Thesis for the degree of Doctor of Philosophy

Moving Networks, a Better Way to Serve Vehicular Users

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Gothenburg, 2016
ISBN 978-91-7597-441-5

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie Nr 4122
ISSN 0346-718X

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This thesis has been prepared using LYX.

Printed by Chalmers Reproservice
Gothenburg, Sweden, August 2016.

To *my beloved*

Contents

Abstract

Nowadays, a great number of mobile broadband users are vehicular. It is very common that people are using their mobile devices either for working or entertainment when they are on the go. We are expecting mobile broadband to offer comparable experience everywhere, e.g., at home, in the office or on the go. One of the biggest challenges to serve vehicular users is that their communication is affected by vehicular penetration loss (VPL), which can be very high in well-isolated public transportation vehicles. This thesis investigates how to serve the vehicular users in a cost efficient way by deploying moving relay nodes (MRNs), or moving networks (MNs) on public transportation vehicles. The benefits of using MRNs or MNs are not only that they can circumvent the VPL by proper antenna placement, but also more sophisticated multi-antenna and signal processing schemes can be employed, as public transportation vehicles are less constrained by size and processing power compared to regular mobile devices.

First we consider a single cell setup with one vehicular user served by the network. In [Paper A], by analytic analysis, we show that, in order to minimize the end-to-end outage probability, as the VPL increases, a half-duplex relay node needs to be deployed as close as possible to a vehicular user. This also motivates the use of an MRN to serve vehicular users. In [Paper B], we extend the study of using half-duplex MRN in several aspects, where co-channel interference, practical propagation conditions as well as inter-node handover are taken into account. From the study in [Paper B], we show that the use of MRN has great potential to improve the Quality-of-Service (QoS) for the vehicular users that are affected by moderate to high VPL. In [Paper C], we give an overview of existing solutions, and we discuss the benefits of using MRN to serve vehicular users from a system perspective.

In the near future, it is expected that more frequency bands at higher frequencies will be freed up for mobile communications, especially for small cells. Therefore, in the second part of the thesis, we extend the study of using half-duplex MRNs to a full-duplex moving network (MN) in an ultra-dense urban deployment scenario. Both MRNs and MNs use wireless backhaul links to communicate with the network and form their own cells to serve the vehicular users. However, MRNs use the same frequency at their access links as the backhaul links, while MNs need dedicated frequency for their access links in order to work in a full-duplex fashion. In [Paper D], we show that the most limiting factor for further improving the performance of MNs in the ultra-dense urban scenario is the complicated inter-cell interference. Therefore, we compare the use of various multiple-antenna techniques at the backhaul receivers of MNs to alleviate the inter-cell interference experienced by the backhaul links of MNs. For the access links of MNs, as they are operating in the same frequency bands as small cells which are densely deployed along the road, we propose

to use almost blank subframes (ABSs) to protect the access links of the MNs. By using system level evaluations, we demonstrate that by deploying full-duplex MNs on public transportation vehicles in an ultra-dense urban scenario, the throughput of the vehicular users can be significantly improved, and the impact on regular outdoor users is very limited.

Finally, in [Paper E], we propose a novel way to enhance the uplink quality of vehicular users through cooperative communication enabled by device-to-device (D2D) communication. We show that when the vehicular users are affected by moderate to high VPL, by cooperating with each other to enhance their UL communication, the same amount of data can be sent in a shorter time. Therefore, all participants can benefit from the cooperation.

Keywords: Moving relay node, moving networks, ultra-dense networks, small cells, moving cells, vehicular small cells, vehicular penetration loss, device-to-device communication, interference management.

List of Included Publications

This thesis is based on the following appended papers. They are:

[A] Paper A: **Y. Sui**, A. Papadogiannis, and T. Svensson, "The Potential of Moving Relays–a Performance Analysis", in *Proc. of IEEE Vehicular Technology Conference (VTC)*, Yokohama, Japan, May 2012.

[B] Paper B: **Y. Sui**, Z. Ren, W. Sun, P. Fertl, and T. Svensson, "Performance Analysis of Fixed and Moving Relays for Vehicular Users under Co-channel Interference and Multi-node Handover", submitted to *IEEE Transactions on Vehicular Technology*.

[C] Paper C: **Y. Sui**, J. Vihriala, A. Papadogiannis, M. Sternad, W. Yang, and T Svensson, "Moving cells: a Promising Solution to Boost Performance for Vehicular Users", *IEEE Communications Magazine*, pp. 62-68, Jun. 2013.

[D] Paper D: **Y. Sui**, I. Guvenc, and T. Svensson "Interference Management for Moving Networks in Ultra-Dense Urban Scenarios", *EURASIP Journal on Wireless Communications and Networking (2015) 2015:111. Topical collection on 5G Wireless Mobile Technologies, ISSN: 1687-1499,* Apr. 2015.

[E] Paper E: **Y. Sui** and T. Svensson, "Uplink Enhancement of Vehicular Users by Using D2D Communications", in *Proc. of IEEE Global Communication Conference, Workshops (Globecom Workshops)*, Atlanta, the USA, Dec. 2013.

Acknowledgments

In the spring of 2007, I was struggling whether I should go to the USA or to Sweden. I got admitted by Lund University in April, but I was anxiously waiting for the news from the University of Florida. I heard no news until the end of May, and if I did not apply for the Swedish visa, I would not get it on time to go to Sweden. I discussed this a lot with my family, and finally I decided not to wait any more, and handed in my visa application to the Swedish embassy in Beijing. In the afternoon of the same day that I handed in my Swedish visa application, I got an email from University of Florida saying I got admitted in their master program with scholarship for the first year. After reading that email, I felt complicated inside. I had the impulse to withdraw my visa application, but at the end I decided to follow the lead of the God.

Now eight years later, looking back on the time that I spent in Sweden, I believe that I made a good decision. During the years that I spent in Sweden, I have matured and learned to be grateful. Everyone that knows my past would agree that it is a miracle that I could become the man that I am today, arriving to the destination of my 22 years of education. I got lots of help from different people in my life, but the most support is from my family. We are not a rich family in the P.R. China, but my parents and grandparents offered everything they could to make sure I have the best education. This is a great love that I can never forget. This journey would not have been possible without you.

During the years of my Ph.D study, I feel very grateful, as I got lots of help and support from lots of people. I would like to take this opportunity to express my appreciations. First and foremost, I would like to thank my supervisors, Prof. Arne Svensson and Prof. Tommy Svensson for giving me the opportunity to join one of the best communication systems groups in Europe. The help and support that Tommy has given me during my Ph.D. study was tremendous, both academically and personally. I see you as family now, as you are the one who cares about me a lot. You share all your life experiences with me, even down to the very small details, and not to mention the healthy life style that you helped me to develop. Academically, you have given me lots of protection and let me do the research that I want. Without the support from you, this thesis would never have been done, and I would never have developed to be the kind of independent researcher that I wish to be.

Furthermore, I would like to thank my previous co-supervisor Dr. Agisilaos Papadogiannis. Working with you was always full of pleasure, and you provided me lots of good research ideas and sensible discussions. You taught me several good ways to present and sell good research ideas, and encouraged me when there were setbacks during my studies. Moreover, many thanks to Prof. Ismail Guvenc in the Florida International University for inviting me to visit and do my research with you. You showed me the power of language, and I was impressed by your knowledge in the field of mobile communication standardization. I really appreciate your safeguarding, and you helped me sail through the last phase of my Ph.D. study. Thanks to Prof. Mikael Sternad and Prof. Anna Brunström for your sensible discussions in our VR project meetings. And thanks Prof. Xiaofeng Tao, Prof. Xiaodong Xu and Dr. Xin Chen for a wonderful collaboration experience during our Sino-Swedish IMT-Advanced Mobility project.

Moreover, I would like to thank Prof. Erik Ström for his generosity of sharing his knowledge and his great leadership. Now, we are the biggest group of its kind in Sweden doing research in all aspects in communication systems. I am proud to be a member in this group. I have an enjoyable working environment, and our secretary Agneta Kinnander is the hero behind this. She is always there to help us with all kinds of difficulties. At the moment that I was finalizing my thesis, I heard the bad news that our IT support professional Lars Börjesson passed away. I am really sorry about his death, and I could never forget his help and his dedicated work to provide the IT support for our group.

I am also grateful to Wei Yang, Wanlu Sun, Dr. Peter Fertl, and Zhe Ren for their altruistic contributions to our research works. Thanks Dr. Carmen Botella Mascarell, Jingya Li and Tilak Rajesh Lakshmana for being my great colleagues, and I appreciate your accompaniment in my studies. I am especially grateful to John Eckerdal who not only teaches me lots of advanced C++ programming and Linux skills, but also shares with me many useful tips of how to understand the Swedish culture. I am especially grateful to my colleagues in our group. I love you all.

During my visit in the USA, I received lots of generous help from my colleagues in the MPACT lab, Florida International University. Thanks Arvind Merwaday, Karthik Vasudeva, Bekir Sait Ciftler, Leonardo Babun, and Nadisanka Rupasinghe for taking care of me, and made me feel welcome in a new country. I really enjoyed my stay in the USA.

At the end, I would like to thank all my great colleagues that I got to know during the EU FP7 ARTIST4G and METIS projects. I started the study of moving relay nodes in the ARTIST4G project, and with the help of METIS, I could continue the studies and made all the works in this thesis possible. I am proud to have been a member of these two projects, and it helped me to mature as an independent researcher. Especially, I would like to thank Prof. Petar Popovski, Dr. Elisabeth de Carvalho, Dr. Danish Aziz, Dr. Patrick Marsch, Mr. Michal Maternia, Dr. Emmanuel Pollakis, Dr. Peter Fertl and Dr. Zexian Li for your great leaderships in this project. Thanks Kaifeng Guo for sharing with me your knowledge to help me understand the basics of massive MIMO techniques. I enjoyed a lot to work in this project.

Yutao Sui
Gothenburg, January, 2016

I would like to express my great appreciations to the support from different funding agencies. Thanks to Swedish Governmental Agency for Innovation Systems (VINNOVA), the Swedish Research Council (VR), and the Seventh Framework Program (EU FP7) for providing the funds for our research works. Moreover, thanks to the

Ericsson Research Foundation to provide funding for my visit to Prof. Ismail Guvenc who leads the MPACT lab in the Florida International University. Major part of the simulations in this thesis were performed on resources at Chalmers Center for Computational Science and Engineering (C3SE) provided by the Swedish National Infrastructure for Computing (SNIC).

List of Abbreviations

3GPP	The 3rd Generation Partnership Project
AF	Amplify-and-Foward
AP	Access Point
BER	Bit Error Rate
BS	Base Station
CA	Carrier Aggregation
CCI	Co-Channel Interference
CCRS	Cooperative and Coordinated Relay System
cdf	Cumulative Distribution Function
CoMP	Coordinated Multi-Point
CRE	Cell Range Expansion
CSI	Channel State Information
CSIT	CSI at the Transmitter
CWER	Code Word Error Rate
D2D	Device-to-Device
DF	Decode-and-Forward
EF	Estimate-and-Forward
eICIC	Enhanced Inter-cell Interference Coordination
FeICIC	Further enhanced Inter-Cell Interference Coordination
FRN	Fixed Relay Node
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications

HetSNets	Heterogeneous and Small cell Networks
HO	Handover
HSPA	High Speed Packet Access
ICIC	Inter-cell Interference Coordination
ICT	Information and Communications Technology
IRC	Interference Rejection Combining
ISM	Industrial, Scientific and Medical
LOS	Line-Of-Sight
LTE	Long-Term Evolution
METIS	Mobile and wireless communications Enablers for the Twenty-twenty Information Society
MIMO	Multiple-Input and Multiple-Output
MN	Moving Network
MRC	Maximum Ratio Combining
MRN	Moving Relay Node
MRT	Maximum Ratio Transmission
NLOS	Non-Line-Of-Sight
OFDMA	Orthogonal Frequency-Division Multiple Access
OP	Outage Probability
PCC	Primary Component Carrier
pdf	Probability Density Function
PRB	Physical Resource Block
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technologies
RF	Radio Frequency
RN	Relay Node

RNTP	Relative Narrow-band Transmit Power
RRH	Remote Radio Head
RSRP	Reference Signal Received Power
SCC	Secondary Component Carrier
SINR	Signal-to-Interference-Plus-Noise Ratio
SNR	Signal-to-Noise Ratio
UE	User Equipment
USIM	Universal Subscriber Identity Module
VPL	Vehicular Penetration Loss
VPN	Virtual Private Network
VUE	Vehicular User Equipment
WCDMA	Wideband Code Division Multiple Access

Part I.

Introduction

1. Overview

The field of wireless communication changes much faster than I can anticipate. Now, it has been just 3 years after I got my Licentiate degree, but what had happened during these 3 years in the field of wireless communication astonished me. Three years ago, when I started to work with the EU 5G project METIS[1], only some big cities in Sweden had 4G Long-Term Evolution (LTE)[2] coverage, but now people are excited about the counting down of the coming 5G era. Nowadays, Internet access is no longer considered to be an add-on, but a basic element of everyone's daily life. If the internet service is down, either at home or at work, it causes a great panic for lots of people. Instead of saying "the dog ate my homework", "the dog ate our Internet cable" will become common among the new generation schoolchildren.

For 2015, is the year in which Ericsson predicted that the number of mobile subscriptions would exceed the world's population [1]. As a customer, I was very happy during the year of 2012 and 2013, as the cost of mobile communication, both for voice and data, was significantly lowered by all the major operators in Sweden. However, it was just a very short-lived happiness, when more and more restrictions were added to my mobile subscriptions gradually by my operators. The operators are struggling in all ways to be profitable, competitive and ensure the demand of mobile data does not exceed their network capacity. At the beginning, a throttle was added to my mobile data access when I reached a certain data quota. Nowadays, when I exceed my monthly data quota, the only thing I can expect is a full stop of my mobile data access until I buy extra data. The education from the operators certainly works; however, this only delays but cannot stop the coming of mobile data explosion.

The good news is that the unprecedented demand for wireless data service has driven the fast advancement of the information and communications technology (ICT) field. The economic and social benefits from this is very obvious. On the other hand, it also puts unprecedented challenges on the construction of infrastructure, in order to meet the demand of ubiquitous connectivity. Moreover, the revenue of the mobile operators does not increase at the same speed as the volume of the wireless data grows, even if the per-bit costs is going down constantly. Therefore, how to meet the needs of different mobile users by using the minimum amount of resources is definitely the most important task in our research community.

In the first year of my PhD study, I worked extensively with adaptive coding and modulation when only partial channel state information (CSI) is available at

[1]METIS stands for Mobile and wireless communications Enablers for the Twenty-twenty Information Society.

[2]LTE is a trademark of ETSI.

the transmitter side. This gave me a solid understanding of the physical layers of the communication system as well as different channel modeling techniques. This lays down a good foundation for my later work regarding several different aspects of deploying moving networks (MNs) on public transportation vehicles. My supervisor Tommy and I spend more than four years on the research of MNs, as in our point of view MNs can bring significant benefits to the existing mobile communication systems. In 2010, when we started to work on the performance study of using moving relay nodes (MRNs) to serve vehicular users, Internet access on public transportation vehicles was costly and considered to be luxury. For example, a couple of years back, the Swedish passenger train operator SJ only offered free WiFi service on some of their inter-city trains for travelers in the first class, and others needed to pay substantially to use the WiFi service. But nowadays, in Sweden (and in several other countries), WiFi is free of charge on most of the inter-city trains, coaches, and several cities have plans to deploy WiFi on their metro buses. All these changes are simply because that a significant number of mobile users are vehicular, and having access to wireless broadband services while being in public transportation vehicles becomes a basic needs of the majority of us. As a result of the high penetration of smartphones, tablets and increasingly portable laptops as well as the thriving of music and video streaming services, it is expected that both the number of vehicular users and their data volume will greatly rise in the near further. People are expecting similar levels of quality of service (QoS) and Quality of Experience (QoE) when they are commuting or traveling as they are sitting still in the office or at home. Hence, naturally, public transportation vehicles become hotspots for wireless data traffics. As predicted by the project METIS, the expected number of active vehicular user equipment (VUE) devices will be up to 50 per bus, and 300 per train beyond the year of 2020 [2, 3].

To support ubiquitous QoS and QoE for VUE devices on well-isolated high speed vehicles is very challenging because of the velocity of the vehicles, and the attenuation of the radio signals traveling from the base station (BS) to the VUE devices inside the vehicles. Measurements show that as high as 25 dB vehicular penetration loss (VPL) can be observed in a minivan at the frequency of 2.4 GHz [4]. Higher VPL are expected in well-insulated vehicles of our interests, e.g., high speed trains with double layer metalized glasses, and the VPL will be even larger in higher frequency bands [5], e.g., the 3.6 GHz allocated to future mobile communication systems [6]. Consequently, more radio frequency (RF) power, time and frequency resources need to be used to compensate for the VPL, in order to maintain a certain level of QoS at the VUE devices affected by the high VPL.

The VPL is a significant problem, especially in a coverage limited scenario, e.g, in rural areas. However, in a densely deployed urban scenario, complicated inter-cell interference exacerbated by the street canyon effect makes the situation even worse. In order to meet the capacity demand, network densification is one of the most effective solutions, and a new design paradigm, i.e., the Heterogeneous and Small Cell Networks (HetSNets) was introduced in LTE release 10 [7–9] [10, Chp. 24]. However, as nodes get closer, inter-cell interference becomes a significant problem.

