti Ylä-Jääski, "Improved handover mechanisms to reduce packet forwarding in LTE-Advanced," in *IEEE 9th International Wireless Communications and Mobile Computing Conference (IWCMC)*, Cagliari, Italy, 1-5 July, 2013, pp.831–836.

VI Parth Amin; Nadew Sikuwaru; Edward Mutafungwa; Beneyam B. Haile, Jyri Hämäläinen, Jukka K. Nurminen, “Performance Study for Off-Grid Self-Backhauled Small Cells in Dense Informal Settlements," in *IEEE 25nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Washington, USA, 2-5 Sept, 2014, pp.1–6 (accepted for publication).

The author of this thesis had the main responsibility for Publications [II, III, IV, V], where the author actively participated in planning and analyzing the research ideas, generating the simulation results, and writing the papers. In Publication I, the author participated in writing the paper along with the second author. In Publication VI, the author participated in planning and analyzing the research ideas and writing the paper along with the third author.

List of Abbreviations

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
BIM	Background Interference Matrices
BS	Base Station
BSs	Base Stations
COMP	Coordinated multi-point transmission
CSG	Closed Subscriber Group
DFS	Dynamic Frequency Selection
eICIC	Enhanced intercell interference coordination
GPS	Global Positioning System
HetNet	Heterogeneous Networks
HSPA	High Speed Packet Access
IEEE	The Institute of Electrical and Electronics Engineers
LTE	Long Term Evolution
MAC	Medium Access Control
PCC	Primary Component Carrier
PDCP	Packet Data Convergence Protocol
QOS	Quality of Service
RLC	Radio Link Control
SCC	Secondary Component Carrier
SDU	Service Data Units
SINR	Signal-to-Interference-plus-Noise Ratio
SON	Self-Organized Network
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
UE	User Equipment

UEs	User Equipments
UDP	User Datagram Protocol
WCDMA	Wide-Band Code Division Multiple Access

1. Introduction

1.1 Motivation

Driven by a new generation of wireless user equipment (UE) and the proliferation of bandwidth-intensive applications, user data traffic and the corresponding network load are increasing in an exponential manner. This has been possible by complementary improvements in both radio access networks and mobile backhaul. Moreover, traditional centrally managed wireless network are re-designed to be self-organized by giving more control to the base station (BS) [1].

Most of the new data traffic is being generated indoors, which requires increased link budget and coverage extension to provide satisfactory user experience. As a result, current cellular networks are reaching their breaking point, and conventional cellular architectures that are devised to cater to large coverage areas and optimized for homogeneous traffic are facing unprecedented challenges to meet these user demands. In this context, there has been an increasing interest to deploy relays, distributed antennas, and small cellular access points (such as picocells and femtocells) in residential homes, subways, and offices. These network architectures, which may be either operator-deployed and/or consumer-deployed, and are comprised of a mix of low power cells underlying the macrocell network, are commonly referred to as heterogeneous networks (HetNets). By deploying additional network nodes within the local-area and bringing the network closer to end-users, HetNets can potentially improve capacity and coverage, thus allowing future cellular systems to achieve higher data rates, while retaining the seamless connectivity and mobility of cellular networks. Inspired by the attractive features and potential advantages of HetNets, their development and deployment is well researched in the wireless industry and research communities during the last few years. It has also attracted the attention of standardization bodies, such as Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) and The Institute of Electrical and Electronics Engineers (IEEE) 802.16 Wireless Metropolitan Area Networks. Moreover, network densification is the dominant theme for wireless evolution into fifth generation (5G) of mobile networks. However, HetNets also come with their own challenges, and there are significant technical issues that still need to be addressed for successful roll-out and operation of these networks. Research areas in HetNet include spectrum allocation for macro and small cell deployment, interference analysis, alignment, avoidance, and coordination, restricted access versus open-access femtocells/picocells, power control mechanisms, mobility, load balancing, carrier aggregation and selection, joint transmissions, time synchronization, self-organization and backhaul dimensioning [2–9].

Dense HetNet deployment results to interference among BSs and connected users both in downlink and uplink. BSs transmit synchronization signals on the same channel as the actual payload transmissions. Interference prevents the indoor BSs from achieving time synchronization, which is trying to synchronize to the neighboring BS over the air. Moreover, interference from the neighboring BS may adversely affect the cell-edge UE throughput, which is connected to the distant BS. This calls for the maintenance of radio resources among BSs to prevent interference and achieve time synchronization and improved cell-edge UE throughput.

Network densification may result to enhancement in the data throughput between the base stations (BSs) and mobile devices. But in order to translate this into enhanced user experience, the BSs need to to be connected to the core network and to one another through high-capacity, low-latency backhaul. Mobile backhaul is a link connecting radio access network with the core network, using microwave, copper or fiber access. To address the new challenges operators face as they transition to LTE, mobile backhaul is being upgraded from circuit-switched legacy backhaul networks towards packet-based networks to deliver more capacity and coverage into the mobile network. Research is ongoing to further evolve the backhaul to support the 5G wireless system, based on Cloud-RAN architecture and wireless backhaul technologies. User data is forwarded over mobile backhaul across BSs to support user mobility during handover [1, 10–12]. This calls for optimization of data forwarding algorithms to efficiently utilize the backhaul links connecting the two BSs.

Self-organization and self-adaptation phenomena is well studied in fields of network science and complex systems [13]. With the rapid growth of mobile communications, deployment and maintenance of cellular mobile networks are becoming more and more complex, time consuming, and expensive. In order to meet the requirements of network operators, the telecommunication industry and international standardization bodies have recently paid intensive attention to the research and development of self-organized network (SON). This has resulted to the re-design of the network from centralized control to more independent and self-organized. SON is expected to give cost savings and performance benefits during the network deployment. Example use-cases of SON includes handover optimization, physical cell-id assignment, load balancing, interference coordination, energy savings [7, 14–17].

1.2 Research Questions and Scope

In this thesis we focus on three research areas concerning cellular networks: reducing interference, improving handover mechanism and providing backhaul for small cells. Small cells are low-power base stations such as relays, picocells and femtocells in LTE-Advanced terminology. In our context, we refer to small cells as femtocells, which are deployed indoors inside the home/enterprise building. Throughout, the thesis, we use the terms small cells, femtocells and home BSs interchangeably. Scope of the thesis is limited to answer the following research questions:

1. How a BS achieves phase synchronization over the air in a dense indoor small cell network by reducing interference from the neighboring BSs? Phase synchronization is well studied in the field of wireless sensor network, but not much is known in context of achieving phase synchronization across interference-limited wireless network, where interference limits the spread of timing across the network. Phase synchronization for wireless network is important for LTE which supports time division duplexing (TDD) operation, coordinated multi-point transmission (COMP) and also for the future 5G network.

2. How a BS selects component carriers out of the possible multiple component carriers in a dense small cell network with closed sub-

scriber group (CSG) femtocells and thereby reduce interference on its cell-edge users? CSG is a limited set of users with connectivity access to a femtocell. LTE-Advanced supports multiple component carrier transmission along with HetNet deployment, which generates the need of selecting part of the available spectrum (i.e component carriers), so that interference among macro BS and CSG femtocell and across CSG femtocells is minimal.

3. How to reduce data forwarding across BSs during handover over the backhaul? Efficient data forwarding plays an important role to cater for the user's quality of service (QOS) and Transmission Control Protocol (TCP) throughput requirements during handover and also reduces load on the link connecting the two BSs.
4. How to provide backhaul for small cells in the emerging markets, where the copper or fiber based backhaul does not exist? Network densification through customer-deployed small cells is an attractive model for emerging markets, both to operators and users. For operators, customer-deployed small cells is attractive financially, as it does not need to invest in network densification by deploying more macro BSs. Moreover, for customers, small cells provide better capacity and coverage compared to the distant macro BS. Emerging markets like Africa and Asia lacks the copper or fiber deployment, which makes providing backhaul for customer-deployed small cell challenging.

1.3 Scientific Methodology

The following steps provide a high-level overview of the scientific methodology used in this thesis.

- Literature review, brainstorming and problem delineation.
    - Research and development of practical solutions aiming at exploiting the nature of the problem being tackled as well as addressing issues not solved by prior art.
    - Analytical modeling whenever possible followed by qualitative analysis of the expected results.
    - Modeling, software implementation, testing and quantitative

evaluation of the solutions/algorithms via system level simulations.

- Dissemination of knowledge through conference papers or internal deliverables.

1.4 Contributions of the Thesis

Thesis is a summary of the six publications, of which publications I, II, III and IV are related to radio resource management to reduce interference and publications V and VI are related to backhaul optimization. The contributions of these publications are briefly described below:

- Publication I proposes algorithms to achieve network-wide phase synchronization, where either UE helps in the synchronization or transmitters coordinate their transmissions to reduce interference from synchronous BSs. Network synchronization is significantly improved with macro diversity algorithm, in which all synchronized BSs transmit the same synchronization sequence in a synchronous manner.
- Publication II extends Publication I by achieving network synchronization in a completely self-organized manner and also proposes algorithms to reduce interference from both synchronous and non-synchronous BSs. Interference within dense wireless network divides the network into multiple connected components. We propose algorithms to coordinate the synchronization transmission and reception strategies within connected components, so that connected components grow by bridging interference barriers and thereby improve the network connectivity. We further propose conflict resolution algorithm to cope with conflicts arising due to finite ID space.
- Publication III studies a distributed approach for Primary Component Carrier (PCC) selection to manage interference and to improve cell edge performance in HetNet with overlaid macro BS and densely deployed indoor CSG femtocells. We propose that PCC selection based on path loss between neighboring BSs will not work in HetNet, which is widely used for traditional homogeneous network. PCC has to be reselected based on handover measurements performed by UEs. We propose three strategies of PCC reselection; a Selfish,

Altruistic and Symmetric approach. PCC reselection based on UE measurements completely removes outage and improves cell edge performance.

- Publication IV proposes distributed utility-based algorithm called dynamic frequency selection (DFS) for downlink component carrier allocation in multi-carrier system. BS adds a new component carrier, if the expected utility gain of adding the component carrier is greater than sum of the utility losses reported by each neighbor BSs using the same component carrier. On the contrary, BS removes a component carrier, if the expected utility loss of removing the component carrier is lower than the sum of the utility gains reported by each neighbor BS using the same component carrier. Proposed algorithm aims to reduce interference and thereby maximize the sum utility of the whole system. We consider four different utility functions: mean-rate, weighted fair-rate, proportional fair-rate and max-min.
- Publication V analyses, evaluates and improves the packet forwarding handover mechanism by reducing the amount of forwarded data between BSs. The Packet Data Convergence Protocol (PDCP) of the source BS is responsible for forwarding the data packets to the target BS. The performance criteria considered for evaluating these techniques include the PDCP buffer size at the source BS, the uplink Radio Link Control (RLC) status load and the user object bit rate. We found frequent UE polling by the packet network during handover helps in considerably reducing the unacknowledged PDCP data packets, and thereby reduces the amount of packet forwarding data, as the source BS has upto-date information of the UE reception state.
- Publication VI considers leveraging macro LTE networks to backhaul High Speed Packet Access (HSPA) small cells in the dense informal settlements. As a case study, we present comparative network simulation study based on an example informal settlement. The results of a study highlight the possibilities for cost-effective capacity upgrades dense settlements for even a limited number of unplanned end-user small deployments and self-backhauling via existing macro sites. In the study we also note possible system performance improvements by enhancing the small cell backhaul link through improved antenna design, scaling of carrier bandwidth and

introduction of traffic steering across HSPA and LTE layers.

1.5 Structure of the Thesis

Chapters II and III are related to self-organized radio resource management to manage interference and Chapter IV is related to backhaul optimization. Chapter II discusses contributions from publications I and II, which help in achieving phase synchronization for the dense small cell network by reducing interference across connected components. Chapter III discusses algorithms from publication III and IV to select the component carriers in a multi-carrier LTE-Advanced system and thereby reduce interference in the dense small cell environment. Chapter IV discusses the contributions to improve handover over the backhaul and solutions to provide backhaul for the small cells deployed in the emerging markets, as discussed in publication V and VI respectively. The original papers are presented after conclusions in Chapter V.

2. Achieving Network-Wide Phase Synchronization by Reducing Interference

This chapter discusses the prior art and contributions in publications I-II, which are related to techniques aiding network-wide phase synchronization in an interference limited cellular network. In cellular network, BSs transmit both synchronization pulses and actual payload to its own UEs on the same channel. UE uses synchronization pulses transmitted by BS to determines time and frequency parameters that are necessary to demodulate downlink signals, to transmit with correct timing and to acquire some critical system parameters. Moreover, BS may achieve phase synchronization by listening to the neighboring BSs synchronization sequences over the air. Simultaneous transmissions by the BSs in the dense network do cause interference in the network, resulting to a challenge of achieving network synchronization, while a BS is trying to synchronize with the neighboring BS over the air. The contributions consist of algorithms to reduce interference among BSs having overlapping synchronization pulse and payload transmissions, and thereby achieve better time synchronization in a wireless system.

2.1 Introduction

2.1.1 Types of Network Synchronization

Network synchronization deals with the distribution of time and frequency across a network of clocks often spread over a wide geographical area. The goal is to align the time and frequency scales of all clocks, by using the communication capacity of their interconnecting links. Network synchronization plays a central role in digital telecommunications as it determines the quality of most services offered by the network operator. However, the importance of network synchronization is often underestimated

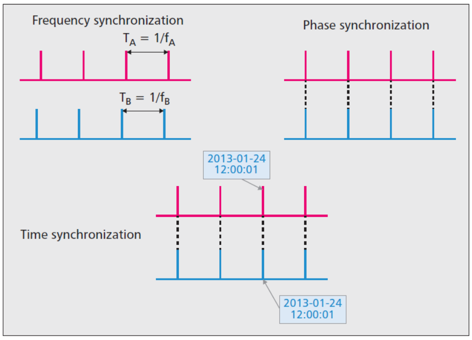

Figure 2.1. Types of Network Synchronization [19]

and how to solve QOS degradation caused by synchronization difficulties can become problematical to all but a synchronization engineer [18]. Different types of synchronization exist — frequency synchronization, time synchronization and phase synchronization, as depicted in the Figure 2.1.