One of the advantages of deploying MNs is that compared to regular user equipment (UE) devices, the MNs are less constrained by power and transceiver complexity. Therefore, more advanced multi-antenna schemes and interference cancellation algorithms can be implemented in the MNs to better alleviate the problem caused by the complicated inter-cell interference. Throughout this thesis, we consider MRNs are in-band and half-duplex, and MNs are out-band full-duplex. This is because our early studies of MRNs are based on the understandings of the standardized decode-and-forward (DF) in-band half-duplex relay node (RN) in LTE release 10. In the 5G era, as it is expected that more frequency bands at higher frequencies can be freed up for mobile communications, especially for small cells, we extend our study of using half-duplex MRNs to a full-duplex moving network MN with focus on an ultra-dense urban deployment scenario. In practice, MRNs and MNs share lots of similarities, and the results that we have obtained from the MRN studies can be extended to MNs, and vice versa. We illustrate in details in Chapter 4.

As VUE devices are a significant portion of the wireless data users in the future networks, it is crucial to design the mobile communication system in a way that the QoS needs of those VUE devices can be met cost-effectively. There are several temporary solutions that use the existing standardized network elements to serve the VUE devices, and we discuss them in more details in Chapter 3. Nevertheless, in our opinion, deploying dedicated MNs on public transportation vehicles is one of the most efficient ways to satisfy the needs of the VUE devices.

Research Project

The research projects in this thesis was part of the EU FP7 projects advanced radio interface technologies for 4G systems (ARTIST4G) and mobile and wireless communications enablers for the twenty-twenty information society (METIS). This work was also supported by the Swedish Research Council VR under the project Dynamic Multipoint Wireless Transmission, as well as by VINNOVA in the MORE4G project within the VINNOVA-MOST program on IMT-Advanced and Beyond.

Outline of the Thesis

The thesis has two parts. Part I offers an introduction of the main topic of the thesis, i.e., the use of MRNs or MNs to serve VUE devices in different scenarios, to facilitate the understanding of Part II which includes the papers leading to the completion of this thesis. Part I of the thesis is organized as follows. Chapter 1 gives an overview of the thesis work, and an overview of the research field. Chapter 2 introduces the concept of HetSNets, the basics of relaying techniques, the metrics used in this thesis for performance evaluation, and the interference management schemes in HetSNets. Chapter 3 reviews the conventional solutions to serve the VUE devices based on using the existing elements in the current mobile communication systems. In Chapter 4, we discuss the benefits and challenges of using MRNs or MNs to serve VUE devices in detail, and in Chapter 5 we present a method based on device-to-device (D2D) communications to enhance the uplink communication of VUE devices. This can be seen as an alternative way to the use of MRNs or MNs. Finally, in Chapter 6, we conclude Part I with some open problems in this research field, and we summarize the contributions included in Part II of the thesis.

2. Introduction

The capacity demand in wireless communication systems is exploding. Network densification is one of the most promising solutions to meet the demands of throughput, and adjust the capacity dynamically. Therefore, a new design paradigm, the HetSNets, was introduced in the 3rd Generation Partnership Project (3GPP) LTE release 10 [7–9] [10, Chp. 24]. In this chapter, we first introduce the general idea of HetSNets, and we introduce the RN assisted transmission. Then, we discuss one of the biggest challenges in the deployment of HetSNets, i.e., the inter-cell interference, and some possible solutions to cope with excessive inter-cell interference in HetSNets. At the end of this chapter, we give the motivation of this thesis work.

2.1. Heterogeneous and Small Cell Networks

Network densification is necessary, in order to meet the fast growing demand of mobile data services, especially in urban areas. HetSNets are identified as one of the key methods to dynamically address the capacity requirement in the next generation mobile communication systems. The idea of HetSNets is to deploy various low power nodes underlying high power macro BSs. The macro BSs offer basic coverage and take care of the high mobility users while various low power nodes are used either to boost the local capacity in hotspot areas or to extend the coverage of the macro BSs. Furthermore, the so called dual connectivity or inter-site carrier aggregation (CA) is standardized in LTE release 12 [11]. Dual connectivity allows the separation of control plane and data plane at a user terminal, and offers the benefits of combining the coverage of macro cells and the capacity of small cells. In this way, the mobility management can be maintained on the macro layer while the throughput can be increased by aggregating the capacity of small cells. In the study of 5G mobile communication systems, a HetSNets deployment is kept in mind from the very beginning [2,12]. For example, in the test case "dense urban information society" of the METIS project, a comprehensive HetSNets model called the *Madrid grid model* was developed based on the characteristics of common European cities [3].

We begin with a simple example as follows. If k subchannels are used for the communication, the approximate capacity of a communication link can be approximated by using the Shannon capacity formula as

$$C = \sum_{i=1}^{k} B_i \log_2 \left(1 + \frac{P_i}{I + N_0 B_i}\right), \tag{2.1}$$

where B_i and P_i are the bandwidth and average received power of the ith subchannel, respectively. The additive white Gaussian background noise power spectral density is N_0 [W/Hz], and here we treat the interference I as white Gaussian noise. As we can see from (2.1), there are two ways to increase the capacity of the communication link, i.e., to improve the received signal-to-interference-plus-noise ratio (SINR) at the receiver and/or increase the bandwidth of the system.

To acquire abundant bandwidth for wireless communication systems is very challenging, as it involves the interests of several parties due to the fact that spectrum is a scarce resources. Although the system bandwidth cannot be easily increased, the use of HetSNets or network densification can still make more bandwidth available per user through effective reusing of the spectrum. This is because when the size of the cell is getting smaller, the number of users competing for the same resources reduces. Hence, from a user perspective, on average more bandwidth are made available.

Intuitively, people may hold the belief that the performance of a cellular network would be degraded by network densification, since the SINR decreases due to the interference level increases in the network. In [13], it is shown that with an ideal HetSNets setup, even though inter-cell interference become significant when transmitters are getting closer, the gain obtained by network densification to a wireless communication system is still noteworthy because the desired signal increases as fast as the interference in a HetSNets deployment.

In practice the interference situation is much worse compared to theoretical studies, due to reasons such as user mobility, unbalanced downlink and uplink coverage, closed-access small cells, etc. Therefore, various methods have been applied in wireless communication systems to manage the interference, ranging from interference coordination, interference mitigation, and sophisticated multiple-input and multiple-output (MIMO) schemes, e.g., coordinated multi-point (CoMP) schemes. In Section 2.4, we discuss the inter-cell interference coordination (ICIC) and interference suppression schemes used in practical wireless communication systems in more details.

As depicted in Fig. 2.1, in a HetSNets setup, several different types of low power nodes are deployed underlying high power macro BSs. If dedicated high speed backhaul connections are available, e.g., optical fiber or line-of-sight (LOS) microwave links, remote radio heads (RRHs) or micro BSs can be deployed in capacity demanding areas,[1] e.g., shopping malls, train stations, stadiums, etc., to improve the local throughput. In office buildings and residence areas, home BSs are randomly deployed and form femtocells to offload the data traffic when users are at work or at home. In the case of lacking dedicated backhaul connections, different types of in-band RNs can be used to meet different needs. We discuss more about the use of RNs in Section 2.2.

In this thesis, we focus on the deployment of two new types of nodes, i.e., the

[1]The difference between an RRH and a micro BS is that a micro BS is a fully functional BS that form its own cell and terminates all the layer-2 and layer-3 communication protocols, whereas an RRH is part of a macro BS and only has limited functionality. RRHs can also have their own cell IDs, but most of the baseband processing is done at the macro BS.

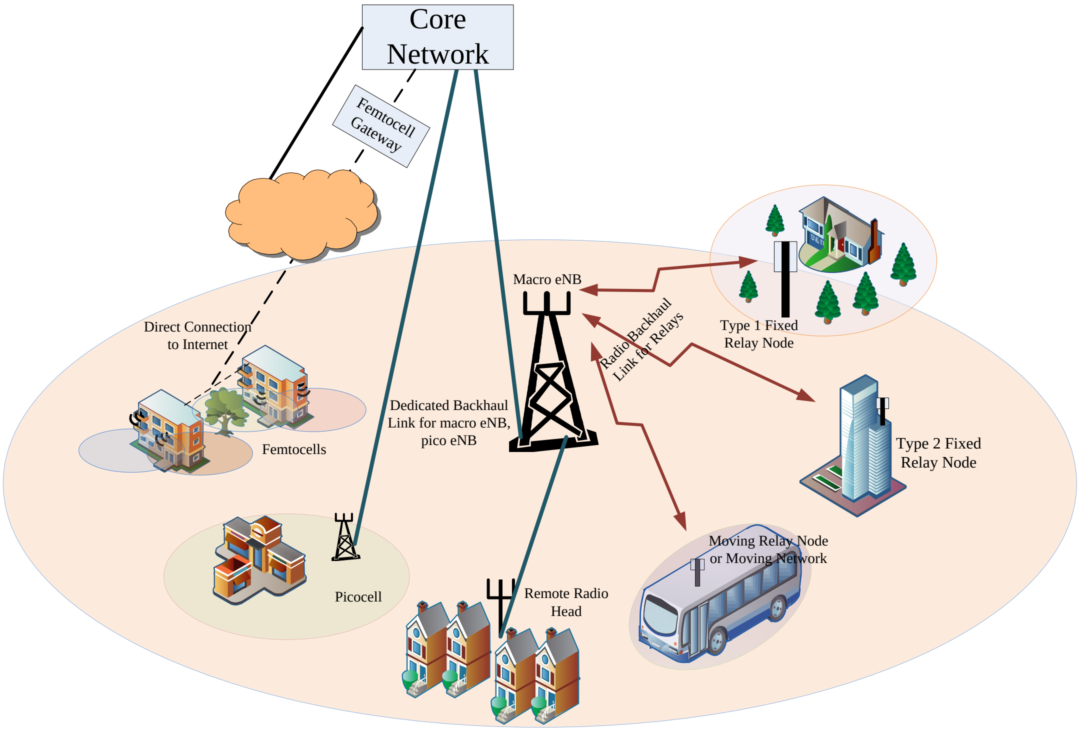

Figure 2.1.: An example of a HetSNets deployment

moving relay node (MRN) and the moving BS, and their impacts on the system. In this study, the difference between an MRN and a moving BS is that MRNs are considered to be in-band half-duplex decode-and-forward RNs that have similar functionality as the fixed relay nodes (FRNs) standardized in LTE. An MN formed by a moving BS, is assumed to be full-duplex, and its backhaul and access links are operating at different frequency bands. Both MRNs and MNs communicate with macro BSs via radio interfaces, and can terminate the layer-2 and layer-3 communication protocols, and therefore identify them as regular BS to the VUE devices on board. The difference is that the MRNs are assumed to be in-band, i.e., the carrier frequency and the bandwidth are the same for the backhaul and access links. MNs, on the other hand, transmit at different frequency bands for their backhaul and access links with different bandwidth. The MN is a natural extension of the MRN.

As mentioned before, the VPL is one of the biggest factors that affect the QoS and QoE at VUE devices. There are several solutions based on the use of current network elements to serve these VUE devices, and we review these solutions in Chapter 3. But in our opinion, the use of dedicated MRNs or MNs deployed on top of public transportation vehicles is an efficient way to combat the VPL and improve the QoS and QoE at VUE devices. By deploying outdoor and indoor antenna units connected via a cable that introduces negligible losses, the VPL can be circumvented. Furthermore, compared to regular UE devices, a public transportation vehicle is less constrained by power, size and transceiver complexity. Therefore, more antenna elements, and more advance signal processing schemes can be employed to further enhance the performance. Moreover, other benefits, e.g., group handover [14], collective CSI feedback for advanced backhaul design [15], etc., can also be realized at the MRNs and MNs. It should be noted that no significant hardware modifications are required for the current user terminals in order to benefit from the use of MRNs or MNs.

2.2. RN Assisted Transmission

An RN is used to relay the information from sources to destinations. The use of relaying techniques to pass messages has a long history. One of the most famous examples is the use of beacon towers built on the Chinese great wall. By using heavy smoke during the day time or bright fire at nights, these beacon towers relayed defensive communication messages from the frontier to the headquarter which was thousands of miles away when enemy troops were approaching. Similar methods were also used in lots of other ancient cultures, e.g., the fryctoria in Ancient Greece. Nowadays, RNs are an indispensable part in modern wireless communication systems, ranging from advanced space exploration to daily mobile communication systems. The use of repeaters in cellular systems can be dated back to the 1980s when the Global System for Mobile Communications (GSM) system was developed. In the current LTE system, the use of more advanced RNs was standardized in the release 10 of LTE [10, Chp. 30]. In this section, we give a short review of different types of RN techniques. Following the 3GPP convention, the link between a source and an RN is denoted as the backhaul link, and the link between an RN and the destination is denoted as the access link.

2.2.1. Amplify-and-Forward RN

Amplify-and-forward (AF) RNs simply amplify the received signals in given frequency bands, and then forward the signals to the destination. This type of RN is easy to implement and has been widely deployed in the current wireless systems, either by the operators or the users. Denoting the signal received by the RN and at the destination as $y_{\mathrm{R}}^{(\mathrm{S})}$ and $y_{\mathrm{D}}^{(\mathrm{S})}$, respectively. We have

$$y_{\mathrm{R}}^{(\mathrm{S})} = h_{\mathrm{R}}^{(\mathrm{S})}\, x + n_{\mathrm{S}}, \tag{2.2}$$

$$y_{\mathrm{D}}^{(\mathrm{S})} = h_{\mathrm{D}}^{(\mathrm{S})}\, x + n_{\mathrm{D}}, \tag{2.3}$$

where x is the signal sent by the source, $h_{\mathrm{R}}^{(\mathrm{S})}$ and $h_{\mathrm{D}}^{(\mathrm{S})}$ are the channel gain from the source to the RN, and from the source to the destination, respectively. The noise at the RN is denoted as n_{S}, and n_{D} is the noise at the destination. Upon receiving the signal from the source, the RN amplifies the received signal, and forwards it to the destination. If the RN has a gain of G, then the received signal from the RN to the destination is

$$y_{\mathrm{D}}^{(\mathrm{R})} = G\, h_{\mathrm{D}}^{(\mathrm{R})}\, y_{\mathrm{R}}^{(\mathrm{S})} + n_{\mathrm{D}}, \tag{2.4}$$

where $h_{\mathrm{D}}^{(\mathrm{R})}$ is the channel gain between the RN and the destination. If we assume there is no direct link between the source and the destination, by comparing (2.3) and (2.4) we can see that one obvious disadvantage of the AF RN is that it amplifies both the desired signal and the noise at the RN. If there are interference present at the receiver of the RN, the interference is also amplified. Therefore, AF RNs must be placed at a spot with SNR or signal-to-interference-plus-noise ratio (SINR) advantages, e.g., from outdoor to indoor, otherwise little improvement of the signal quality at the destination can be expected.

2.2.2. Decode-and-Forward RN

A DF RN has more processing power than the AF RN. The DF RN first decodes part or all of the received signal, and then it re-encodes the decoded message and forwards it to the destination. On the one hand, the DF RN does not have the same problem of noise or interference amplification as the AF RN. On the other hand, it may cause error propagation, if the RN does not decode the message from the source correctly. In order to reduce the risk of error propagation, in practical wireless communication systems, e.g., the LTE system, a cyclic redundancy check (CRC) is used to verify the decoded message. If an error is detected, instead of forwarding the message, the RN may request a re-transmit of the message from the source. Moreover, there are some extra delays introduced by DF RNs, due to the decode and re-encode process.

There is no general expression for the end-to-end SNR or SINR when using the DF RN. Instead, outage probability (OP) can be used as a metric to indicate its performance. As a DF RN needs first to decode the message from the source, and then forwards the re-encoded message, as long as one of the hops is in outage, an outage occurs for the end-to-end communication. In Section 2.3, it is pointed out that the QoS requirement can be translated to a minimum SNR or SINR target at the receiver. Therefore, we can declare an outage, if either of the links falls below a given SNR or SINR threshold. Let us denote the threshold as $\gamma_{\mathrm{th}_{\mathrm{R}}}$, then the end-to-end OP for the DF RN assisted transmission can be expressed as

$$P_{\mathrm{out}_{\mathrm{R}}}\left(\gamma_{\mathrm{th}_{\mathrm{R}}}\right) = \Pr\left(\min\left(\gamma_{\mathrm{R}},\, \gamma_{\mathrm{D}}\right) < \gamma_{\mathrm{th}_{\mathrm{R}}}\right), \tag{2.5}$$

where the received SNR or SINR at the RN and the destination is denoted by γ_{R} and γ_{D}, respectively. Expression 2.5 is used as the metric to characterize the performance of DF RNs throughout this thesis.

Lots of works consider to use this type of RNs to either improve the capacity or extend the coverage of wireless networks [16–19]. The studies in [20] demonstrate that the use of half-duplex DF RNs in an LTE-advanced networks outperforms the use of full-duplex AF RNs in terms of spectral efficiency. The studies in [16, 17, 21] show that the DF RNs can be placed in optimal positions either to improve the total cell capacity or total cell-edge capacity in a wireless communication system. In addition, studies in [16, 22, 23] investigate the coverage extension possibilities of using DF RNs from both downlink and uplink point of view in a cellular system. Other aspects of DF RNs, e.g., energy efficiency, power allocation, resource allocation, signaling overhead reduction, etc., are also extensively investigated in previous studies [24–28, and the references therein].

The advanced RNs standardized in LTE release 10 also operate in DF mode. Therefore, previous studies of DF RNs serve as a handy starting point as well as good references for our research of MRNs and MNs. As discussed in Section 4.1, we have used a DF half-duplex FRN as one of the reference schemes in our early studies of MRNs. Moreover, we have considered several performance metrics used in the evaluations of DF RNs in our studies of MRNs and MNs, as well as in setting up our system models. Nevertheless, as the coverage of RNs are usually smaller than regular macro BSs, and the RNs considered in previous studies are usually placed in fixed positions, the results obtained from the studies of fixed RNs cannot be directly applied to our research of MRNs or MNs.

2.2.3. Other types of RNs

There are several other types of RNs that are being intensively studied, both academically and in the standardization bodies. They can be applied in various scenarios where they have clear advantages. These types of RNs include but are not limited to estimate-and-forward (EF) RNs, hybrid AF/DF RNs, and compress-and-forward (CF) RNs. A good review of the recently developed RN schemes is given in [29]. However in this thesis, we do not focus on the use of these RN schemes.

2.2.4. Full-duplex versus Half-duplex

An RN is called half-duplex, if it cannot simultaneously transmit and receive in both directions. More specifically, in a half-duplex RN assisted transmission, it takes two channel uses to transmit one symbol. In contrast, a full-duplex RN can simultaneously transmit in both directions, which implies a higher throughput than the half-duplex RN. However, this comes at a cost of hardware complexity, since high isolation between the transmitter and receiver RF modules is required for the full-duplex RNs. This is especially challenging, if the RN needs to transmit and receive at the same frequency bands at the same time. For the standardized advanced RNs in the LTE system, a half-duplex mode is employed.

2.2.5. In-band versus out-band

"In-band" RNs are RNs that use the same frequency bands for both the backhaul and access links, while "out-band" RNs uses different frequency bands to communicate with the source and destination nodes. One advantage of using "out-band" RN is that the isolation between the transmitter and receiver RF modules can be easily implemented, and therefore, they have the potential to operate in a full-duplex mode, whereas due to self-interference between the transmitter and receiver RF modules, it is challenging to implement a full-duplex in-band RN.

One may argue that a full-duplex out-band RN is similar to a micro BS with wireless backhaul link. However, in the LTE systems, RNs can re-use the existing radio interface used for BS-to-UE device communication, and therefore, they can operate in both LOS and non-line-of-sight (NLOS) propagation conditions. In general, dedicated microwave backhaul links for micro BSs require LOS connections[2], and the interfaces between the core network and the micro BSs are usually manufacture specific. Hence, better compatibility between manufactures can be expected between macro BSs and RNs.

2.2.6. The Use of RN in the Current LTE Systems

In practical cellular communication systems, the use of RNs is fairly common. Analog repeaters have been extensively used from the age of the GSM systems to extend the coverage of macro BSs to heavily shadowed areas or to indoor users affected by severe penetration loss. FRNs with more advanced functionality are standardized in the LTE release 10. In the initial study stage, two types of RNs, i.e., type-1 and type-2 RNs, were defined. Type-1 RNs are non-transparent, both to UE devices and their serving BSs (a.k.a. Donor eNB or DeNB in LTE[3]). From the point of view of a UE device, a type-1 RN appears as a regular BS, which has its own cell ID, control channel, reference and synchronization signals, etc. It also terminates all the layer-2 and layer-3 communication protocols [10, Chp. 30]. Hence, a type-1 RN can be used for both coverage extension and local capacity boosting. From the serving BS perspective, during the initial attachment procedures, most of the standardized radio interfaces for regular BS-to-UE communication are reused. After the initial attachment, the RN identifies itself to the network. Three classes of type-1 RNs are considered during the 3GPP studies, i.e., out-band full-duplex, in-band half-duplex, and in-band full duplex RNs, but at the end, only the in-band half duplex type-1 RNs are finalized in the 3GPP LTE release 10.

In contrast, type-2 RNs only receive a functional description in the 3GPP studies, and no standardization efforts have so far been spent on this type of RNs. Type-2 RNs are fully transparent to the UE devices, and they do not have their own cell IDs. The initial idea was to use this type of RNs to cooperate with the serving BS to improve the local capacity of certain hotspot areas. The standardization of type-2 RNs require much more efforts than the type-1 RNs, as new air interfaces and communication protocols need to be defined to support the cooperation between the serving BSs and the type-2 RNs. Therefore, type-2 RNs are not standardized yet,

[2]Microwave connections also work in certain environment that have strong reflectors or at certain angles of diffraction, but it does not work in a general NLOS environment [30].

[3]Evolved Node B abbreviated as eNodeB or eNB refers to Evolved Universal Terrestrial Radio Access (E-UTRA) Node B. An eNB is a special name in the E-UTRA of LTE for a BS

but they give opportunities for technologies such as CF, EF, and hybrid AF/DF RNs in the future wireless communication systems.

The use of RN has several advantages compared to other low power nodes, e.g., micro or femto nodes, although a micro BS with dedicated backhaul may offer better service to the users than a half-duplex RN node, since there is no half-duplex loss. The deployment of micro BSs requires dedicated backhaul connections, either by wire or LOS microwave connections, which is difficult to achieve in many locations. On the other hand, the advanced FRNs standardized in the current LTE systems, work both in LOS and NLOS backhaul conditions, which is a huge advantage in densely populated cities or in rural areas. Certainly, the half-duplex loss introduced by the standardized FRNs in the LTE systems raises some concerns, and therefore the deployment of the FRNs should be careful, otherwise they may even downgrade the QoS or QoE at the target UE devices. Hence, certain metrics must be considered before introducing a new type of node into the existing network. In next section, we discuss one of the most important metrics, OP, which is usually used to measure the QoS at a UE device.

2.2.7. Mobile Ad Hoc Network

The general idea of using mobile devices as relays to serve users outside the coverage of a BS is not new. In an ad hoc manner, mobile devices can form a mobile ad hoc network (MANET). Without (or with limited) network infrastructure, mobile devices can communicate directly within a MANET [31]. Nowadays, due to the increasing popularity of D2D communications, especially in the next-generation mobile communication systems [32–34], MANET attracts more attentions. Previous studies show that a mobile communication network can benefit from mobile-device-enabled relaying in various ways. For example, as demonstrated in [35], considerable energy savings can be achieved by using randomly parked vehicles to form a nomadic network to relay transmission from BSs to UE devices. Other related studies show that by using D2D-enabled relaying, the coverage of a mobile network can be extended, the system capacity can be increased, and the communication OP can be lowered [33, 34, 36–38].

One challenge faced by MANET is interference management, especially in a densely deployed network. This is because that there is usually no central control nodes in a MANET, and therefore power control or coordinated transmission can only be implemented in a distributed manner [39]. This usually leads to a local optimal or sub-optimal solution. If a central control node is available, certainly MANETS can bring more gains to a mobile communication network [37, 40, 41]. Another challenge of MANET is that it only provides limited support for high mobility users. If there are many high mobility UE devices in a MANET, the network topology may change very fast. Therefore, it may be very difficult to even to find a node to relay the information. As pointed out in section 2.4, complicated inter-cell interference is one of the biggest factors limiting the gains of HetSNets. Therefore, in an interference-limited scenario with high-mobility users, e.g., to serve VUE devices in a densely deployed urban scenario, the MANET solutions cannot be directly applied.

2.3. Outage Probably and QoS Aspects

From a QoS point of view, we can always define a minimum bit error rate (BER) or a code word error rate (CWER) requirement for a service. If these requirements are not satisfied during a given time period, the service may be interrupted and an outage is declared. The tolerances of such disturbances varies from person to person, and this is well exploited in the design of some mobile communication systems, and applications. One classic example is the voice call handling in the current mobile communication systems. During a voice call, if data packets get lost or corrupted, the speech codec error concealment will be triggered, and the lost speech frames will be replaced either by repetition or an extrapolation of the previous correctly decoded speech frame(s). This certainly lowers the voice quality, but as long as it does not occur too often, people can go along with it, or by simply saying "pardon" or "vad sa du"[4], the meaning goes through sooner or later, as the conversation continues. On the other hand, if the call drops very often due to bad connections, lots of people would get upset very easily.

Moreover, the frequency and duration of the outage are also very important when it comes to customer satisfaction. Even if the OP is low on average, the perceptions of customers may tell a different story as people take what they have for granted, and just remember the bad quality of service. For example, the road to support wideband audio (a.k.a. high definition voice quality for telephony audio or HD voice) is very bumpy. The technology has been there for quite a long while, but operators are dallying to support it in their networks. If customers get used to the crystal clear wideband audio services, they will no longer be happy to have the voice quality in the age of GSM. Offering such service will just take more system capacity but not generate much more income for the operators, especially more and more operators have flat rate monthly plans for voice, SMS, MMS and data services. Certainly, the argument of how to provide economical services that satisfy most of the customers never ends, especially when the customers become more demanding, and the foreseeing investment of building infrastructure of the next generation mobile communication systems is tremendous for the operators. Nevertheless, in this thesis, we use the error probabilities as our metric to indicate the QoS, which can be quantified mathematically.

The BER or CWER targets can be mapped to average minimum requirements of the received SNR or SINR at the receiver side. This gives an easier way for the calculation of OP, since a maximum BER or CWER requirement can be translated

[4] "vad sa du" is one of the most common phrases used in Swedish, which means "What are you talking about". People in Sweden use this phrases very often to make sure they understand each other correctly. Please visit http://uncyclopedia.wikia.com/wiki/Swedish_language for more information.

to a corresponding minimum received SNR or SINR [42, Chp. 12]. Therefore, we can express the OP as

$$P_{\text{out}} = \Pr\left(\gamma < \gamma_{\text{th}}\right) = \int_{0}^{\gamma_{\text{th}}} f_{\gamma}\left(\gamma\right)\, d\gamma, \tag{2.6}$$

where γ and γ_{th} are the instantaneous received SNR or SINR and the minimum target of the received SNR or SINR, respectively. The $f_{\gamma}\left(\gamma\right)$ is the probably density function (pdf) of γ. With simplified assumptions, e.g, Rayleigh fading and no shadowing, the closed form expression of $f_{\gamma}\left(\gamma\right)$ can be obtained easily, but when considering practical propagation models together with the effects of inter-cell interference, it is even difficult to obtain $f_{\gamma}\left(\gamma\right)$ numerically, which makes the calculation of the exact OP very challenging. OP can also be used to estimate the design margin of the average received SNR or SINR to guarantee a certain level of QoS [42, Chp. 12].

2.4. Interference Cancellation and Coordination in HetSNets

The potential benefits of using HetSNets are reviewed in Section 2.1. In practical system design, several factors need to be taken into consideration in order to better exploit the advantages of HetSNets. As mentioned before, as the network gets dense, the inter-cell interference becomes one of the factors that limits further improvement of cellular systems. The problem of inter-cell interference becomes more significant after the introduction of cell range expansion (CRE) in 3GPP LTE Release 10 [9,10, Chp. 24 and 31]. CRE is a way to expand the coverage areas of small cells, and therefore more offloading gain can be achieved. In CRE, at small cells, a positive offset is added to their reference signal received power (RSRP), and therefore, more macro users can be offloaded to small cells. The overall uplink quality of the network can be improved [9, 43, 44]. However, due to severe inter-cell interference, CRE degrades the downlink performance, especially for UE devices at the edge of small cells. In order to better exploit the gain from CRE and protect victim UE devices suffering from excessive co-channel interference CCI, the study of ICIC schemes is critical in the setup of HetSNets [7,43,45]. Both frequency and time domain solutions have been extensively investigated to combat the inter-cell interference [46, 47].

In this thesis, we consider the downlink of a communication system when studying the performance of using MRNs or MNs to serve VUE devices. Recall that in this thesis MRNs are assumed to be in-band half duplex DF RNs, while MNs work in a full-duplex fashion with backhaul and access links operating in different frequency bands. More details regarding the application of MRNs and MNs are given in Chapter 4. The use of MRNs are evaluated either in a noise limited system or in a scenario with limited CCI. We do not consider any ICIC schemes, as we are aiming at understanding the worst case performance. However, in order to further understand the use of full-duplex MNs in a typical urban scenario, a more practical deployment scenario needs to be considered. In our work [48, Paper D], we identify that besides the VPL, in an ultra-dense HetSNets urban scenario, inter-cell interference is one of the most significant factors that limit the performance of MNs. Therefore, in order to further improve the performance of MNs in typical urban setups, we need to resort to various interference cancellation and coordination schemes. Besides to eliminate the VPL, another advantage of using MNs is that compared to regular UE devices, public transportation vehicles are less constrained by power, size and transceiver complexity. Therefore, more antenna elements and more advanced signal processing algorithms can be used at the backhaul receivers of the MNs. In this section, we briefly discuss the tools that we can use for interference cancellation and coordination in the current mobile communication systems for the downlink of the communication, especially in the deployment of HetSNets. The performance study of deploying MNs in an ultra-dense HetSNets urban scenario by employing various interference management schemes is presented in Chapter 4.

2.4.1. Solutions Based on Frequency Reuse and Power Control

Various frequency reuse schemes are the classic solutions to reduce inter-cell interference in mobile communication systems. In the GSM systems, where the frequency reuse factor is smaller than 1,[5] neighboring cells are allocated to different carrier frequencies, in order to minimize the interference. Then, the same frequency can be reused in the cells that are at certain distance away, where the interference level is below a given threshold. Frequency reuse with a frequency reuse factor smaller than 1 lowers the spectrum efficiency of the system due to the reuse distance, but this is an effective solution, especially for a system like GSM that only offers fixed data rate voice communications. Another tool that is used to control the inter-cell interference is power control. For example, in a GSM system, as frequency reuse factor is smaller than 1, cell splitting is used to increase the number of available channels in areas that have high call volumes. By adjusting the transmit power levels and possibly together with reducing the antenna height, the coverage area of a cell is reduced, and therefore, the same frequency can be reused in a much shorter distance [42, Chp. 17]. In wideband code division multiple access (WCDMA) systems, even though the frequency reuse factor is 1, i.e., all the cells can transmit at the same frequency at the same time, power control is still commonly used to combat the cell breathing effects [49].

The LTE systems also have a frequency reuse factor of 1, therefore, power control and dynamic frequency reuse are integrated to the LTE system, from the very beginning of the system design stage. For example, a common way to handle the inter-cell interference in through the so-called soft frequency reuse or coordinated scheduling schemes. Soft frequency reuse is a static solution, and the idea of soft frequency

[5]In this thesis, we adopt $1/K$ as frequency reuse factor, where K is the number of cells that cannot transmit at the same frequencies. In some literature, K is called frequency reuse factor.

reuse is that the BS can serve the cell center users by using all the available spectrum, but each cell is restricted to only use part of the available bandwidth to serve the cell-edge users. In order to adapt to the dynamic traffic demand, coordinated scheduling schemes are introduced. A group of neighboring cells coordinate their physical resource block (PRB) allocations to minimize the inter-cell interference. In order to support soft frequency reuse and coordinated scheduling, the relative narrow-band transmit power (RNTP) indicators are defined in the LTE system to indicate the power allocation status of PRB, and RNTP indicators are exchanged via the standardized X2 interface between BSs to facilitate the scheduling decisions. An example of using RNTP information for interference coordination is given in [50].

2.4.2. Time Domain Solutions

The solutions in the early release of the LTE system are very coarse, and they are mostly targeting at a homogeneous deployment. People begin to notice their limitations in a HetSNets setup, especially with densely deployed micro and femto cells. Therefore, as a result of the extensive studies of enhanced inter-cell interference coordination (eICIC) schemes in 3GPP LTE release 10, the use of almost blank subframes (ABSs) is standardized [10, Chp. 31.2.2] [44,51–53] to protect UE devices that are subject to severe CCI. The idea behind the ABSs is that the aggressor BSs inflicting severe CCI onto others can be periodically muted for some subframes, so that the victim UE devices can have chance to get service from their serving BSs. In ABSs, no user data is transmitted. However, control channels and cell-specific reference signals still need to be transmitted during these subframes, possibly with reduced power. In 3GPP LTE release 11, the use of ABS has been further extended to reduce the power in the ABS as a part of the further enhanced inter-cell interference coordination (FeICIC) framework [54] , where instead of completely muting the user data, the data channel can also be transmitted on with reduced power.

Fig. 2.2 shows an example of the use of ABSs at the downlink of a macro cell. The macro BS configures a set of ABSs, and the ABS pattern is sent to the micro BS through the X2 interface. During these ABSs, the micro BS prioritizes its UE devices at the cell edge, typically in the CRE region, to receive the downlink information, both control and user data. In our study, we consider to both configure ABSs at macro BS sectors, and micro cells to protect the backhaul and access links of MNs. Detailed results are presented in Section 4.2.