Frequency Synchronization

Two BSs are frequency synchronized when their transmissions are controlled by reference timing signals with their corresponding significant instants occurring at nominally the same rate. Frequency synchronization is required by all mobile systems, in order to minimize disturbance and facilitate handover between BSs. In order to fulfill regulatory requirements, the radio signal must be generated in strict compliance with frequency accuracy requirements [20].

Time Synchronization

Time synchronization in the network requires the BSs to share the same clock reference. Recent migration of the telecom networks from time division multiplexing (TDM) to packet based technologies (e.g. LTE) has required the industry to define new methodologies for distributing accurate timing reference across the network towards the radio BS. Time synchronization is an essential problem in networking, which has commanded much attention in the research community [21–38].

Phase Synchronization

Phase synchronicity is a milder form of synchronicity than strict time synchronicity— where all BSs have access to a reference timing signal whose rising edges occur at the same instant [21, 22, 26–28, 30, 32–41]. If there is time synchronicity, phase synchronicity automatically follows, whereas to get time synchronicity from phase synchronicity, one needs to agree of a global count of events.

2.1.2 Need of Phase Synchronization

Phase synchronization is required in the case of TDD wireless systems because uplink and downlink transmissions use the same frequency bands but different time slots. In order to avoid interference between adjacent cells, BSs need to be phase aligned. In particular, when LTE is based on TDD, the timing between base stations must be accurate to within 3 μs (for cells of equal or less than 3 km radius) and 10 μs (for cells of more than 3 km radius) [42–47]. For wireless networks, phase synchronicity may be desirable for multiple reasons related to Medium Access Control (MAC) or Radio Resource Management. Examples discussed in the literature are duty-cycle and MAC optimization for sensor networks [24–29,31,34], interference reduction in Time-division Multiple Access or TDD systems [22,36], or distributed sensing and other cooperative network actions [30,33,37].

The main motivation of the research comes from future cellular networking, where small cell wireless networks are foreseen to complement traditional macro cellular networks. The introduction of new LTE-Advanced features, often related to small cell deployments, may now introduce new requirements for distributing both time and phase synchronization to BSs. Achieving phase synchronization will play an important role delivering the promise made by such future HetNets, where synchronization will be beneficial for TDD operation, efficient performance of COMP, inter-cell interference cancellation and management techniques, relaying, positioning and mobility operations. Enhanced intercell interference coordination (eICIC) and coordinated scheduling requires the time/phase accuracy of 1 μs and 1.5 μs respectively [19,48]. With the upcoming 5G small cells, the time/phase accuracy is further reduced to 510 ns [49,50].

2.1.3 Techniques to Achieve Phase Synchronization for Small Cells

Small cells can achieve phase synchronization using following techniques [51].

1. The Global Positioning System (GPS) - If a small cell contains a GPS receiver and can acquire the GPS synchronization signals, then GPS provides the most accurate synchronization accuracy (on the order

of 100 ns). However, GPS receivers do not always work in some important scenarios (e.g. indoors.)

2. IEEE 1588 v2. - Under good backhaul conditions (e.g. operator controlled fiber / Ethernet), IEEE 1588 v2 can provide sub-microsecond level accuracy. However, such good backhaul conditions may not always be possible. In particular backhaul over cable and DSL modems have significant jitter and delay variations. This resulting error may be up to many milliseconds, rendering IEEE 1588v2 not well-suited for the applications of LTE-Advanced and future cellular technologies.
3. Network Listening - is a distributed synchronization technique where a BS is synchronized directly with another BS over-the-air, based on BS-BS measurements. Network listening can be used in scenarios where GPS and IEEE 1588 v2 do not work. For this reason, network listening is an essential synchronization scheme for 5G small cells, which does not need centralized coordination [49].

2.1.4 Interference Preventing Network Listening to Achieve Network-Wide Phase Synchronization

There are two ways to achieve network listening based synchronization – either using external clock or without using external clock. BSs in a cellular network may use the external clock from e.g., GPS, IEEE 1588 v2 or synchronization to a wide area umbrella BS. In [24, 25, 29, 31], wireless networks are synchronized by generating a spanning tree rooted at a node with an external timing reference. On the contrary, BSs may synchronize with the neighbor nodes by listening to each other, without external clocks, as addressed in [21, 22, 26–28, 32–38]. In publication I, we assume one node per building is synchronized to an external clock and the remaining nodes self-synchronize themselves using spanning tree based network listening technique. On the contrary, in publication II, we consider self-organized spanning tree synchronization problem, where no external source of timing exists, and where the network nodes synchronize based on listening to transmissions from each other forming independent spanning trees.

In modern cellular systems, such as LTE [52], synchronization between infrastructure BS and UEs is based on periodic transmissions of known synchronization sequences using the same radio resources that are used

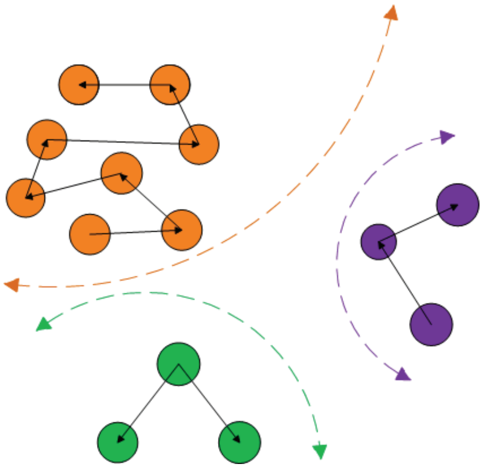

Figure 2.2. Network divided into three connected components which are separated by SINR-barriers[extracted from Publication II]

for data transmissions. When synchronizing a network of BSs, it is natural to use the same, or similar synchronization channels. Thereby, reserving a specific channel just for network synchronization would be wasteful. As a consequence, synchronization based on listening to other nodes would suffer from interference [51].

Both synchronous and non-synchronous BSs would disturb a non-synchronous BS trying to synchronize with another BS. From this it follows that interference often prevents the whole network from synchronizing - the network is divided into multiple connected components, as depicted in the Figure 2.2 so that no BS in one component is able to hear any BS in another. Within a connected component, self-organizing synchronization would be possible, but between these components, there would be interference barriers preventing synchronization. Further we discuss the prior art and our contributions to reduce interference across connected components to achieve the complete network synchronization.

2.2 Related Work and State of the Art to Improve Network Listening

In Network Listening, a BS maintains synchronization only with a single neighbor, as explained in [53]. In [54,55], algorithm is proposed to get synchronization from multiple neighbors and thereby improve network listening synchronization. UE assisted synchronization was proposed in our publication I, which was also presented latter in [56], where distributed clock synchronization scheme employs the clock drift ratio (CDR) information available at UEs to achieve synchronization between the two non-synchronized BSs.

Little is known in the literature regarding methods to spread synchronization within a connected component and also across components. Connected components do have barriers of interference caused by usage of the radio resources not only for transmitting synchronization pulses by also for transmitting the actual payload. In [30], it was suggested that nodes should transmit with higher power with a specific pattern, which would increase the Signal-to-Interference-plus-Noise Ratio (SINR) of synchronization signals when heard by nodes on the other side of interference barriers. This solution would be wasteful in the sense that power amplifiers, the most expensive analog components of a radio, would have to be dimensioned for synchronization purposes only. Moreover, such a network would be energy inefficient consuming more energy due to high power transmissions of the synchronization signals.

2.3 Simulation Scenario

In both publications, we assume distant dependent pathloss and each BS continuously transmits payload data and synchronization pulses, which causes interference to neighboring BSs.

Various femtocell network deployments exist which includes pico-cell networks, hot spots, office networks, Home BSs, relay networks, etc. In publication I, we have considered a modern office building with multiple floors, large offices and corridors, as well as an atrium with glass inner walls and without floors, as depicted in the Figure 2.3. The motivation for investigating an office building with an atrium is that such a building design will cause heavier inter-BS interference, providing a more challenging environment for the self-organizing network studies, than a building without an atrium. UEs are also are dropped in an office building. The UEs select the serving BS based on the best SINR, and also measure neighboring BSs. We assume that one of the randomly selected BS is synchronized with the external clock and the remaining BSs try to synchronize using spanning tree approach.

In publication II, we simplify the simulation scenario by dropping BSs in a unit square. We further achieve synchronization in a distributed manner, without any external clock reference, where each BS tries to syn-

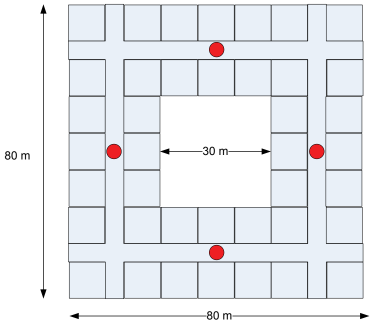

Figure 2.3. One floor layout of the office building in the Atrium building path loss model. Red dots represent BSs.[extracted from Publication I]

chronize with its neighboring BSs.

2.4 UE Assisted Network Synchronization

In cellular network for e.g. dense network deployment, a BS is able to listen and thereby synchronize with limited number of neighbor BSs, due to lower SINR of the synchronization pulse transmissions from neighbors. We propose UE assisted synchronization in publication I, where, in addition to direct BS-BS measurements, UEs attached to a BS, help with listening to the synchronization signals of neighboring BSs. UE assistance in synchronization does result to significant improvement in the network connectivity and thereby time synchronization within the network. The UEs report differences in cell timing of the neighboring BSs to the serving BS and thereby enhance the number of connected neighbors per BS. Neighbor cell timing measurement comes at a cost for the UE, with the increased idle state power consumption and implementation complexity. Network listening synchronization with UE assistance has higher number of neighbors per BS compared to network listening synchronization without UE assistance. In other words, network listening synchronization with UE assistance provides better network connectivity and increases the network synchronization with the limitation of additional UE power consumption.

2.5 Coordinated Transmission Strategies

Part of BSs, which are synchronized among each other coordinate to transmit the synchronization pulses to avoid interference. We propose three coordinated transmission algorithms in publication I to reduce interference and achieve network synchronization, which includes: Stratified, Fully Orthogonal and Macro Diversity based synchronization, as depicted in the Figure 2.4. In Stratified synchronization interference come from only the stratum (i.e. layer in a spanning tree) transmitting the synchronization signals and not from rest of the synchronized strata. In this technique, interference is reduced using silencing periods among the synchronized BSs. In Fully Orthogonal synchronization, BSs use orthogonal sub-carrier signals to transmit synchronization pulses and thereby avoid interference. Thereby, there is no interference from any of the synchronized strata, which is also an additional advantage in comparison to Stratified synchronization. Macro Diversity based synchronization is a mechanism to increase the power of synchronization signals and thereby reduce interference. Moreover, this technique does not suffer from the limitation of requiring orthogonal codes. All synchronized BSs transmit the same synchronization sequence in a synchronous manner. A non-synchronized BS receives the signal with the signal powers added over the air, and thus enjoys a macro diversity advantage from all synchronized BSs transmit power. Interference comes from all other non-synchronized BSs. The received signal power is the sum of the received signal powers from all synchronized BSs. The proposed coordinated transmission techniques reduce the interference and thereby achieve better network synchronization. Of the proposed techniques, Macro diversity based synchronization performs much better than Stratified and Fully Orthogonal Synchronization. Macro diversity transmissions are capable of bridging the gaps between connected components significantly better than the single-BS transmission.

2.6 Coordinated Reception Strategies

We propose coordinated reception algorithms in publication II and also compare them with the coordinated transmission algorithms proposed in publication I. Moreover, we also combine the coordinated reception algorithms with the coordinated transmission algorithms. Lastly, we make

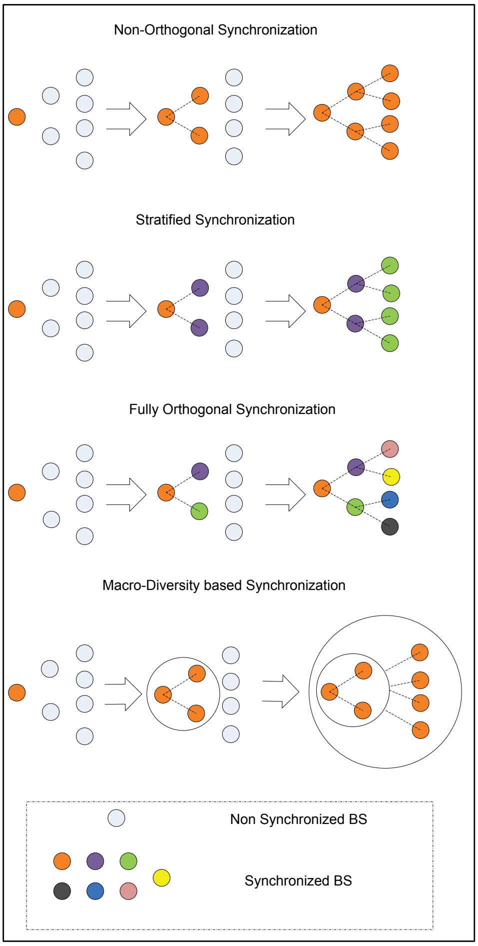

Figure 2.4. Proposed Coordinated Transmission Algorithms to Improve Network Listening Synchronization; Different Colors Represent Orthogonal Synchronization Channels[extracted from Publication I]

coordinated transmission and reception self-organizing. For this, we follow a common practice in distributed algorithms [57, 58], by using identifiers (IDs) to break symmetry, which in this case is related to the direction of growth of colliding synchronized connected components of the network. We provide a conflict resolution algorithm which is capable of dealing with a finite ID space. We observed that coordinated reception bridges interference barriers better than coordinated transmission, because coordinating reception within a connected component removes interference from closer sources. The simulations show that the discussed self-organizing algorithm is able to significantly improve network connectivity in an interference limited situation. Combining macro diversity transmissions with coordinated reception provides the best performance.

2.7 Open Questions

In our research we deal with the problem of achieving initial phase synchronization for a dense femtocell network i.e. how the clocks within each BSs be phase synchronized among each other by crossing the interference barriers. We do not deal with the problem of runtime synchronization within a network i.e. how to keep time alignment between BSs despite of the different clock functions resulting to clock drifts. Moreover, propagation delays of the synchronization pulses due to the distance between the BSs is also not considered. We analyzed the performance of the UE assisted synchronization using static UEs. Related research topic is about studying the impacts of mobility of the UE along with propagation delays towards UE on the performance of UE assisted synchronization. The proposed synchronization algorithms were simulated using system level simulations. It would be worth simulating the algorithms on the software defined radio testbed and also latter on the actual live network and test the performance of the algorithms, considering initial phase synchronization, runtime synchronization and propagation delays.