2.4.3. Multi-antenna Solutions

As mentioned before, the public transportation vehicles have their natural advantages of deploying more antenna elements compared to the regular UE devices. Therefore, in this section we discuss the multi-antenna solutions considered in our studies. In this thesis, we consider a single antenna at each sector of the macro BS,

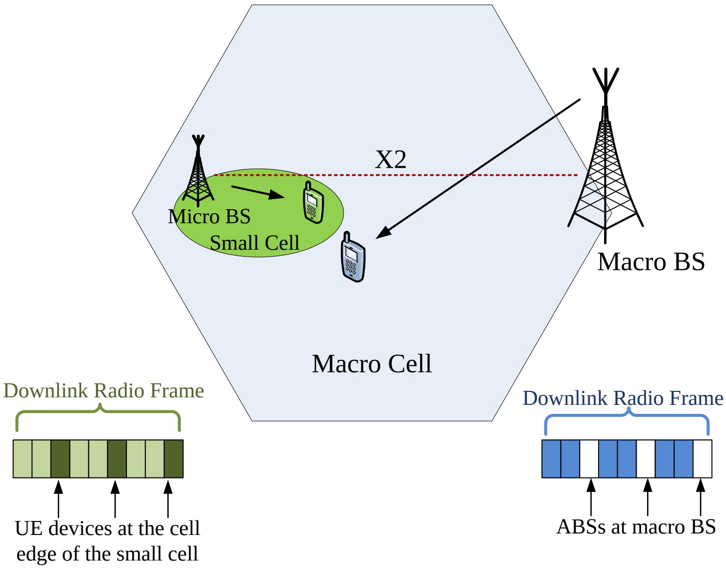

Figure 2.2.: An example of using ABSs at the macro cell. Macro cell configures the ABSs to protect the UE devices at the cell edge of the small cell. The ABS pattern is communicated through the X2 interface. The micro BS priorities the cell edge UE devices in the ABSs configured by the macro BS.

and the receivers at the backhaul links of the MNs are equipped with multiple antennas. The concept of using multiple receiving antennas in wireless communication systems has a long history [42, Chp. 20]. In practical deployment, depending on the availability of CSI from the interferer, various schemes can be applied to improve the received SINR [42, Chp. 20]. In this study, we consider two methods, i.e., maximum ratio combining (MRC), and SINR maximization by suppressing the interference.

Suppose there are p antennas at the receiver, and in a frequency flat fading case, e.g., within a PRB, at time k, the received signal is given as

$$\mathbf{y}_k = \mathbf{h}_k\, x_k + \sum_{j=1}^{L} \mathbf{h}_{j,\,k}\, x_{j,\,k} + \mathbf{n}_k, \tag{2.7}$$

where x_k and $x_{j,\,k}$ are the desired signal and the interfering signal from the jth interferer, respectively. The $p \times 1$ column vector $\mathbf{y}$ is the received signal at each antenna. Moreover, the desired and jth interfering signal propagation vectors are represented by $\mathbf{h}_k$ and $\mathbf{h}_{j,\,k}$, respectively, and $\mathbf{n}_k$ is the thermal noise. The desired signal and interfering signals are assumed to be uncorrelated. At the receiver, at time k, let $\mathbf{w}_k$ represent a vector that contains the weights applied at each antenna, and then the combined output signal $\mathbf{z}_k$ is given as

$$z_k = \mathbf{w}_k^{\mathrm{H}}\, \mathbf{y}_k = \mathbf{w}_k^{\mathrm{H}}\, \mathbf{h}_k\, x_k + \sum_{j=1}^{L} \mathbf{w}_k^{\mathrm{H}}\, \mathbf{h}_{j,\,k}\, x_{j,\,k} + \mathbf{w}_k^{\mathrm{H}}\, \mathbf{n}_k. \tag{2.8}$$

The received SINR at time k is calculated as

$$\gamma_k = \frac{\mathbf{w}_k^{\mathrm{H}}\, \mathbf{h}_k\, \mathbf{h}_k^{\mathrm{H}}\, \mathbf{w}_k}{\mathbf{w}_k^{\mathrm{H}} \left(\sum_{j=1}^{L} \mathbf{h}_{j,\,k}\, \mathbf{h}_{j,\,k}^{\mathrm{H}} + \mathbf{R}\right) \mathbf{w}_k}, \tag{2.9}$$

where $(\cdot)^{\mathrm{H}}$ denotes the complex conjugate transpose, and $\mathbf{R}$ is the noise covariance at the receiver antennas, same for all k. In this study, we assume the noise at each of the antennas is independent and has the same power σ_{n}^2, i.e., $\mathbf{R} = \sigma_{\mathrm{n}}^2\, \mathrm{I}_{p\times p}$, where $\mathrm{I}_{p\times p}$ represents the identity matrix of size p. The problem becomes how to maximize γ_k.

If only the CSI of the desired signal can be estimated at each of the antennas, i.e., $\mathbf{h}_k$, but the interfering channel vectors $\mathbf{h}_{j,\,k}$ cannot be obtained, MRC can be used to combine the desired received signal from each antenna constructively. Therefore, the desired signal power can be maximized, i.e, an MRC receiver is optimal in terms of SNR [55]. The MRC solution is given by using the combining weights as $\mathbf{w}_k^* = \mathbf{h}_k$, and yields the instantaneous output SINR as

$$\gamma_k = \frac{\mid \mathbf{h}_k^{\mathrm{H}}\, \mathbf{h}_k \mid^2}{\mid \sum_{j=1}^{L} \mathbf{h}_k^{\mathrm{H}}\, \mathbf{h}_{j,\,k}\, x_{j,\,k} + \mathbf{h}_k^{\mathrm{H}}\, \mathbf{n}_k \mid^2}. \tag{2.10}$$

MRC is a good choice in situations where there are relatively large number of interfering signals with similar strength. However, a message from (2.10) is that though at a given time k the output power of the desired signal is maximized, the SINR is not necessary maximized because of the interfering signals. Nevertheless, if no CSI from the interferer can be observed, MRC is the best we can achieve to maximize the received desired signal power.

We can do better if the CSI of the interfering signals, i.e., $\mathbf{h}_{j,\,k}$ can be obtained, as we can exploit the use of multiple receiving antennas to suppress the interfering signals, and therefore maximize the output SINR. This method falls into the category of interference rejection combining (IRC) [56] [57, Chp. 10]. To find the optimal combining weights that maximize the output SINR, we have to solve the following problem

$$\mathbf{w}_k^* = \arg\max_{\mathbf{w}_k} \frac{\mathbf{w}_k^{\mathrm{H}}\, \mathbf{h}_k\, \mathbf{h}_k^{\mathrm{H}}\, \mathbf{w}_k}{\mathbf{w}_k^{\mathrm{H}} \left(\sum_{j=1}^{L} \mathbf{h}_{j,\,k}\, \mathbf{h}_{j,\,k}^{\mathrm{H}} + \mathbf{R}\right) \mathbf{w}_k}. \tag{2.11}$$

This problem is a generalized eigenvalue problem, and the solution for the optimal combining weights $\mathbf{w}_k^*$ is given as [56]

$$\mathbf{w}_k^* = \mathrm{EIG}_{\max}\left(\left(\sum_{j=1}^{L} \mathbf{h}_{j,\,k}\, \mathbf{h}_{j,\,k}^{\mathrm{H}} + \mathbf{R}\right)^{-1} \mathbf{h}_k\, \mathbf{h}_k^{\mathrm{H}}\right), \tag{2.12}$$

where $\mathrm{EIG}_{\max}(\cdot)$ denotes the dominant eigenvector of a matrix[6].

[6] A dominant eigenvector is the eigenvector corresponding to the eigenvalue of the biggest magnitude.

The detailed evaluations of using ABSs and the aforementioned MRC and IRC solutions at MNs in an ultra-dense urban deployment are presented in details in [48, Paper D], and summarized in Section 4.2.

2.5. Motivation of the Thesis Work

In this thesis, we focus on a particular user group, i.e., the VUE devices. This is not only because the number of VUE devices will be significant in the near future, but also it is very challenging to serve them cost-effectively, especially when ubiquitous connectivity and QoS are expected by these VUE devices. In this thesis we are not aiming at developing a new air interface, new coding and modulation schemes, or new relaying schemes to serve the VUE devices, but we would like to understand whether there are benefits and what are the associated challenges of introducing new type of nodes, i.e., MRNs and/or MNs, to the existing mobile communication systems to serve the VUE devices.

In our opinion, the use of MRNs or MNs is one of the most promising solutions to meet the service needs at the VUE devices, but it is always challenging to add a new type of node to the existing system. In order to understand the potential benefits of using MRNs or MNs, we begin our work with the study of using MRNs to serve the VUE devices. The MRNs we have studied are assumed to be in-band and half-duplex, which is similar to the standardized FRNs in the current LTE system. In order to compare the performance, we use the BS-to-VUE direct transmission as well as transmission assisted by FRNs as our baseline cases. Furthermore, for a fair comparison, in our studies that involved FRNs, the positions of the FRN are optimized either by analytic study, numerical optimization, or through extensive system level simulations. In our current studies of MRNs or MNs, only the downlink of a communication system is considered.

We begin our study in a noise limited system in the presence of flat Rayleigh fading. We observe that as VPL increases, the use of MRNs can significantly lower the end-to-end OP at the VUE devices. Moreover, if we keep the end-to-end OP requirement at the VUE devices, the use of MRNs can significantly lower the total system radio frequency (RF) energy consumption compared to the baseline cases. The study continues to a system where the communication is corrupted by limited amount of co-channel interference (CCI), where a 2-cell setup is considered, and practical channel models are employed. Furthermore, due to the mobility of the VUE devices, a comprehensive framework of optimizing the handover (HO) parameters of MRNs are proposed. In such scenarios, the MRN shows great advantage compared to both BS-to-VUE and FRN assisted transmission at lowering the end-to-end OPs at the VUE devices. Finally, the performance of full-duplex MNs deployed in an ultra-dense urban scenario is investigated within the agreed setup of the EU 5G project METIS. Firstly, the interference situation is identified at both of the backhaul and access links of MNs. Then, several different interference coordination and interference cancellation schemes are compared. We have shown that by using advanced interference coordination and interference cancellation schemes, the use of MNs can improve the throughput at the VUE devices noticeably with little impacts on the regular outdoor UE devices. Those details are presented in Chapter 4.

The rolling out of MRNs or MNs may take some time. Therefore, as an alternative to the use of MRNs or MNs, we also study the possibilities of using D2D enabled cooperative transmission between VUE devices to enhance their uplink communication with the BS. We have shown that when the communication is affected by high VPL, by using the cooperative transmission between VUE devices, even when we include the energy consumed by the D2D transmission, the energy expanded on per information bit by each VUE device is significantly lowered compared to the VUE-to-BS direct communication. The details of this scheme are given in Chapter 5.

3. Conventional Solutions to Serve Vehicular Users

The difference between a mobile communication system and a wireless communication system is that in a mobile communication system, there are mechanisms to support user mobility, while mobility support in a general wireless communication system, e.g., a WiFi system, is not mandatory. For LTE systems, it is required to support up to a velocity of 350 km/h when a UE device is moving, and depending on the frequency band, in some extreme cases, the LTE system can offer service to UE devices at a velocity of 500 km/h [10, Chp. 1]. However, due to the difficulties of obtaining CSI at the BS side, various diversity schemes need to be used for high speed terminals, and therefore, compared to stationary or low speed users, much lower user throughput is achieved at high mobility user terminals.

We are expecting a significant amount of data hungry VUE devices in the near future, and this becomes a big challenge in a mobile communication system. When a group of VUE devices are traveling together in a high speed vehicle, it is likely that they are sharing a limited amount of the time and frequency resources from the same BS, especially in suburban or rural areas. In addition, the communication is affected by the VPL, which means some of the time and frequency resources are required to compensate the power loss caused by the VPL. Therefore, it is very challenging to provide high throughput for the data hungry VUE devices. Several solutions based on using the existing system elements to serve these VUE devices are discussed in 3GPP [58]. These solutions include optimizing the deployment of macro cells, using layer-1 repeaters or WiFi access points (APs). However, these are temporary solutions, and all these solutions have their limitations. As the number of VUE devices increases, in our opinion, the dedicatedly deployed MRNs or MNs on public transportation vehicles, is one of the best and ultimate solutions to provide service to the VUE devices. In Chapter 4, we discuss the use of MNs in details, while in this chapter, we briefly review the solutions that can be offered by the current system in terms of their pros and cons. All layer-1 repeaters, WiFi APs MRNs and MNs communicate with the macro cell through radio interfaces, but there are two differences between the use of MRNs or MNs and the other schemes. Firstly, the VUE devices see the MRNs or MNs as regular BSs. Secondly, MRNs and MNs can potentially support multi-RAT, e.g., LTE, HSPA, GPRS, GSM etc.[1], and even WiFi can be integrated as a part of the access links of MRNs and MNs.

[1]RAT: Radio Access Technologies; GPRS: General Packet Radio Service; HSPA: High Speed Packet Access.

3.1. Dedicated Deployment of Macro BS

The use of an umbrella cell approach to serve users with different mobility is not new. In the age of 2G, a common practice for operators is to use different antenna heights (often at the same site) with various power levels to create co-located "large" and "small" cells that provides service for users with different mobility [59, Chp. 2]. This approach has been further developed under the concept of HetSNets in the current mobile communication systems, where more network elements are introduced (see Section 2.1). As the routes of the public transportation vehicles are usually known, especially for high speed trains and inter-city coaches, by proper site planning, the coverage of the macro BSs can be optimized along the routes of the public transportation vehicles.

In addition to the solutions offered by the umbrella cell approach, the HetSNets toolbox offers more elements that can be used to further improve the performance at the VUE devices. For example, with carrier aggregation (CA), the primary component carriers (PCCs) are transmitted by high-power BSs, and low-power nodes, which can be deployed along the routes of the public transportation vehicles, can transmit the secondary component carriers (SCCs). By using cross-carrier scheduling, the control signals can be carried by the PCCs, and the SCCs can be used to boost the data rate at the VUE devices. If CA is not possible, e.g., due to limitation of spectrum, RRHs can be used. Since RRHs can have the same cell ID as the macro BSs, the closest RRH can serve the high speed VUE devices without triggering HO. The standardized dual connectivity is another a good alternative. User terminals that support dual connectivity, can receive the control signals from the high power macro BSs, but acquire the data channels from the close-by small cells. Therefore, due to the wide coverage area of the macro cells, the HO overhead at the network side for high speed VUE devices can be reduced, and the data capacity can be boosted by the small cells.

However, these solutions cannot combat the VPL, which significantly attenuates the received signal power at the VUE devices. Furthermore, site acquisition and maintenance are also problems for the operators, due to the requirement of dedicated backhaul connections, power supplies, etc. Furthermore, as this is a dedicated solution for VUE devices on trains or inter-city coaches, it is challenging to extend it to densely deployed urban scenarios, where VUE devices on metro buses or trams are not the solo concerns in the network. In Section 4.2, we give detailed discussion regarding this scenario.

3.2. The Use of Layer-1 Repeaters

Layer-1 repeaters are analog, which amplify and forward signals in given frequency bands. Layer-1 repeaters can be deployed on well-insulated vehicles, and by proper placement of the outdoor and indoor antennas, the VPL can be overcome, and therefore, the user terminal transmit power can be lowered. Since little signal processing is needed, these repeaters are relatively low cost compared to the advanced FRNs in LTE. Moreover, on the vehicles of our interest, the repeaters can work in a full-duplex mode, as sufficient isolation between the transmitter and receiver chains can be achieved by well separation of the outdoor and indoor antennas. This is an advantage compared to the half-duplex RNs standardized in LTE.

However, there are several obvious disadvantages of using layer-1 repeaters. The layer-1 repeaters are less controlled by the network. Hence, fast power control and advanced interference management schemes cannot be applied. Although the VPL can be circumvented, it is not certain that the SINR can be improved by using the layer-1 repeaters, since rather than regenerating the signals, they just amplify and forward the received signals in the given frequency bands. Therefore, these repeaters can only be applied at positions with SINR advantages, and the interference is not the primary concerns. This certainly is very challenging at vehicles with high mobility as well as in densely deployed urban areas with complicated interference situations.

3.3. LTE as Backhaul, WiFi as Access Scheme

In order either to improve competitiveness in the market, or satisfy the needs of internet access for users on board, train companies and cities begin to deploy WiFi APs on trains or metro buses. There are several companies offering various commercial solutions to build WiFi networks on public transportation vehicles. As most of the smartphones, not to mention tablets and laptops, are WiFi-capable, this solution causes minimum impacts on the current mobile communication systems. Moreover, WiFi only devices can also benefit from this solution, and bring extra income for the service providers. Similar to the Layer-1 repeaters, a wireless backhaul node with antennas outside the vehicle is used to communicate with the cellular network as a regular UE device, while the data services are provided to the VUE devices through one or several WiFi APs inside the vehicle. In this way, the VPL can be circumvented, and group HO of the data users can also be done. If both the network and the VUE device support WiFi calling, it can use the WiFi connection for all services, e.g., voice, messages and data [60, 61]. Otherwise, a VUE device can directly connect to the cellular networks for the regular phone calls and messages services, while the data traffic can be routed through the WiFi connections. Depending on the solution providers, some advanced functions, e.g., data compression, traffic optimization, aggregation of backhaul links from different cellular networks, can also be added on at additional costs [62].

However, having a tight integration of the WiFi technology to the current cellular network to provide seamless experience to the users is still very challenging. The recent 802.11x extension of WiFi, offers roaming possibilities for the WiFi networks. However, the current WiFi technology is not as secure as the cellular networks, and man-in-the-middle attacks are almost unavoidable, due to the lack of proper user identification and mutual authentication capabilities. The use of virtual private network (VPN) can be one of the ways to improve the security at some additional costs, but the users need to be educated and get used to it. Another solution is to use the universal subscriber identity module (USIM) in the user terminals for the authentication process, e.g., the architecture used in WiFi calling, but this solution needs the support from both mobile operators and devices. Hence, it is not certain that the cost could be less than the deployment of MRNs or MNs. Furthermore, since WiFi is operating on the open industrial, scientific and medical (ISM) radio bands, the interference conditions is less controlled compared to in the dedicated frequency bands owned by operators. Although the 802.11e amendment of WiFi standards has QoS support, it only works when all the WiFi APs belong to the same WiFi network. Even on the trains or inter-city coaches, people are using either their mobile phones or dedicated devices to create WiFi hotspot for data tethering, not to mention in densely populated cities, where WiFi APs are deployed randomly almost everywhere. Therefore, this solution only works in a best-effort fashion to serve the VUE devices, and it is impossible to promise similar levels of QoS as a user may expect from cellular networks. The use of LTE in unlicensed spectrum is standardized in LTE release 13, which gives another advantage of using MRNs or MNs over the WiFi based solutions.

4. The Benefits and Challenges of Deploying Moving Networks

Compared to solutions discussed in Chapter 3, dedicated deployment of MRNs or MNs on public transportation vehicles provide a new cost-effective way to better serve the VUE devices on board. MRNs or MNs are low power nodes mounted on the public transportation vehicles to serve the VUE devices on board, as shown in Fig. 2.1. The advantages of deploying a dedicated MRN or MN is not only because the VPL can be circumvented by proper antenna deployment but also since they are not limited by size or power as regular UE devices, more antenna elements and advanced signal processing schemes can be used to further boost the performance. For example, in a cooperative and coordinated relay system (CCRS) deployed on top of a train [63], several backhaul antennas can be interconnected. In this way, the backhaul link can be strengthened by using antenna selection techniques. The studies in [64,65] demonstrated the gains of deploying mobile relays in LTE-advanced networks. In [15, 66], the so called predictor antennas are tested on a minivan to facilitate the channel prediction. It is demonstrated that reliable CSI can be obtained to support various advanced closed-loop MIMO schemes for high speed user terminals. Moreover, most of the standardized physical layer interfaces of the FRN in the current LTE system can be reused by the MRNs or MNs. At the access links of the MRNs and MNs, there is also the possibility to support multi-RAT functionalities, i.e., GSM, GPRS, HSPA, LTE, WiFi etc. In addition, by regarding the MRNs or MNs as super users in the system, group HO of the VUE devices served by the same MRN or MN can be performed at the RAT side, which is very beneficial from a system architecture point of view, since the HO failure probabilities can be lowered [14]. From a system perspective, in [58,67,68], several different architectures have been proposed and studied in order to support the deployment of MRNs or MNs into the current mobile communication systems.

In this chapter, we begin the discussion of the deployment of MRN, in both a noise limited system and a system with limited CCI as well as the mobility aspects of MRNs. After addressing the use of MRNs, we discuss the use of MNs in an ultra-dense urban scenario. Recall that in this thesis MRNs are assumed to be in-band half duplex DF RNs, while MNs work in a full-duplex fashion with backhaul and access links operating in different frequency bands.

4.1. The Use of MRN to Serve VUE Devices

In order to understand the benefits of introducing a new type of node to the current system to serve the VUE devices, we begin our study with deploying a half-duplex DF MRN in a noise limited, single cell setup. The detailed study of this scenario is given in [69, Paper A], and the end-to-end OP is used as the metric to evaluate the performance. As pointed out in Section 2.3, OP is defined as $P_{\text{out}} = \Pr(\gamma < \gamma_{\text{th}})$. If a half-duplex DF RN is assumed, to support the same end-to-end rate of $\mathcal{R}$ bits/sec/Hz at the UE device, it is required that both the backhaul and the access links need to support a rate of $2\mathcal{R}$. Thus, we need to satisfy $\min(\gamma_{\text{RN}}, \gamma_{\text{UE}}) \geq \gamma_{\text{th}}$, where $\gamma_{\text{th}} = 2^{2\mathcal{R}} - 1$, and γ_{RN}, γ_{UE} are the instantaneous received SNR or SINR at the RN and the UE device, respectively.

Compared to the direct BS-to-VUE transmission, the half-duplex MRN assisted transmission shows its advantage when the communication is affected by moderate to high VPL and the VUE device is moving away from the BS. A half-duplex decode-and-forward FRN assisted transmission is also used as reference, where the FRN position is optimized. In [69, Paper A], we show that if the position of the VUE device is known, the optimized FRN position that minimizes the end-to-end OP at the VUE device is a function of the VPL and the ratio between the transmit power of the BS and the FRN. Fig. 4.1 plots the optimal FRN position as a function of VPL assuming the VUE device position is known, and a typical urban propagation condition is considered. The plot indicates that, an FRN should be placed to a VUE device as close as possible, if the communication is affected by a high VPL. This motivates the use of MRNs to serve VUE devices affected by high VPL.

In a system where the communication is affected by limited amount of CCI, the use of MRNs has more advantages than just circumventing the VPL. The access links of an MRN use much lower power compared to a macro BS, and therefore the interference generated by the access link of an MRN is much lower. Moreover, the vehicle itself can further attenuate the interference leaked from the access link of an MRN. In [70], we investigate the performance of serving a VUE device by MRN assisted transmission in a two cell setup, where the communication is corrupted by CCI. When only small scale fading together with pathloss is considered, at moderate to high VPL, we show that MRN can significantly lower the end-to-end OP at the VUE device compared to direct BS-to-VUE and FRN assisted transmission. For example, at 30 dB VPL, on average, the half-duplex MRN considered in the study can lower the end-to-end OP by 65% compared to the direct BS-to-VUE transmission.

Our study of the use of MRNs is further extended to a more comprehensive setup in [71, Paper B], where for different links, practical propagation models including pathloss, shadowing, as well as small scale fading are considered. Moreover, in [71, Paper B], we proposed a general framework that optimizes the HO related parameters in order to better study the end-to-end OP performance of using MRNs when considering the effect of HO between the BS and the MRNs or FRNs. The studies in [71, Paper B] show that in order to minimize the ping-pong effect, i.e.,

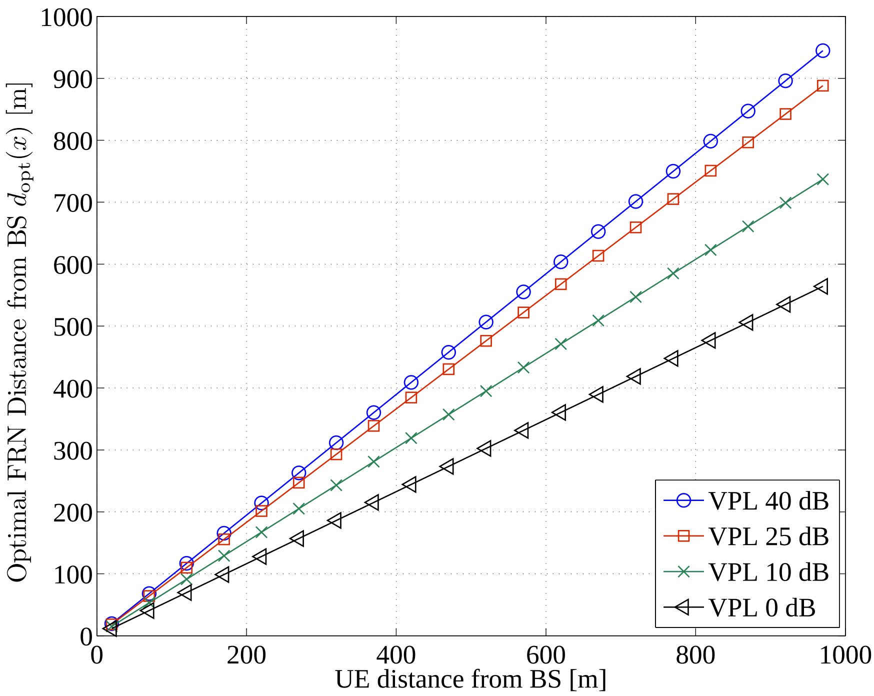

Figure 4.1.: Optimal FRN position in a noise limited system when the position of the VUE device is known.

a VUE device is handed over back and forth between the BS and the MRN, it is necessary to observe relatively long time before performing the HO. Furthermore, when VPL is moderate, it is preferred that the VUE devices are served by the BSs for a longer time before they are being handed over to the MRNs. However, when the VPL is higher, the VUE devices prefer an early HO to the MRNs in order to lower the OP.

Figs. 4.2 and 4.3 plot the end-to-end OP of the considered schemes at different VPL values, where the HO parameters and the position of the FRN are optimized against the end-to-end OP at the VUE device with a velocity of 70 km/h. The optimal FRN position is at 825 meters for both cases. In the plots, the MRN worst case refers to the case that the interfering MRN generates the most interference. As a comparison, we also use the HO parameters obtained for the MRN average case to study the performance for the MRN worst case setup, which is labeled as non-optimized in the plots. Furthermore, the HO parameters are cell specific, i.e., we use the same HO parameters for different positions when the performance of the VUE device is studied.

From the plots, we can see that when the VPL is moderate, i.e., VPL is at 10 dB, the half-duplex MRN assisted transmission gives almost the same performance as the BS-to-VUE direct transmission after the VUE device is handed over to the MRN. This is because higher received SINR is required for the backhaul link to compensate the half-duplex loss (recall that the required date rate need to be doubled

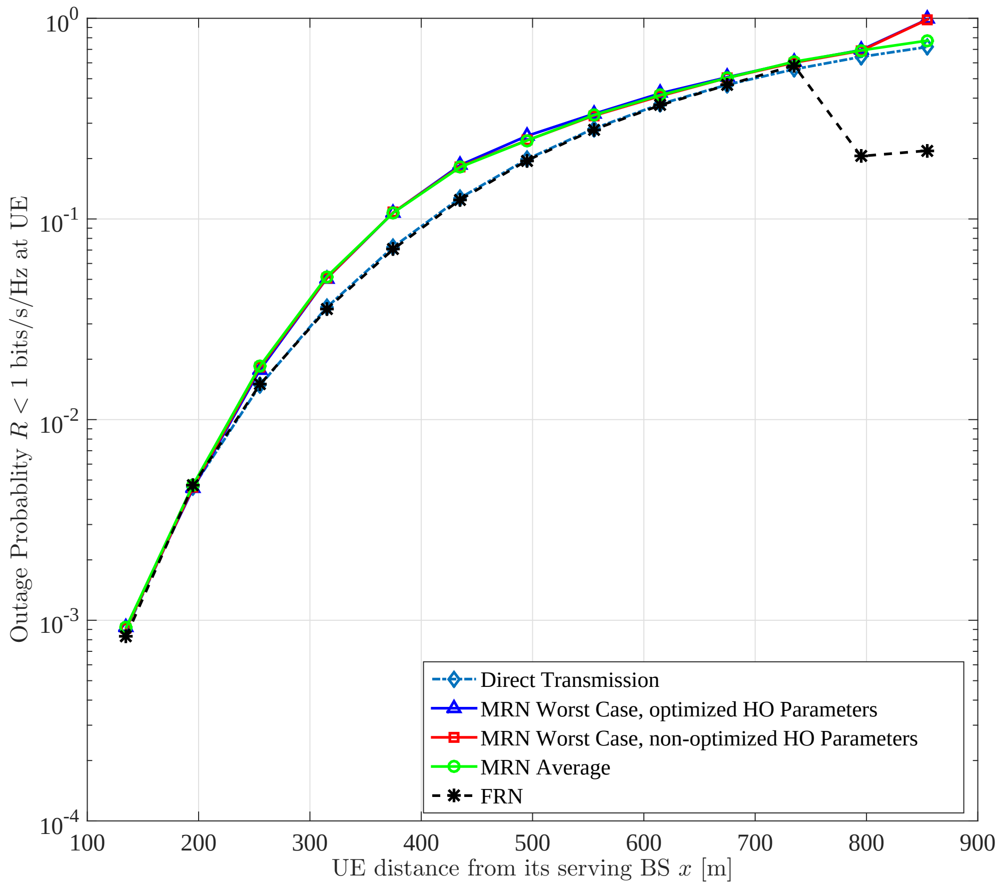

Figure 4.2.: OP at the VUE device when the VPL is at 10 dB.

to compensate for the half-duplex loss). When the VPL increases to 30 dB, the advantage of using MRN to serve the VUE device is very significant compared to the BS-to-VUE direct transmission, and the half-duplex FRN assisted transmission. This is not only because the MRN can eliminate the VPL, but also that the vehicle can attenuate the CCI to the access link from the neighboring cell. Detailed results and analysis are given in [71, Paper B]. Moreover, the interference generated by the access link of the MRN can be well isolated inside the vehicle, and therefore less interference from the access link of the MRN is generated for the UE devices outside the vehicle. This is much appreciated in a densely deployed urban scenario, which we will discuss more in details in the next section.

When the VPL is high, i.e., VPL is at 30 dB, applying the non-optimized HO parameters to the MRN worst case gives a bit better performance comparing to the optimized HO parameters for the MRN worst case when the VUE device is near the serving BS. This is because the HO parameters are cell specific, i.e., regardless of the VUE device position, the same HO parameters are used. Therefore, when the VUE device is closer to the serving BS, its situation is more similar to the MRN average case, as the interference from the MRN in the other cell is small,

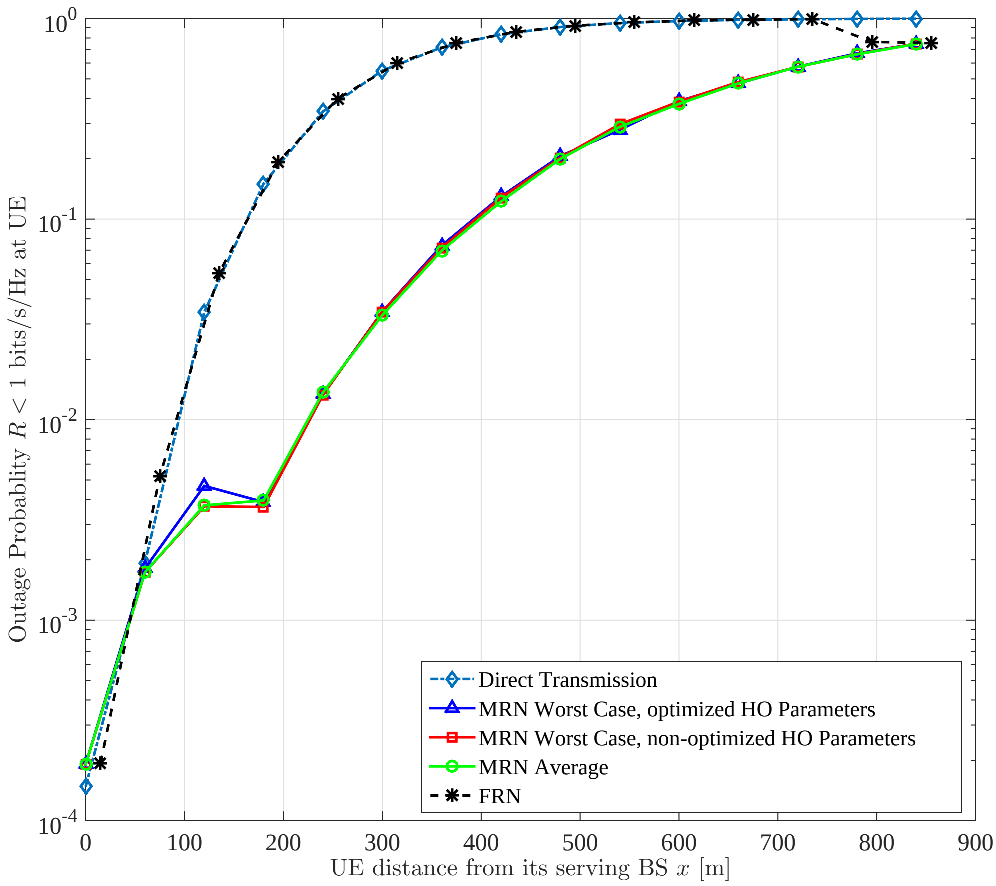

Figure 4.3.: OP at the VUE device when the VPL is at 30 dB.

and the HO parameters obtained from the MRN average case are more suitable for these positions. However, the overall average OP observed for all three cases are quite similar (see [71, Paper B]). Therefore, we can safely apply the HO parameters obtained by the average case to all cases, which will ease the network planning and HO parameter optimization process.

As we can see from Figs. 4.2 and 4.3, after a VUE device has been handed over to an FRN, the use of FRN can help to lower the OP at the VUE device. However, because of the low output power of the FRN as well as the half-duplex loss, the benefit of using an FRN to serve a VUE device is very limited. For most of the time, the VUE device prefers to be served by the BS directly. If HO is not possible between the serving BS and the FRN, then very high OP is observed for the FRN assisted transmission, especially at high VPL [71, Paper B].