3. Dynamic Carrier Selection to Reduce Interference on Cell-Edge Users

This chapter discusses the prior art and contributions in publications III-IV, related to managing interference in heterogeneous network with dense small cells deployment, by distributed carrier selection, based on UE measurement reports of the serving and neighboring BSs, to avoid interference in a multi-carrier system.

3.1 Introduction

Frequency reuse is the traditional way of sharing the spectrum in cellular networks. A basic hard frequency reuse scheme assigns to each cell a fraction 1/N of the whole spectrum, which usually differs from the assignment of neighboring cells. As a result, the UE experienced Signal to Noise ratio $SINR$ is increased, but at the cost of reduction of the available spectrum per cell. Shannon's formula defines the capacity of the wireless system and is a function of both $SINR$ and amount of spectrum used for transmission [59] as

$$C = BW * \log_2(1 + SINR), \tag{3.1}$$

where C is the channel capacity in bits/sec, BW is the bandwidth of the channel in hertz and $SINR$ is the Signal to Noise ratio of the channel expressed as a linear power ratio.

Frequency reuse may work well with homogeneous network, where interference coupling among neighboring BSs may be symmetrical i.e. interference what one macro BS cause to its neighbor may be nearly same as the interference neighbor causing on the prior macro BS. Interference coupling may become asymmetrical in heterogeneous network, with dense small cells overlaid by macro BS. Interference caused by CSG small cell on macro BS may be higher than what macro BS causes on CSG cell, in

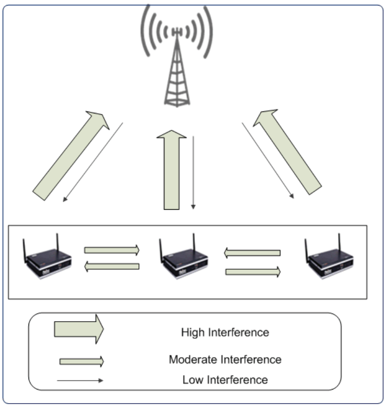

Figure 3.1. Multiple femto BSs causing high interference to indoor macro UEs and also interfering among each other[extracted from Publication III]

a scenario, where macro UE is close to the CSG femto, where it is unable to connect. Moreover, in a dense small cell deployment, interference among CSG femtocells is also significant. In other words, three types of downlink interferences are possible in HetNet scenario with macro BS and dense CSG femtocells which includes:

1. CSG femto causing interference to the nearby macro UE, which is connected to the macro BS.
2. CSG femto causing interference to the nearby femto UE, which is connected to the neighboring femto BS.
3. Macro BS causing interference to the femto UE.

Figure 3.1 depicts the typical case of interference, when macro UEs are located indoors along with dense femto CSG UEs, resulting to two major types of interferences which includes femto CSG interference to macro BS and interference among CSG femto BS. Interference among BSs can be reduced using Inter-cell interference coordination (ICIC) approaches namely: Time domain, Frequency domain and power control techniques [60–76]. In our research, we focus on two major downlink HetNet interference avoidance using frequency domain techniques, which includes CSG femto to macro interference and interference among CSG femto BSs.

The introduction of small cells to complement traditional macro site installations raises the question on spectral efficiency of introducing small cells having minimal impacts on the existing macro UEs and also requires careful consideration of femto to femto interference. Carrier aggregation is introduced in LTE-Advanced to support high data-rate transmissions over wide frequency bandwidths with multiple component carriers. This leads to the problem of component carrier selection - a BS may operate on any subset of the component carriers. Each BS may select one component carrier as a primary component carrier (PCC), which provides complete cell coverage. A BS may further select secondary component carriers (SCCs) depending on the offered traffic and interference couplings with the surrounding cells [77, 78]. In our research we focus on the problem of selecting component carriers (i.e. PCC and SCCs) by each BSs in a distributed manner, in such a way that interference from CSG femto BS to macro BS and among CSG femto BSs is minimum.

3.2 Related Work and State of the Art

In [79], authors propose component carrier selection algorithm for uplink. Related packet scheduling work is done in [80, 81], where power control is applied across carriers. [82–86] proposes carrier selection algorithms along with power control on the component carriers (in this case sub-bands). In [87], component carriers are further divided into sub-bands and primary sub-bands are allocated in a centralized manner, whereas secondary sub-bands are allocated in a distributed manner by each BSs. [88] applies the concept of component carrier selection in the spectrum sharing by the operator. In [89], authors propose dynamic algorithm to protect the downlink control signals in LTE-Advanced system with dense wireless networks.

The carrier selection problem in LTE-Advanced is studied independently and not combined with packet schedulers in [90–95]. The studied problem is directly related to the well studied frequency assignment problem [96–98], where a carrier is either used or not used. In [90,91,93,96,97,99], BSs avoid interference from neighbors by selecting carrier based on pathloss. In other words, each BS aims to reduce interference from other BSs by selecting a carrier, on which the closest other BS operating on this carrier is furthest away. Such PCC selection suffers from couple of problems. One of the problem is the requirement for a BS to stop transmissions in downlink, when it is measuring path loss from the neighboring BSs in a frequency division duplexing (FDD) system. Pathloss is the path attenuation or the reduction in power density of an electromagnetic wave as it propagates through space. In addition, BS-BS path loss does not reflect the actual radio conditions experienced by connected UEs. Thereby, in HetNet, PCC selection based on inter-BS path loss may result to outage for macro UEs, located close to the CSG femto BS, due to high interference from the CSG femto BS.

Autonomous component carrier selection (ACCS) is a distributed carrier selection technique proposed in [90–92], where BSs exchange background interference matrices (BIM) (i.e. worst interference couplings) with neighboring BSs. The BIM entries stored in a BS per each neighbors represent the amount of interference neighbors cause on the UEs of the serving BS. A primary carrier is selected based on the maximum path loss to the neighboring BS using the same carrier [90, 91, 93, 96, 97, 99], which may result to outage of macro UEs close to the CSG femto BSs in HeNet. Secondary carriers are selected based on BIMs exchanged with neighbors, based on the UEs measurement reports of the serving and neighboring BSs. The performance of cell edge UEs in the serving and neighboring cells are maintained by applying protection thresholds on PCC and SCCs in the system.

In [95], a BS adds a carrier, calculates the corresponding capacity gain on its served user equipments (UEs) and receives the capacity loss from the neighbors. If the capacity gain of its served UEs is greater than sum of the capacity losses of the neighbors, then the carrier is kept, else the carrier is dropped. The limitation of the approach is it may result to many unnecessary carrier re-selections in the network.

3.3 Simulation Scenario

In both publications III and IV, we consider the 3GPP dual strip dense urban scenario with densely deployed femtocells in buildings as depicted in the Figure 3.2, which cause high interference to the neighboring BSs. Path loss and channel models are based on typical urban deployment as defined in 3GPP [100]. In publication III, along with dense femtocell deployment, we also consider overlaid macro BS to generate asymmetric pathloss coupling across macro and CSG femto BSs. Macro UEs are dropped randomly inside the building. Closed access of femto BSs cause a challenging interference on indoor macro UEs, resulting in degraded user experience and potentially cell outage.

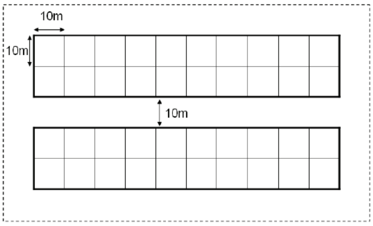

Figure 3.2. 3GPP dual strip dense urban scenario[extracted from Publication IV]

3.4 Carrier Selection Based on Handover Measurements and not Pathloss

In publication III, we study a distributed approach for PCC selection to manage interference and to improve cell edge performance in HetNet. PCC selection based on path loss between base stations causes cell outage in HetNet, when macro users are close to femto base stations, which use a CSG configuration. To avoid cell outage caused by PCC selection based on path loss between neighboring BSs, we argue that carrier reselection based on handover measurements performed by UEs is necessary. Each UEs reports the signal strength of the serving BSs and strength of the interference of the neighboring BSs to the served BS. Based on the number of such UE measurement reports, BS can identify both the cell edge UEs and also the neighbor BSs, which cause the most interference to its own UEs. These values are shared by the serving BS with neighboring BSs. Once each of BSs exchange the interference values with its neighbors and also the component carriers presently in use, each BS can independently reselect the component carrier.

System performance is analyzed based on proposed three strategies of PCC reselection: a Selfish, Altruistic and Symmetric approach, based on avoiding interference caused by neighboring cells, avoiding causing interference to neighbors, and avoiding both, respectively. In Selfish algorithm, each BSs selects the carriers in such a way that they minimize the incoming interference from the neighbors. In Altruistic algorithm, each BSs selects the carriers in such a way that they attempts to minimize the outgoing interference to the neighbors. Moreover, Symmetric algorithm attempts to combine the advantages of both Selfish and Altruistic algorithm, by minimizing the sum of the incoming and outgoing interference in the system. The performance of the proposed strategies are compared with existing PCC selection based on path loss between BSs, in a HetNet scenario, where multiple CSG femto BSs cause high interference to users of a single macro BS. The Symmetric PCC reselection algorithm improves cell edge performance considerably in the studied HeNet scenario. Also, the Altruistic strategy works significantly better than the Selfish strategy. All three considered strategies work equally well in a homogeneous network. We conclude that in HetNet, PCC reselection based on UE measurements reduces user outage and improves cell edge performance.

3.5 Carrier Selection by Predicting the Capacity Gain/Loss of Adding/Removing a Component Carrier

In publication IV, we propose a dynamic frequency selection (DFS) algorithm which estimates the capacity gain or capacity loss in the wireless system, while either adding or removing a carrier, based on handover measurements performed by UEs of the serving and neighboring BSs. This information is used by BSs to decide whether to add or remove a carrier in a distributed manner. We avoid carrier re-selections by predicting the capacity differences resulting from potential dropping or adding a carrier at the neighbors. These per-carrier capacity differences are reported to the neighbors as estimated prices, which the neighbors may take into account when deciding their actions. Instead of having a single interference price over the complete bandwidth as in [90–92], we have a price (i.e. capacity gain/loss) per carrier. Component carriers used by each BS along with capacity gain or capacity loss per carrier can be exchanged among neighboring BSs on reselecting a carrier in the form of low-rate control signaling over the X2 interface connecting the two BSs [101].

We consider multiple utility functions to model the degree of satisfaction of the users in the system i.e maximizing the mean rate in the system, weighted fairness, proportional fairness and lastly maximizing the minimum rate in the system. The performance of the DFS algorithm with different utility metrics is analyzed in terms of $SINR$ and throughput of the UEs, the amount of the bandwidth used by the BSs, and network convergence of the algorithm. Performance is compared with universal reuse (where each BSs use the complete bandwith) and autonomous component carrier selection algorithm proposed in [90–92]. Simulation were performed for the dense small cell deployment, but the results of the simulations are also applicable for the HetNet scenario with the overlaid macro cell and dense small cell network deployment. Simulation results show that the proposed algorithm is effective in predicting the capacity gain/loss in the system, and thereby helps in the decision of either to add or remove a carrier in a BS. DFS enhances not only the sum data rate of a system but also the degree of fairness in resource sharing among users. The sum rate of the system is highest with Mean DFS, whereas the cell edge rate of the system is highest with Max-min DFS. Max-min DFS, Weighted fair DFS and proportional fair (PF) DFS improve fairness in the system, by improving the cell edge performance and without impacting the mean performance of the UEs in the system.

3.6 Open Questions

In our research we deal with the problem of lower cell-edge user throughput performance in a multi-carrier LTE-Advanced heterogeneous network. We solve the problem by selecting part of the component carriers out of the available ones and thereby improve the performance of the cell edge users. The problem of cell-edge users outage can also be solved in time domain and power domain by scheduling the users in different time slots and using different powers to transmit to each user. It would be interesting to combine the proposed techniques of component carrier selection along with time domain muting and power control. Moreover, more detailed study is also required to evaluate load on the backhaul, connecting the BSs, due to the information sharing among BSs resulting from the proposed algorithms of component carrier selection. It would be worth simulating the algorithms on the software defined radio testbed and also latter on the actual live network and test the performance of the algorithms to evaluate the trade-off of the cell edge user throughput gain and the load on the backhaul links connecting the BSs.

4. Backhaul Dimensioning in a Cellular System

This chapter discusses the need of backhaul dimensioning, prior art and contributions in publications V-VI, related to reducing amount of forwarded data over the backhaul during handover and using LTE, as a wireless backhaul solution for the HSPA small cells deployed in the emerging markets respectively.

4.1 Introduction

The rapid growth in mobile broadband in recent years is driving operators to improve and densify their Radio Access Network (RAN) and also upgrade and optimize the mobile backhaul. With the ongoing preparation of rolling-out LTE-Advanced, which supports aggregation of the operator's spectrum will generate a need to also upgrade the backhaul capacity many folds. Along with exploiting the capacity road-map that LTE and LTE-Advanced offer at the macro-cellular layer, operators are clear that they will need small cells to complement the macro cells, which further worsens the looming challenge of backhaul capacity. The cost of the backhaul network becomes a main burden of operators, and the requirement of reducing the backhaul cost and optimizing the backhaul is raised in both Third Generation Partnership Project (3GPP) and Next Generation Mobile Networks Alliance (NGMN) [1, 11, 12, 102–104].

In our research, we deal with problem of reducing the data forwarding over the backhaul during the handover and also providing wireless backhaul for small cells deployed in the emerging markets, where the wired backhaul does not exist.

4.2 Improved Handover Mechanisms to Reduce Packet Forwarding Over Backhaul

Handover is one of the key components in cellular network mobility management and has the most stringent latency requirement on service interruption time since the end-user experience is determined by it. In the design of IMT-Advanced systems, the scalability and flexibility to support various fourth generation (4G) network deployments is also very crucial while meeting the latency requirement on handover. In [105], article presents the state-of-the-art handover schemes considering various deployment scenarios in IEEE 802.16m1 based next-generation WiMAX networks and 3GPP LTE-Advanced. Also, to minimize and optimize handover latency to fulfill the requirement for quality of service (QOS) during handover, various procedural advanced handover schemes are being developed, proposed, and analyzed by IEEE 802.16m and 3GPP. Handover schemes in IEEE 802.16m and 3GPP provide lower link layer handover latency while providing the required QOS level than the existing link layer handover schemes.