4.2. Moving Networks in an Ultra-dense Urban Scenario

In the previous section, we discussed the performance of using an MRN to serve a VUE device in a well isolated vehicle. The OP at the VUE device can be much improved. Previous assumptions assume the MRN is in-band, half-duplex and decode-and-forward. However, if there are possibilities to free up more frequency bands in the future, MRNs can work in a full-duplex fashion, and formulate the so call MNs inside a public transportation vehicle. In the point of view of the EU 5G project METIS, a HetSNets deployment is inevitable in the next generation mobile communication networks, where high power macro BSs are used for basic coverage and small cells are used to boost the local capacity for low mobility users. In order to further understand the benefits and challenges of deploying full-duplex MNs in an ultra-dense urban scenario, in [48, Paper D] we study the downlink of a densely deployed mobile network in the presence of MNs by using the HetSNets framework defined in the METIS framework, i.e., the Madrid grid model [3]. We show that by using MNs together with effective interference management schemes, the QoS at VUE devices can be noticeably improved with negligible impact on the throughput of regular outdoor users.

Fig. 4.4 shows the abstract and simplified HetSNets deployment in the Madrid grid model suggested by METIS, where the performance of MNs are studied. We follow the setup of the calibration deployment given in [3, Table 3.7], where the macro BS has 3 sectors and operates at 800 MHz frequency band with a 20 MHz bandwidth, and each micro BS has two sectors and operates at 2.6 GHz frequency band with a 80 MHz bandwidth. The MNs are deployed on the buses with the backhaul links communicating with the macro BS at the 800 MHz frequency band, and serve their VUE devices at the 2.6 GHz frequency band. The same physical layer setup as the current LTE system is used, i.e., the PRB size, the subframe length, the modulation and coding schemes, and the link adaptation constraints.

In an ultra-dense urban scenario, besides the VPL, the inter-cell interference exacerbated by the urban canyon effect plays another important role in limiting the improvement of the system performance. Fig. 4.4 also plots the SINR that typical outdoor UE devices experience on the street in the considered Madrid grid setup. The outdoor UE devices are assumed to always connect to the strongest cell (5 dB CRE is considered for the micro cells). Clearly, we can observe that in a densely deployed scenario, being close to a BS does not guarantee a high SINR all the time, e.g., between macro sector 2 and sector 3. Similar situation applies for the VUE devices served by the MNs. Although the VPL can be circumvented by using MNs and the SNR at the VUE devices is much improved, due to the severe inter-cell interference, the SINR improvement at the VUE devices is very limited, as the VPL attenuates the desired signal and the interference by the same factor. Fig. 4.5 plots the cumulative distribution function (cdf) of SNR and SINR at backhaul receivers of MNs, and the VUE devices when the VPL is 15 dB. As we can see from Fig

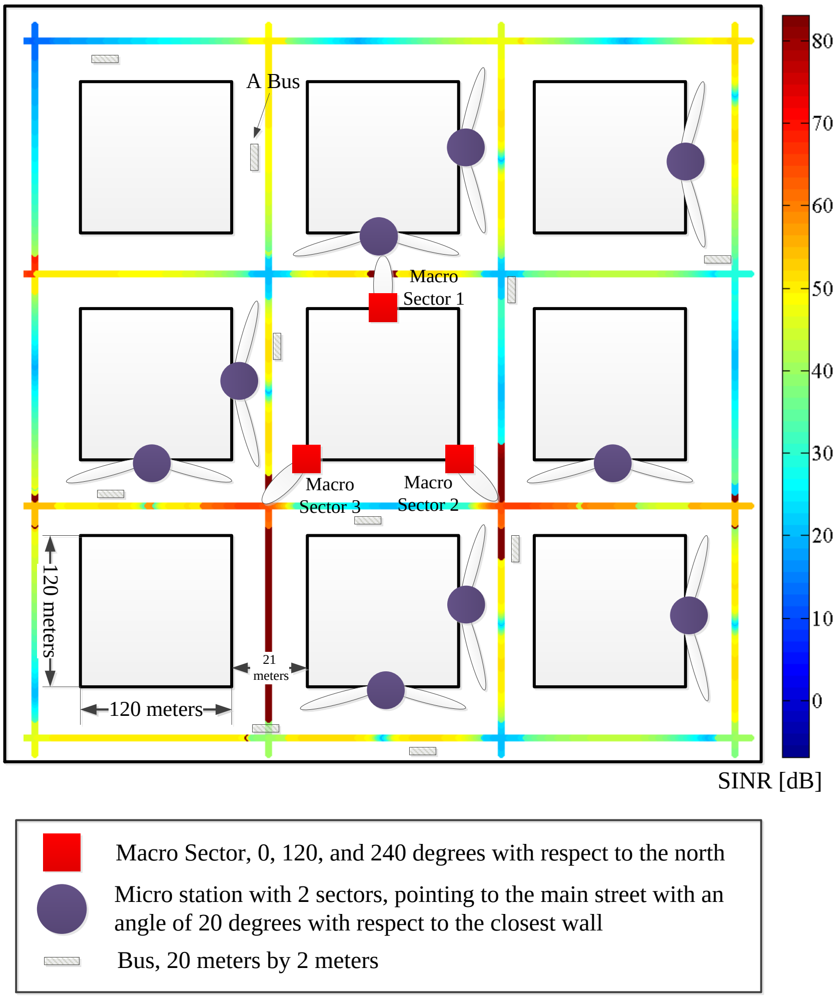

Figure 4.4.: Simplified Madrid grid model with a heterogeneous deployment of micro and macro BSs. The detailed parameters used for this plot are given in [48, Paper D].

4.5, the SNR improvement at VUE devices is very significant, but only slightly improved SINR at the MN backhaul links can be observed due to better propagation conditions for the desired signal.

Therefore, in order to improve the performance of using MNs to serve VUE devices, we have to alleviate the problem caused by the inter-cell interference. As discussed in Section 2.4, there are several ways to combat the inter-cell interference in a HetSNets setup. In [48, Paper D], at macro cells, we consider to use the time domain method, the ABS, or the use of multi-antennas at the receivers of the backhaul links of MNs to alleviate the impact of inter-cell interference. The use of multi-antennas at MNs is another advantage compared to regular UE devices, as MNs are less constrained by power, size and transceiver complexity. Therefore, more antenna elements can be accommodated, and more advanced signal processing

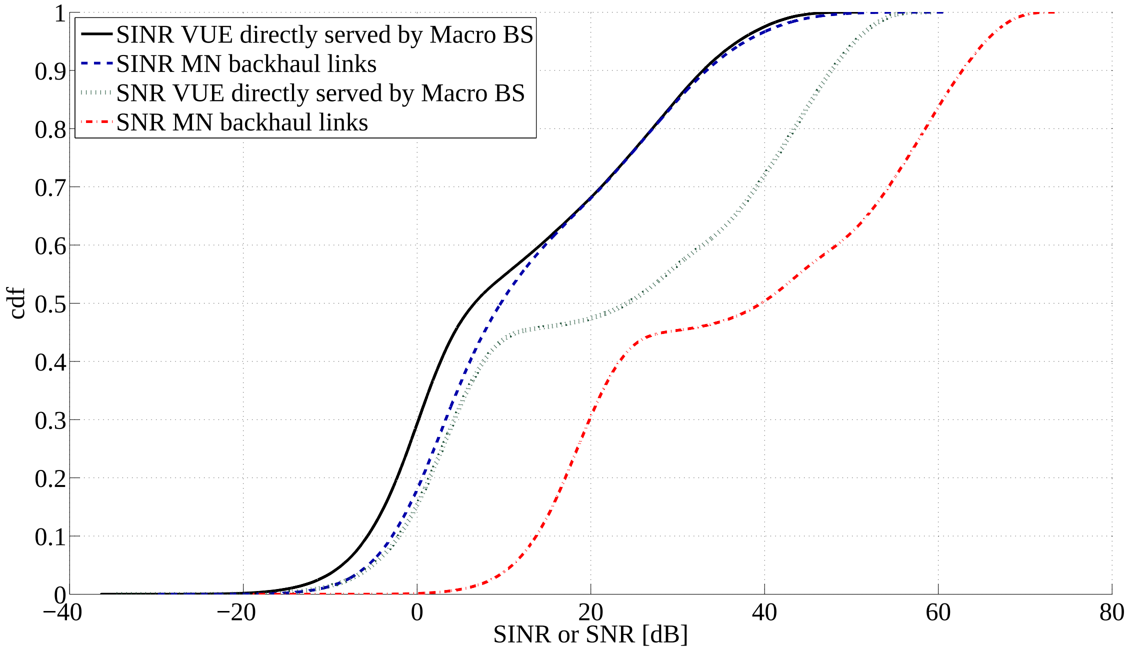

Figure 4.5.: SNR and SINR plot at backhaul links of MNs or at the VUE devices when the VPL is 15 dB.

algorithms can be implemented at the MNs. Regarding the access links of MNs, as they are operating at the same frequency bands as micro cells, they are subject to the interference from the densely deployed micro BSs. The micro BSs are usually operating at much lower power compared to the macro BS, but due to lower antenna height and high deployment density, the interference brought by the micro cells to the access links of MNs is still significant. In the worst scenario, the access link of an MN can suffer from the interference of several micro cells at the same time. In [48, Paper D], we consider to configure ABSs at the micro cells to reduce the impact of the inter-cell interference from the micro cells to the access links of MNs.

Certainly, if we would like to improve the performance of VUE devices, a simple way to do this is to allocate more resources to the backhaul links of the MNs. However, this is not fair to the regular outdoor UE devices. Therefore, in addition to the study of different ICIC schemes, another factor we need to consider is when improving the performance of VUE devices, the fairness between VUE devices and regular outdoor UE devices cannot be sacrificed. Therefore, at the macro cells, we use proportional fairness (PF)-based resource allocation to ensure a balance between system throughput and fairness among the users.

As an example, we plot the 5-percentile versus 90-percentile user throughput for the VUE devices and the macro UE devices in Section 4.6, and the throughput of the micro UE devices in Section 4.7. The VPL is 30 dB. VUE devices are dropped randomly on each vehicle with a uniform distribution $\mathcal{U}(1, 50)$, and 50 outdoor UE

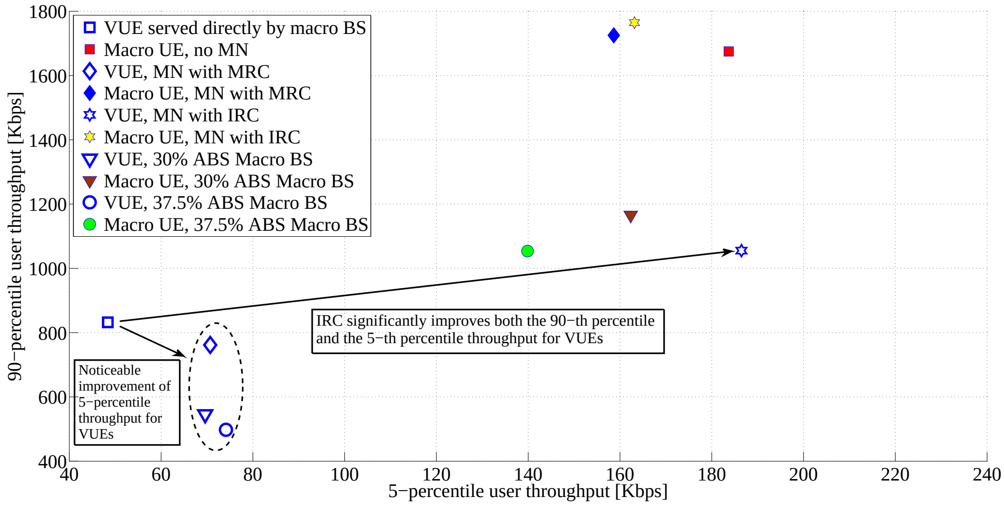

Figure 4.6.: 5-percentile vs. 90-percentile user throughput for macro UE devices and VUE devices. The number of VUE devices is uniformly randomly drawn between 1 to 50 for each vehicle and VPL is 30 dB.

devices are dropped on each street. The outdoor UE devices are associated to the cell that have the strongest RSRP with 5 dB CRE at the micro cells. More plots and detailed discussions are given in [48, Paper D]. From the plot we can observe that when the VPL is high, the throughput at the VUE devices is improved by the use of different interference management schemes. The best performance is when the IRC receivers are used at the backhaul links of the MNs. Moreover, there is no obvious degradation of the throughput at the macro UE devices. Regarding the throughput of micro UE devices, we can observe a slight degradation of their throughput due to the use of ABSs. In [48, Paper D], results are also given at moderate VPL, i.e., the VPL is 15 dB. When the VPL is 15 dB, only the use of IRC receivers at the backhaul links of the MNs can improve the performance at the VUE devices. Moreover, when the VPL is at 15 dB, as more ABSs are required at the micro cells to protect the access links of MNs, a bit more degradation of the throughput at the micro UE devices can be observed. But in general, the degradation is not significant.

4.3. Summary and Discussion

As pointed out in Chapter 1, MRNs and MNs share lots of similarities, and therefore the discussions in this chapter can be applied to both cases. We observe that for both MRNs and MNs, the backhaul links are the bottlenecks to further improve the performance. The quality of the access links are generally very good, and therefore they can always accommodate the traffic from their backhaul links. Although the used methods may be different for a noise limited system compared to an interference limited system, as long as the quality and throughput at the backhaul links can be

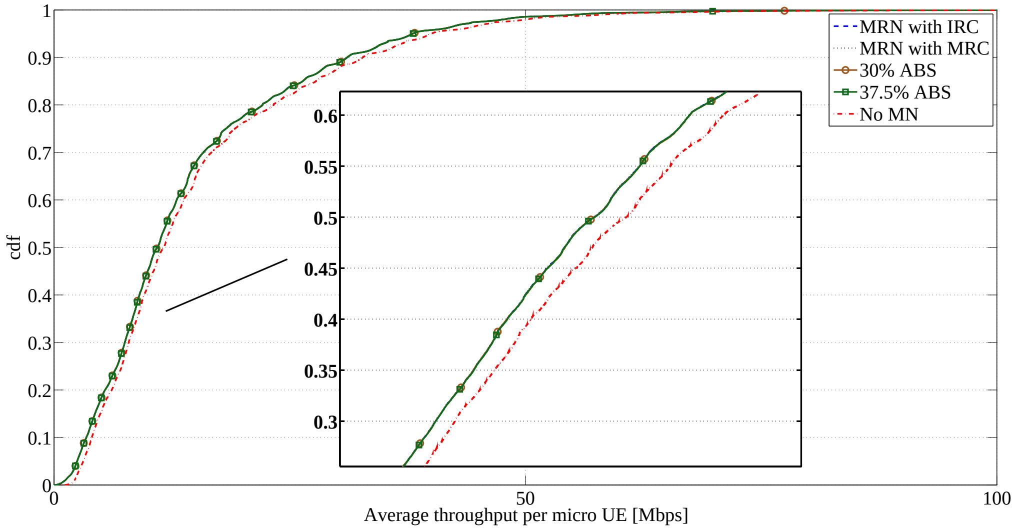

Figure 4.7.: The cdf of micro UE device throughput and the VPL is 30 dB.

improved, the performance at the VUE devices can be further enhanced by using the MRNs or MNs.

Furthermore, we have learned that the interference created by the access links of the MRNs and MNs to the UE devices outside the vehicle or the VUE devices on other vehicles are very limited, and can be neglected. This is because of the very low transmit power of the access links, as well as the vehicle can further attenuate the interference leaked from the access links to outside of the vehicles. Moreover, the vehicle can also protect the access links by attenuating the interference from outside of the vehicles. Therefore, as discussed in Section 2.1, the use of MRNs and MNs are very beneficial from a frequency reuse perspective. This is another advantage of using MRNs and MNs.

The discussion in Section 4.1 focuses on a noise limited system or a system with limited interference, and only one single VUE device needs to be served. In such setups, out-band full-duplex MNs can bring in the same benefits as in-band half-duplex MRNs by eliminating the VPL and reducing the experienced interference at the access links of the MNs. In addition, it is foreseeable that the backhaul links of MNs are still the bottleneck to further improve the performance of the system.

In Section 4.2, the system model is developed to study the performance of out-band full-duplex MNs in an ultra-dense urban HetSNets deployment. This model can also be extended to incorporate in-band half-duplex MRNs. The general conclusion that the complicated inter-cell interference is the most limiting factor in an ultra-dense urban HetSNets deployment still holds.

The studies discussed in Section 4.1 assume that the same amount of radio resources are used for both backhaul links and access links of the MRNs, i.e., the data received in the first time slot at the MRN is decoded and then forwarded to the VUE device in the next time slot. However, during the studies of MNs deployed in an ultra-dense urban scenario in Section 4.2, as both VUE devices and regular outdoor devices are considered, we have considered the use of a PF-based resource allocation to maintain fairness between VUE devices and regular outdoor macro UE devices. We further discuss this problem in Chapter 6.

5. Uplink Enhancement of VUE Devices by Using D2D Communication

In the previous chapters, we discussed several different aspects of using MRNs or MNs to serve VUE devices. The QoS of VUE devices can be noticeably improved by using MRNs or MNs. The rolling out of dedicatedly deployed MRNs or MNs on public transportation vehicles takes time. So before the MRNs or MNs are deployed, it may also be interesting to investigate whether there are other ways to help the VUE devices that are affected by high VPL. The newly developed network assisted D2D communication can be one of them. In this chapter, based on our limited study of energy efficiency, we briefly discuss the potential of using cooperative transmission enabled by the use of D2D communication between VUE devices to enhance their uplink communication.