Packet-switched wireless communication system such as 3GPP LTE does not support soft handover, on the contrary to the predecessor Wide-Band Code Division Multiple Access (WCDMA). Handover procedure being one of the important functionalities of a mobile system is designed according to the distributed nature of the LTE architecture. In LTE, at each handover the user context, including user plane packets and control plane context are relocated from the source BS to the target BS. The Packet Data Convergence Protocol (PDCP) of the source BS is responsible for forwarding the data packets to the target BS. The forwarded data is finally sent to the UE by the target BS on the handover completion. The mechanism for handling the packet forwarding is specified in the 3GPP LTE specification [77, 101, 106], during which all the unacknowledged PDCP Service Data Units (SDUs) are sent from the source BS to the target BS. Message sequence during handover between UE, source BS and target BS is depicted in the Figure 4.1.

Of these forwarded PDCP SDUs, many will be discarded by the target BS, as the UE has already received some of these PDCP SDUs, a fact which could be indicated in a PDCP Status report sent by UE to its target BS. If the PDCP Status report is not sent by the UE, then PDCP SDUs will be sent from the target BS to the UE. The UE may discard these

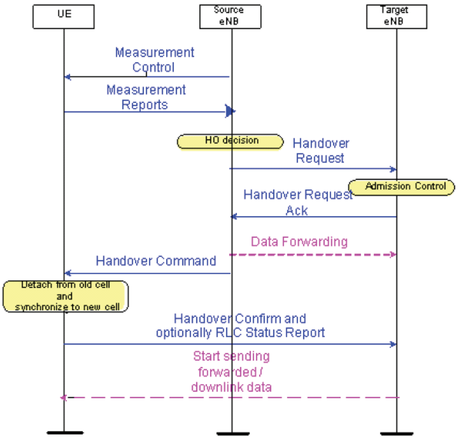

Figure 4.1. Message sequence between UE and BS during Data Forwarding in LTE[extracted from Publication V]

SDUs, if it has already received them from the source BS [107]. In our research, we try to reduce the amount of data forwarded from PDCP of the source BS to the target BS during handover, which improves the QOS of the end user and also reduces the load on the X2 link, which connects the two BSs.

4.2.1 Related Work and State of the Art

Efficient data forwarding plays an important role to cater for the user's QOS and transmission control protocol (TCP) throughput requirements during handover [108, 109]. In [110], the handover prediction algorithm is proposed to improve TCP performance during the LTE handover. Data forwarding is also important during handover across different technologies for e.g. between LTE and WiMAX [111]. In [112], delay injection algorithm is proposed for reducing packet forwarding during LTE. In [113], authors proposes an optimization of the handover mechanism between a BS with a satellite S1 interface and a BS with a standard terrestrial S1 interface. In [114], authors analyze the impact of amount of data to be forwarded and corresponding capacity of X2 interface (which connects the two BSs) on the user's QOS. In [115], authors analyze the performance of TCP and User Datagram Protocol (UDP) during LTE handover. The mobile users experience performance degradation due to the interference between source and target BSs. Moreover, the impact on delay sensitive service such as VoIP is analyzed due to interruption during handover. Authors in [116] investigate the X2 bandwidth requirement to support data forwarding for both control-plane traffic and user-plane traffic during handovers. The X2 bandwidth requirement may potentially increase significantly when groups of UEs perform handover simultaneously across BSs. The QOS during the handover depends on: detach time (during which the UE is not connected to the system); the delay of the forwarded packets and the delay difference between the direct path and the forwarded path.

In [117, 118], authors propose that UE sends Radio Link Control (RLC) status report along with measurement report. Similarly, in [119], authors propose that UE sends PDCP status report along with measurement report. Both of these status reports will enable source BS to have updated information about what UE has received, and thereby forward just the missing data to the target BS. The limitation of both of these techniques is the requirement of supporting inter-layer messages (i.e. between Radio Resource Control and RLC / PDCP), in 3GPP LTE standard, which is not acceptable to the standardization community.

4.2.2 Simulation Scenario

LTE simulator consisting of FTP client/server, TCP/IP, PDCP, RLC and MAC protocol layers is used to test various techniques to improve the data forwarding mechanism. The object bit rate is calculated based on the data rate experienced by a FTP client. The system is modeled for a single user, who performs a FTP download of a 100 MB file, 50 times, while being connected to the BS. Data is forwarded from the source BS to the target BS, during the ongoing handover. We selected the FTP traffic model instead of web browsing, as FTP gives more data to be forwarded during handover.

4.2.3 BS Polling the UE Frequently During Ongoing Handover

In order to reduce the data forwarding during handover, in publication V, we propose the source BS should poll the UE during handover and the polling rate should be based on DL data rate. BS polling rate should be high, if the UE specific downlink data rate is high and on the contrary, the source BS should poll the UE less often, during the lower downlink data rate. The proposed solution tries to decrease the amount of data that is already sent over the air but not yet acknowledged by the UE. Increasing the UE polling frequency allows the source BS to be as up-to-date to the

UE reception state as possible, and thus reduces the data buffer at the PDCP of the source BS. There exists a trade-off between the PDCP data forwarding buffer size in the BS and the uplink RLC status report load. When the source BS polls the UE more often to decrease the PDCP buffer size, the uplink RLC status report load increases. Similarly, when the source BS polls the UE less often, even though the uplink RLC status report load is lower, PDCP buffer size however increases.

Based on the simulation results, the proposed technique proves to be the most efficient in terms of lower PDCP buffer size at the source BS, lower uplink RLC status load and higher user object bit rate. Moreover, the technique does not need any changes in the 3GPP standards. We also recommends the LTE network to optimize value of RLC $pollByte$, which controls the BS polling rate, considering the trade-off between the PDCP data forwarding buffer size in the BS and the uplink RLC status load.

4.3 Self-Backhauled Small Cells in Dense Informal Settlements

Mobile broadband technologies are increasingly the most common, and in most cases, the only economically-feasible means for providing broadband connectivity for the masses in emerging regions, such as, Africa, where the fixed-line penetration has remained virtually flat over the last decade [120]. Typically, the mobile broadband network coverage is mostly provided by 3G WCDMA and HSPA macro cellular networks. The increased mobile broadband subscriptions, traffic growth and intensifying competition has prompted most operators in the region to upgrade their networks to evolved HSPA and increasingly LTE networks in major urban areas [121, 122]. Network densification through rollout of new cell sites allows operators to increase reuse of their limited spectrum and provide needed capacity gains in urban areas, particularly in the fast expanding dense informal settlement areas [123]. Customer deployed small cells is one of the attractive alternative both for operators and end-users, considering operators does not need to invest in maintaining cell-sites and end-users get higher throughput and coverage, being near to the small cells compared to the macro cells. However, rolling out of new sites in those settlements is complicated by lack of fixed lines for backhaul, energy scarcity, need for securing network assets at sites and limited average revenue per user (ARPU) to justify the additional investment [120]. This calls for alternative approaches for network densification and operation models suitable for that aforementioned environment. Furthermore, the limited and/or unreliable access to power from the grid presents challenges in operating the small cells [124].

4.3.1 Related Work and State of the Art

Existing backhaul solutions for small cells include wired and wireless options [12, 102, 125]. Wired backhaul solution uses either copper cable or optical fiber and is an expensive technique, not existing in the emerging markets. Wireless backhaul solutions are based on either microwave radio links or satellite wireless link, which requires network planning and is thereby not suitable for customer deployed small cells. Alternative backhauling mechanism is needed for customer deployed small cells in the emerging markets, which is the subject of our research. In [125, 126], authors study Wifi IEEE 802.11, WiMax IEEE 802.16 and millimeter-wave technology to provide high-capacity backhaul for cellular networks.

4.3.2 Simulation Scenario

In publication VI to exemplify a high-density urban informal settlement we have used Hanna Nassif ward in Dar es Salaam, Tanzania, as a simulation study area. Hanna Nassif has an estimated population of 40000 people, living in a 1 km2 land area. The area includes around 3000 (mostly single story) buildings and is located on a terrain with a topographical difference of 19 m. The radio coverage estimations are based on realistic three dimensional building vectors and topographical data for the Hanna Nassif area and are evaluated using the dominant path model implemented in the WinProp propagation modeling tool. The small cells are deployed at random buildings by end-users in the service area. We consider two possible deployment scenarios: indoor deployment and rooftop deployment (akin to a television antenna). Indoor deployment enables small cells to provide indoor coverage and indoor-to-outdoor coverage for other UE in close proximity of the building. Rooftop deployed small cells provide increased range for outdoor coverage, but at the expense of reduced signal strength for indoor users (outdoor-to-indoor coverage) due to building penetration losses. Static system-level simulations are performed to investigate network performance, whereby, small cells are dropped at random building locations for each snapshot, while half of the UEs (HSPA and LTE UEs) are dropped in clusters around small cells and the rest of the UEs are dropped randomly over whole area.

4.3.3 LTE based Self-Backhaul for HSPA Small Cell

In publication VI, we consider the alternative densification scenario through small cell deployment in the informal settlements. The HSPA macro site represents the legacy deployment with majority of UE in the settlements assumed to HSPA-compliant. Macro LTE upgrades are then implemented to cater for minority but gradually expanding base of LTE UEs [121, 122]. The HSPA small cells are then deployed to offload traffic from highly-loaded HSPA macro cells. Unplanned deployment of shared access small cells by end users (households, microenterprises etc.) provides a cost-effective network densification from operators perspective and affordable connectivity from user perspective. Moreover, it potentially allows for novel business models that provide incentives (e.g. revenue share) for end users deploying and operating the small cells.

We consider self-backhauling of small cells through the use of macro LTE and LTE-Advanced enhancements to provide low-cost and flexible backhauling for the unplanned HSPA small cells in the informal settlements, as depicted in the Figure 4.2. Extensive simulations are carried out to verify the feasibility of the considered self-backhauling approach and observe the overall performance impact on the HSPA and LTE users in the network. Our study also reviews various powering options for the small cells in informal settlements and considers deployments that enable off-grid operation of the small cells. Key contributions of the publication VI, include verifying the feasibility of using LTE as a self-backhauling technique for HSPA small cell, analyzing the impact of self-backhauling on existing LTE UE throughput and enhancement in small cell LTE backhaul link to minimize the impact on LTE UE.

4.4 Open Questions

In our research we deal with the problem of reducing the data forwarding data among BSs during handover. To achieve the same, we propose the LTE network to poll the UE more frequently during the ongoing handover scenarios to reduce the amount of packet forwarding among BS. It would be worth analyzing trade-off between the PDCP data forwarding buffer size in the BS and the uplink RLC status report load on the UE due to the

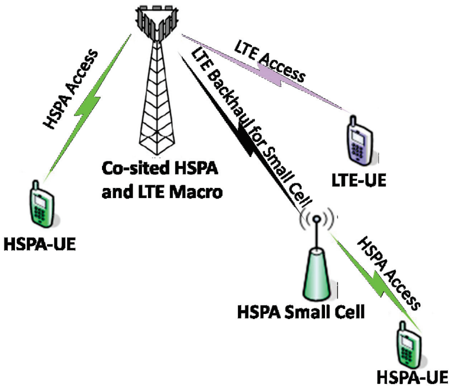

Figure 4.2. Self-backhauling of HSPA small cell deployments overlaid by HSPA/LTE macro cells[extracted from Publication VI]

polling of the LTE network during handover. We also dealt with the problem of providing backhaul access to the small cells deployed in the emerging markets. Future work is required to investigate joint radio resource management schemes across different layers and link segments (access and backhaul) for the deployment scenario considered in this study. Furthermore, research is required on SON algorithms for optimum load balancing across different layers and energy-sustainable operation of off-grid small cells in this context.

5. Conclusions

The huge appetite for mobile broadband, has resulted to continuous and complementary improvement in both radio access technology and mobile backhaul of cellular networks, along with network densification. The main motivation of the research comes from future cellular networking, where femtocells are foreseen to complement traditional macro base stations (BSs) in Long Term Evolution (LTE) and fifth generation (5G) of cellular networks. The contributions of the thesis are two folds. One is to propose distributed radio resource management algorithms for radio access technology to reduce interference and thereby improve network synchronization and cell-edge user equipment (UE) throughput for heterogeneous network. Second is to dimension the mobile backhaul link for handover and provide wireless backhaul for femtocells.

Deployment of femtocells, introduce new requirements for distributing phase synchronization and interference management in heterogeneous network. Achieving phase synchronization for indoor femtocells will be beneficial for time division duplexing (TDD) operation and inter-cell interference cancellation and management techniques, but challenging to achieve as global positioning system does not work indoors. In this thesis, we propose coordinated transmission and reception algorithms to reduce interference among BSs, and thereby spread the synchronization across the dense femtocell network over the air. We also cover the problem of selecting component carriers (out of the possible multiple component carriers) to improve the performance of either macro or femto user equipments (UEs) being interfered by the neighboring closed subscriber group (CSG) femtocells. We propose three strategies: Selfish, Altruistic and Symmetric for primary carrier selection and remove the outage of the macro UEs near the CSG femtocells. Further, we propose dynamic frequency selection algorithm for component carrier selection, where decisions to select or drop a carrier are based on gain/loss predictions made from UE handover measurements. We thereby maximize the sum utility of the whole system, which includes mean-rate, weighted fair-rate, proportional fair-rate and max-min utility.

Mobile backhaul dimensioning is studied to improve the handover and provide the cost-effective backhaul opportunity for femtocells deployed in emerging markets. In a packet-switched wireless system e.g. LTE, data packets are forwarded between BSs during handover over the backhaul. The problem lies in efficiently forwarding the needed data across BSs to cater the user's quality of service and reducing load on the links connecting the two BSs. We analyze, evaluate and improve the packet forwarding handover mechanism by reducing the amount of forwarded data between BSs. Another challenge lies in equipping the femtocells with backhaul, where copper cable, optical fiber or microwave radio links are expensive options for unplanned emerging market case. We consider leveraging macro LTE networks to backhaul High Speed Packet Access (HSPA) femtocells, thereby highlight the possibilities for cost-effective capacity upgrades of dense settlements.In the study we also note possible system performance improvements by enhancing the femtocell backhaul link through improved antenna design, scaling of carrier bandwidth and introduction of traffic steering across HSPA and LTE layers.

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