Exchange information between UE devices without going through a network infrastructure, e.g., by using Bluetooth, or through WiFi [72], is not new. However, tightly integrating D2D services to a mobile communication system has become a hot topic for both the industrial and the academic researchers. D2D is not only under investigation by the 3GPP standardization partners but also recognized as an indispensable part of the 5G system concept in the EU 5G project METIS [2,73,74]. Different from the user-controlled information exchange by using the ISM radio bands, D2D enabled devices can directly exchange data with each other by using the spectrum of the cellular network [73]. D2D communication enables a range of different proximity-based services not only for social and adverting purposes but also for public safety applications, as D2D communication gives at least local connectivity even in the disastrous scenarios when the cellular infrastructures are not fully functional. Moreover, by using D2D communication, the communication latency between devices can be reduced, and due to the gain from spectrum sharing, the capacity of the mobile communication system can be improved, as well as the power savings because of the favorable propagation conditions for short range communications.

In [75], we demonstrated a new method to enhance the uplink communication of VUE devices by using D2D communication. As most of the VUE devices are power limited, and the uplink communication is further affected by the VPL of the vehicle, more time and/or frequency resources are required to compensate the power loss caused by the VPL. Moreover, when several active VUE devices are closely located, they are competing for a limited amount of shared time and frequency resources, which makes the situation even worse. The newly introduced D2D communication technique brings in a good opportunity for these active VUE devices, since the uplinks of these VUE devices can be enhanced through cooperation enabled by the D2D communication.

If we assume by using D2D communications, several VUE devices can exchange their uplink data, they can cooperate with each other to steer the transmit signal towards the BS, when the CSI is available at these VUE device. This can be regarded as a distributed antenna system when all the transmitter antennas are transmitting the same data. In this way, the received SNR at the BS can be significantly enhanced. In general, this scheme also applies in other indoor scenarios as well, e.g., in a shopping mall or in an office; however, in a train carriage or a bus, the overhead of finding cooperative D2D partners is comparatively small, as the positions of the VUE devices are relatively stable. Furthermore, in the cooperation, the uplink data of the VUE devices is sent by using the same time and frequency resources, and therefore, the spectrum efficiency of the system can also be improved.

In the study in [75], we compare the total RF transmit energy spent on the cooperative communication, including both the RF energy for D2D cooperation and uplink communication between VUE devices and the BS with individual VUE-to-BS communications. We show that when the communication is affected by high VPL and as the public transportation vehicle is moving away from the BS, there is a clear energy saving for the VUE devices using cooperative uplink transmission enabled by D2D communications compared with individual VUE-to-BS communication. This is very beneficial for the VUE devices, especially the one with limited battery lives.

In Figs. 5.1 and 5.2 we plot the average expended energy per information bit when different number of VUE devices participate in the cooperation at 20 dB and 30 dB VPL, respectively. As the vehicle moves away from the BS, the more VUE devices participate in the cooperation, the less energy is spent on per information bit. Compared to the individual VUE-to-BS communication, when the VPL is high, i.e., 30 dB VPL, even when two VUE devices are cooperating with each other, significant energy saving can be observed. However, when the VPL is moderate, i.e., 20 dB VPL, the VUE-to-BS direct transmission is preferable. This is mostly due to the energy used by the D2D communications when exchanging information between VUE devices. We assume the VUE devices use a fixed output power when exchanging information with each other. We do not consider any power control schemes for the D2D communications. In the practical system, the energy consumed by the D2D communication could be lowered, if efficient power control scheme is employed. Therefore, even at moderate VPL, there might also be potential to further improve the energy efficiency performance.

It is worth mentioning that in the scenario considered by us, the interference management overhead for D2D communications in the cellular system is much lower compared to other outdoor scenarios, as the interference generated by the D2D communication can be isolated inside the vehicles. The study in [75] is under ideal assumptions, i.e., we assume the perfect CSI at the transmitter side (CSIT), and the synchronization of the D2D communication is perfect. Nevertheless, as we showed,

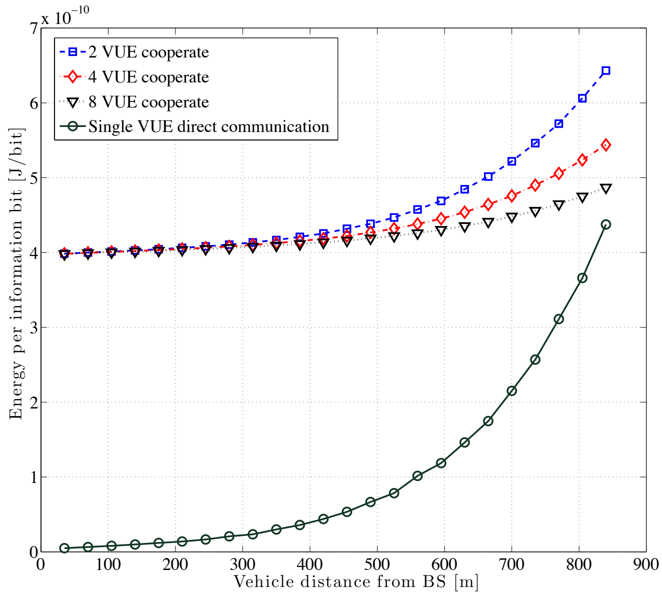

Figure 5.1.: Energy per information bit when VPL = 20 dB

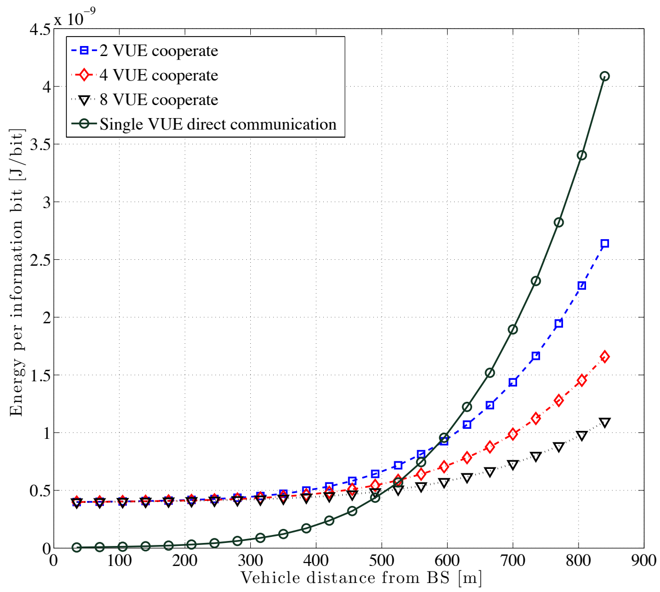

Figure 5.2.: Energy per information bit when VPL = 30 dB

gains can be observed even when two VUE devices are cooperating. Therefore, D2D communication brings in new opportunities for the VUE devices affected by high VPL. The study in [75] can be very well extended to disastrous scenarios. For example, a group of people trapped in a car accident could use this scheme sharing their RF power to communicate with BSs at a faraway distance that no single mobile device has enough transmit power to reach.

6. Contributions and Future Works

This thesis focuses on a special group of users, i.e., the vehicular users. In this chapter, we first reflect on what we have learned from the studies of how to better serve the vehicular users. Then, we discuss the open challenges and opportunities of using MNs to serve VUE devices in public transportation vehicles. Furthermore, we outline some of the important future research directions of deploying MRNs and MNs. At the end of this chapter, we summarize the contributions from the five papers that lead to this thesis. A brief summary of each paper is given, as well as the contributions to the research community.

6.1. Conclusions

This thesis focuses on the study of using MRNs or MNs to serve VUE devices. This is because of both the significant numbers of VUE devices that needs to be served in the near future, and the challenges of meeting the QoS and QoE requirements expected by these VUE devices. The focus of this thesis is not to develop new technologies, e.g, new air interface, new coding scheme, new relaying schemes, or etc., to better serve the VUE devices. Rather, we would like to understand what are the advantages and challenges of introducing a new type of nodes, i.e., MRNs or MNs, to the existing system to serve the VUE devices. This thesis includes both analytic studies that motivates the use of MRNs to serve VUE devices and extensive system level evaluations about the deployment of MNs in a densely deployed HetSNets urban scenario. This thesis contains a step by step study showing the motivations and challenges by using MRNs or MNs to serve the VUE devices in different scenarios.

As discussed in Section 4.1, in a noise limited system or a system with limited interference, the use a half-duplex DF MRN can help to lower the end-to-end OPs at the VUE devices that are affected by moderate to high VPL. This is not only because the MRN can circumvent the VPL, but also the use of an MRN can help to reduced the interference from outside of the vehicle.

In a densely deployed urban scenario, the system is interference limited. Therefore, we have studied several different interference management schemes in order to improve the performance of the MNs. We show that by using MNs together with effective interference management schemes, the experienced throughput of the VUE devices can be considerably improved with negligible impact on the regular outdoor users. For the backhaul links, we have studied the use of ABS in time domain. In addition, we have studied the use of multi-antenna receivers at the backhaul links of the MNs to combat the inter-cell interference. Two methods, i.e., the MRC and

IRC receivers, are considered.

As expected, because the system is interference limited, the use of IRC at the backhaul links of the MNs gives the best performance. These two schemes require no CSIT, and therefore we can expect no impact on the network side. Certainly, as discussed in Section 2.4.3, the use of IRC is more complex than MRC, because using IRC requires that the CSI of the interfering cells can be obtained at at each of the receiver antennas. For MRC receivers, it only requires to estimate the desired channel coefficient for each of the antennas of the receiver. Nevertheless, compared to regular UE devices, there is another advantage of using MNs. Because MNs are less constrained by size and power, more sophisticated signaling processing schemes can be employed and more antenna elements can be accommodated. In addition, in the current wireless communication systems, there are already mechanisms in place to support obtaining the CSI from the neighboring interfering cells (see [48, Paper D] for the details). Therefore, it is very feasible to use IRC schemes at the backhaul links of the MNs.

As we have discussed in previous chapters, MRNs and MNs share lots of similarities, and therefore the most of our observations for MRNs can be applied to MNs and vice versa. From the discussion in Chapter 4 and our studies in [48, Paper D] [69, Paper A] [70] [71, Paper B], the backhaul links are the bottlenecks to further improve the performance of both the use of MRNs and MNs, since the quality of the access links are good enough to accommodate the traffic from their backhaul links. Regarding the access links, we notice that not only a vehicle can attenuate the interference from the outside of it, but also due to low output power and the attenuation of the vehicles, the access links of MRNs or MNs create negligible interference outside the vehicle. This is very beneficial from a system point of view, as the same frequency can be reused more often in the system.

At the end, as mentioned in Chapter 5, the rolling out and deployment of MRNs or MNs can take some time. Therefore, at the end of the thesis, we have considered another potential way to help improve the VUE experience by using cooperative transmissions enabled by D2D communication to enhance the uplink communication of the VUE devices. We have chosen to use energy efficiency as our metric for the evaluation. This is because from a user perspective energy efficiency is one of the most relevant factors concerned by energy limited users. Our studies on this scheme are limited, and in order to have better understandings of the proposed scheme, there are several other aspects that are worth to be considered, e.g., OP, system throughput, or VUE device throughput. Nevertheless, from our limited results, we can still see the potentials by using cooperative transmissions enabled by D2D communication to better serve the vehicular users.

6.2. Challenges and Opportunities of Using Moving Networks

It is worth mentioning that the discussion in Section 4.1 is based on the assumption that the backhaul and access links use the same amount of radio resources. This is because we are investigating the performance of one single VUE device, and we make a simplified assumption. However, in practice if we consider multiple user devices (booth regular outdoor UE devices and VUE devices) in a system, extra dimensions need to be taken into consideration. For example, based on the number of VUE devices that need to be served in a vehicle, we can dynamically allocate resources between MRNs and regular outdoor UE device, as well as resources between the backhaul and access links of the MRNs. When considering these factors, MRNs can potentially bring more benefits to the network, especially when considering extra time diversity obtained by letting data to be shortly cached at the MRNs.

Furthermore, in [48, Paper D], we demonstrate that the current LTE system design also limits the further improvement of the backhaul links of MRNs or MNs. In the current LTE systems, the PRBs allocated to the same user terminal at one subframe are required to use the same coding and modulation schemes. This has more impact on the backhaul links of the MRNs or MNs than regular UE devices, as more PRBs are needed to be allocated to the backhaul links of the MRNs or MNs in order to satisfy the QoS or QoE requirement at the VUE devices on board. This certainly limits the gains from frequency adaptive transmission.

Furthermore, as shown in [48, Paper D], though the SINR at the backhaul links of MNs is improved by using effective interference management schemes, the throughput of the backhaul links saturates due to the coding and modulation schemes used in the LTE systems. In LTE Rel 10, only up to 64-QAM is used, and if a single antenna is employed at the BS, the throughput saturates at 30 dB SINR [8, Chp. 5]. In an ultra-dense deployed urban scenario, together with effective interference management schemes, much higher SINR than 30 dB can be observed, e.g., for an ideal IRC receiver, more than 80% of the PRBs at the backhaul links of MNs have an SINR above 30 dB [48, Paper D]. With the use of higher order modulation, e.g., 256-QAM in LTE Rel 12, further improvement of using MNs to serve VUE devices can be expected in a densely deployed urban scenario.

Obviously, in order to support the deployment of MRNs or MNs in the current mobile communication systems, certain modifications are expected. At the network side, as pointed out in [58, 67, 68], new protocols and possibly new architectures are needed to support the mobility of the MRNs or MNs. The mobility management advantages of using MRNs is demonstrated in [14, 68]. The number of HO failures and ping-pong HOs can be noticeably lowered by using MRNs on high speed trains.

Nevertheless, the most significant cost resides in the installation of MRNs or MNs on the public transportation vehicles. This cost, however, can be recouped by introducing more business opportunities for public transportation companies, service providers and operators. For the public transportation companies, better services improve the customer loyalty, and the same argument applies for the operators. Moreover, the operators and service providers can exploit the location based service enabled by the MRNs and MNs to push personalized information to travelers, e.g, weather or traffic information. This may potentially generate more revenue for the operators and service providers. Moreover, the use of MRNs or MNs brings in several benefits at the network side. In particular, the use of MRNs or MNs is an indispensable enabler for context aware services and content caching [76–78]. Compared to the content caching at regular macro BSs, MRNs or MNs on public transportation vehicles have a more targeted user group, and similar day to day user behaviors and habits are expected for commuters. Therefore, at different times of the day, the MRNs or MNs can cache the commonly accessed content beforehand. This both reduces the latency and lower the load at the macro cells.

6.3. Future Works

In our studies, we have found that the backhaul links are the bottleneck links in order to further improve the performance of using MRNs or MNs to serve VUE devices. Therefore, to further improve the performance of the backhaul links is very necessary. As mentioned before, compared to regular UE devices, it is easier to accommodate more antenna elements on a public transportation vehicle, and more advanced signal processing algorithms can be used due to less power and transceiver complexity constraints. Therefore, the backhaul link of MRNs or MNs can be further enhanced. As an example, in [15, 79, 80], it is demonstrated that reliable CSI can be obtained at the backhaul links of high speed MNs by using the so-called predictor antennas mounted on top of a vehicle. Therefore, the support of more advanced closed-loop MIMO schemes can be expected.

The difference between half-duplex and full-duplex RNs as well as in-band and out-band RN operations are discussed in Section 2.2.4 and Section 2.2.5. Throughout this thesis, the MRNs are assumed to work in a in-band half-duplex mode, and MNs operate in an out-band full-duplex fashion. Nevertheless, if no dedicated frequency bands are available for the operation of the backhaul and access links, the use of in-band full-duplex RNs is another way to improve the system performance. The challenges of implementing in-band full-duplex RNs are outlined in Section 2.2.4. However, the deployment scenario of MRNs or MNs bring in better opportunities for the implementation of in-band full-duplex RNs. The vehicle itself can provide very good isolation between the transceiver of the backhaul and access links, as well as advanced MIMO and signal processing schemes can be applied to further suppress the self-interference [81]. Therefore, the use of in-band backhauling full-duplex relays is less challenging. However, for in-band full-duplex MRNs, the inter-cell interference problem becomes more challenging, especially in a densely deployed urban scenario, as both macro and micro cells are using the same spectrum. Certainly, the observation in Section 4.2 that at high VPL the access link of an MN or MRN creates negligible interference to other MNs or MRNs still applies for in-band full-duplex MRNs, but improved ICIC schemes among all other links need to be studied.

As discussed in Chapter 4 that resource allocation and scheduling are other interesting areas worth looking into. In Section 4.2 we have briefly discussed the use of PF-based resource allocation to ensure fairness between regular macro UE devices and VUE devices served by MNs. Due to the elastic nature of the mobile broadband service, data can be shortly cached at the MRNs or MNs. In moderate and high mobility scenarios, good time diversity can be expected at the backhaul links of the MRNs or MNs, and therefore, there is a potential to further exploit the gain from resource allocation and scheduling to further improve the performance of the backhaul links.

Moreover, with the introduction of millimeter wave (mm-wave) frequency spectrum into the 5G cellular network, more system bandwidth will be available, and more antenna elements can be utilized [82,83]. Therefore, there are more opportunities to further improve the performance of MRNs or MNs, especially in an ultra-dense urban scenario. As vehicles are moving along the streets, there is a high probability to have LOS links for the backhaul links of MRNs or MNs compared to the indoor or pedestrian UE devices. As pointed out in [83], one of the challenges to apply mm-wave beamforming is the accuracy of beam selection and tracking. The situation is less challenging for MRNs or MNs, as the routes of vehicles are highly predictable, which can help to improve the reliability of the beam tracking. In addition, instead of tracking individual vehicular VUE devices, since an MRN or an MN can act as a super-user that aggregates the traffic of its VUE devices, the computational burden required by beam tracking at the serving BS can be foreseeable reduced. Therefore, it is worth to investigate the use of various techniques developed in the context of mm-wave to further enhance the performance of MRNs or MNs.

Throughout this thesis, we have presented extensive studies on the application of MRNs or MNs in different scenarios. In simple scenarios, e.g., a single cell noise limited system or a two cell setup, analytic or numerical study is possible. System level simulations are the only practical ways in order to understand the benefits and impacts of deploying MRNs or MNs to a practical mobile communication system. Moreover, new system architectures and protocols need to be developed to support the mobility of MRNs or MNs [68]. In a densely deployed HetSNets urban scenario, as the number of users and the number of different types of nodes are very large, it is very challenging to conduct system level evaluations, due to the difficulties of collecting enough statistics. We have to scale down the system, in order to finish the simulation, and even by doing so, it takes several weeks in order to complete all the simulations. Therefore, it is useful in the future to investigate more practical models for the deployment of MNs to conduct analytic or numerical study, especially in a grid based model, such as the Madrid/Manhattan grid model.

6.4. Included Papers

Please notice that in the included papers, the meaning of the terminologies has evolved. In [Paper A], we only assumed a simple DF in-band half-duplex MRN that forwards data from source to destination. In later studies, we assumed the MRN was in-band half-duplex but it also had advanced functionality, i.e., similar to the advanced RNs standardized in LTE release 10. The MRN terminated the layer-2 and layer-3 communication protocols, and therefore identified itself as a regular BS to the VUE devices on board. Throughout the thesis and in the included papers, MNs were assumed to be full-duplex that transmitted at different frequency bands for their backhaul and access links with different bandwidth. The MNs also terminated the layer-2 and layer-3 communication protocols, and identified themselves as regular BS to the VUE devices on board.

However, the meaning of MN has been extended in recent research activities. For example, in METIS, the concept of MNs not only covered the scenario of offering VUE devices with mobility robust high data-rate communication but also included flexible demand-driven network deployment, e.g., serving UE devices outside vehicles. Moreover, the MNs are envisioned to offer low-latency communication road safety and traffic efficiency. Such a definition of the MNs is not adopted in this thesis nor in the included papers.

Paper A: The Potential of Moving Relays–a Performance Analysis

This paper is the initial study of using MRNs to serve VUE devices on board. The study is conducted in a simple one cell noise limited system with one VUE device on a public transportation vehicle. In order to understand the potential benefits of using MRNs to serve VUE devices, both BS-to-VUE direct communication and FRN assisted communication are used as references. The end-to-end OP is used as the metric to study the performance of the considered system. A performance lower bound for FRN assisted transmission is derived when assuming the VUE position is known. The FRN lower bound shows that the best solution to serve a VUE device affected by high VPL is to place the FRN as close to the VUE device as possible, and this motivates the use of MRNs on well-insulated vehicles. Moreover, in order to achieve a fair comparison, we optimize the FRN position that minimize the average end-to-end OP at the VUE device when only knowing the distribution of positions of the VUE devices. From the results in this paper, we can see that the use of MRN can both lower the end-to-end OP at the VUE device, and improve the system ergodic capacity, when the communication is affected by high VPL.

Throughout the work, based on discussions with Dr. Papadogiannis and Prof. Svenssion, I have set up the system model and defined the metrics to evaluate the performance. Then, I am responsible both for the analytic study and simulations.

The following papers complement the study in Paper A, but are not included in this thesis.

- **Y. Sui**, A. Papadogiannis, W. Yang and T. Svensson, "The Energy Efficiency Potential of Moving and Fixed Relays for Vehicular Users", in *Proc. of IEEE Vehicular Technology Conference (VTC)*, Las Vegas, the USA, Sep. 2013.

This paper studies the energy efficiency aspects of the use of MRNs in a noise limited system. It shows that as the VPL increases, compared to BS-to-VUE direct communication and FRN assisted communication, the use of MRNs can lower the total RF energy of the system to fulfill the same end-to-end OP requirement at a VUE device.

- A. Papadogiannis, **Y. Sui**, and T. Svensson, "The Potential of a Hybrid Fixed/User Relay Architecture-A Performance Analysis", in *Proc. of IEEE Vehicular Technology Conference (VTC)*, Québec City, Canada, Sep. 2013.

This paper studies and compares the performance of using FRNs and nomadically deployed user terminal as relay nodes under a HetSNets setup. We show that low SNR UE devices can benefit from the use of FRNs, while the user terminal relays can be used when the channel conditions to the destination UE devices are more favorable.

Paper B: Performance analysis of fixed and moving relays for vehicular users under co-channel interference and multi-node handover

In this paper, we extend our study in Paper A to a more practical scenario. The end-to-end OP of serving a VUE device by using an MRN is studied in a two cell setup, where the communication is affected by CCI. Practical propagation models for pathloss, shadowing, and small scale fading are considered for different links. The end-to-end OP performance is studied in systems both with and without HO capabilities. We propose a comprehensive framework that optimize the HO parameters in the system. Similarly to Paper A, both BS-to-VUE direct communication and FRN assisted communication are used as references, and the FRN position is optimized numerically to minimize the average end-to-end OP at the VUE device, in systems both with and without HO capabilities. The results show that if the communication is corrupted by CCI, the use of MRN is actually a better solution compared to the reference cases. This is not only because the VPL can be circumvented, but also the vehicle itself can both reduce the CCI at the access link of the MRN, and attenuate the power leaked out from the vehicle by the access link of the MRN, which reduces the total amount of interference in the system.

In this paper, I have been looking into the methods of how to model the CCI for different links and the proper metrics to evaluate the performance. Furthermore, HO between different nodes are also considered in this work. Based on previous studies and discussions with the co-authors, I have proposed a framework to optimize the HO parameters. I am also responsible for most of the analytic studies and simulation works in this paper.

The following papers contribute to the completion of Paper B, but are not included in this thesis.

- **Y. Sui**, A. Papadogiannis, W. Yang, and T. Svensson, "Performance comparison of fixed and moving relays under co-channel interference", in *Proc. of IEEE Global Communication Conference, Workshops (Globecom Workshops)*, Anaheim, the USA, Dec. 2012.

This paper studies the end-to-end OP at a VUE device in a two cell setup, where the communication is affected by CCI. Only the effects of small scale fading and pathloss are considered. It shows the potential benefits of using MRNs to serve VUE devices in scenarios with limited amount of CCI.

- **Y. Sui**, Z. Ren, W. Sun, T. Svensson, and P. Fertl, "Performance study of fixed and moving relays for vehicular users with multi-cell handover under co-channel interference", in *Proc. of International Conference on Connected Vehicles and Expo (ICCVE)*, Las Vegas, the USA, Nov. 2013.

In this paper, we develop a framework to optimize HO parameters when MRNs are present in a mobile communication system. A two cell setup is considered, and in addition to the effects of small scale fading and pathloss, the influence of shadowing is also taken into consideration. Different links are modeled based on practical propagation assumptions by using well-known channel models. We show that, after being handed over to an MRN, the performance of a VUE device can be significantly improved at moderate to high VPL.

Paper C: Moving cells: a Promising Solution to Boost Performance for Vehicular Users

This article gives an overview of the motivations and challenges of deploying MRNs in the current mobile communication systems. It also summarizes the current available solutions considered in 3GPP to serve the VUE devices. Furthermore, initial system level evaluation results of using MRNs to serve the VUE devices on board done by our partner is presented. The idea of using the so-call predictor antenna solution to enhance the backhaul links of MRNs is also introduced in this paper.

In this paper, I have conducted an extensive literature study, and analyzed the pros and cons of the old solutions to serve VUE devices. Together with the co-authors, I have also presented the latest understanding of using MRNs developed in the EU project Advanced Radio Interface Technologies for 4G Systems (ARTIST4G).

The following paper complements the study in Paper C, but is not included in this thesis.

- A. Papadogiannis, M. Farber, A. Saadani, M. Nisar, P. Weitkemper, **Y. Sui**, T. Svensson, D. Ktenas, N. Cassiau and T. Moraes, "Advanced relaying concepts for future wireless networks", in *Proc. of Future Network & Mobile Summit*, Berlin, Germany, Jul. 2012.

This paper summarizes the studies of different kind of RNs in the EU project ARTIST4G.

Paper D: Interference Management for Moving Networks in Ultra-Dense Urban Scenarios

In order to further understand the performance of using MNs to serve VUE devices in a densely deployed urban scenario, we perform extensive system level evaluations within the HetSNets framework defined by the EU 5G project METIS. Different from the scenarios considered in Paper A and Paper B, in addition to the VPL, in an ultra-dense urban scenario, the complicated inter-cell interference exacerbated by the urban canyon effect is another factor that limits the performance of using MNs to serve VUE devices. Therefore, we evaluate the use of several different interference management schemes, both in time domain and the use of multi-antenna receivers, to handle the inter-cell interference.

I have studied the ultra-dense urban scenario defined in METIS, I have developed a sophisticated system level simulator to study the performance of MNs within the METIS frame work. Based on previous studies as well as the input from Prof. Guvenc and Prof. Svensson, I have finalized the interference management scheme for both the backhaul and access links of MNs. By using system level simulations, I demonstrate that by using MNs together with effective interference management schemes, the throughput at the VUE devices can be improved without significant impact on the performance of regular outdoor UE devices.

The following papers contribute to the completion of Paper D, but are not included in this thesis.

- **Y. Sui**, I. Guvenc and T. Svensson, "On the Deployment of Moving Networks in Ultra-dense Urban Scenarios", in *Proc. of International Conference on 5G for Ubiquitous Connectivity* (5GU), Levi, Finland, Nov. 2014.

This paper is an initial study of the performance of deploying MNs in an ultra-dense urban scenario. In this paper, multi-antenna receivers are used at the backhaul links of MNs to handle the inter-cell interference from the macro BS sectors, and ABSs are configured at the micro cells to protect the access links of MNs. We show that significant gains can be achieved at the VUE devices by using the aforementioned interference management schemes.

- **Y. Sui**, D. Aronsson and T. Svensson, "Evaluation of Link Adaptation Methods in Multi-User OFDM Systems with Imperfect Channel State Information", in *Proc. of Future Network & Mobile Summit*, Warsaw, Poland, Jun. 2011.

This paper studies the link adaptation performance when only partial CSI is available at the transmitter side. This study gives fundamental understanding of the trade-off between signaling overhead and system performance improvement. We show that when only partial CSI is available at the transmitter side, the per-PRB link adaptation does not give as much gain as in an ideal situation. In addition, the signaling overhead to support the per-PRB link adaptation is significant, which further decrease the gain by using per-PRB link adaptation.

Paper E: Uplink Enhancement of Vehicular Users by Using D2D Communications

This paper demonstrates a novel solution to enhance the uplink communication of VUE devices by using cooperative transmission enabled by the D2D Communication. This is an alternative to the use of MRNs or MNs before they are rolled out. Under ideal assumptions, we have shown that when the communication is affected by high VPL, the cooperative communication can lower the energy cost for all the VUE devices that participate in the transmission, even when considering the overhead of the D2D Communication.

After coming up with the ideas of cooperative uplink communication of VUE devices, I have conducted an extensive literature study to investigate what could be the proper schemes that can be used. Then, by using system level simulations, I have demonstrated the energy savings of the proposed scheme.

Bibliography

[1] Ericsson, “Ericsson mobility report: Global 4G/LTE divide will be wide in 2019,” Tech. Rep., 2014, [Online] http://www.ericsson.com/ accessed 2016-07-01.

[2] P. Popovski, V. Braun, H.-P. Mayer, P. Fertl *et al.*, “ICT-317669-METIS/ D1.1 Scenarios, requirements and KPIs for 5G mobile and wireless system,” Tech. Rep., [Online]: https://www.metis2020.com accessed 2016-07-01.

[3] P. Agyapong, V. Braun, M. Fallgren, A. Gouraud *et al.*, “ICT-317669-METIS/D6.1 Simulation guidelines,” Tech. Rep., 2013, [Online]: https://www.metis2020.com accessed 2016-07-01.

[4] E. Tanghe, W. Joseph, L. Verloock, and L. Martens, “Evaluation of vehicle penetration loss at wireless communication frequencies,” *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2036–2041, Jul. 2008.

[5] S. Stavrou and S. Saunder, “Factors influencing outdoor to indoor radio wave propagation,” in *Proc. Int. Conf. in Atomic Physics (ICAP)*, 2003.

[6] Huawei Technologies, “Whitepaper on spectrum,” Tech. Rep., Feb. 2013, [Online] http://www.huawei.com accessed 2016-07-01.

[7] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji *et al.*, “A survey on 3GPP heterogeneous networks,” *IEEE Trans. Wireless Commun.*, vol. 18, no. 3, pp. 10–21, Jun. 2011.

[8] 3GPP TR 36.872, “Small cell enhancements for E-UTRA and E-UTRAN - physical layer aspects,” Tech. Rep., 2013, [Online] http://www.3gpp.org/ accessed 2016-07-01.

[9] P. Ökvist and A. Simonsson, “LTE HetNet trial - Range expansion including micro/pico indoor coverage survey,” in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2012-fall.

[10] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution: From Theory to Practice*, 2nd ed. West Sussex, UK: John Wiley & Sons Ltd., 2011.

[11] Nokia Networks, “LTE-Advanced carrier aggregation optimization,” Tech. Rep., 2015, [Online] https://networks.nokia.com/ accessed 2016-03-08.

[12] J. G. Andrews, S. Buzzi, W. Choi, S. Hanly *et al.*, "What will 5G be?" *IEEE J. Sel. Areas Commun., Special Issue on 5G Communication Systems*, vol. 32, no. 6, pp. 1065–1081, Jun. 2014.

[13] H. S. Dhillon, R. K. Ganti, F. Baccelli *et al.*, "Modeling and analysis of K-tier downlink heterogeneous cellular networks," *IEEE J. Sel. Areas Commun.*, Apr. 2012.

[14] W. Li, C. Zhang, X. Duan, S. Jia *et al.*, "Performance evaluation and analysis on group mobility of mobile relay for LTE-Advanced system," in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2012-Fall.

[15] M. Sternad, M. Grieger, R. Apelfrojd, T. Svensson, D. Aronsson, and A. B. Martinez, "Using 'Predictor Antennas' for long-range prediction of fast fading for moving relays," in *Proc. IEEE Conf. Wireless Commun. and Netw. (WCNC) Workshop*, 2012.

[16] R. Yin, Y. Zhang, J. Zhang, G. Yu *et al.*, "Optimal relay location for fading relay channels," in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2010-Fall.

[17] B. Lin, P. Ho, L. Xie, X. Shen, and J. Tapolcai, "Optimal relay station placement in broadband wireless access networks," *IEEE Transactions on Mobile Computing*, vol. 9, pp. 259 – 269, Jun. 2009.

[18] Q. Wang, K. Xu, G. Takahara, and H. Hassanein, "Locally optimal relay node placement in heterogeneous wireless sensor networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, St. Louis, MO, Dec. 2005.

[19] M. Nikolov and Z. J. Haas, "Relay placement in wireless networks: Minimizing communication cost," *IEEE Trans. Wireless Commun.*, vol. 15, pp. 3587 – 3602, May 2016.

[20] A. B. Saleh, S. Redana, B. Raaf, T. Riihonen, J. Hamalainen, and R. Wichman, "Performance of amplify-and-forward and decode-and-forward relays in LTE-Advanced," in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2009-Fall.

[21] O. A. Elgendy, M. H. Ismail, and K. Elsayed, "On the relay placement problem in a multi-cell LTE-Advanced system with co-channel interference," in *Proc. IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2012.

[22] S. Khakurel, M. Mehta, and A. Karandikar, "Optimal relay placement for coverage extension in LTE-A cellular systems," in *Proc. National Conference on Communications (NCC)*, 2012.

[23] J. Zhao, I. Hammerstroem, M. Kuhn, A. Wittneben, M. Herdin, and G. Bauch, "Coverage analysis for cellular systems with multiple antennas using decode-and-forward relays," in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2007-Spring.

[24] A. Papadogiannis, A. Saadani, and E. Hardouin, "Exploiting dynamic relays with limited overhead in cellular systems," in *Proc. IEEE Global Commun. Conf. (GLOBECOM) Workshops*, 2009.

[25] T. Beniero, S. Redana, J. Hamalainen, and B. Raaf, "Effect of relaying on coverage in 3GPP LTE-Advanced," in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2009-Spring.

[26] Y. Yao, X. Cai, and G. B. Giannakis, "On energy efficiency and optimum resource allocation of relay transmissions in the low-power regime," *IEEE Trans. Wireless Commun.*, vol. 4, pp. 2917 – 2927, Nov. 2005.

[27] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1536-1284, Aug. 2002.

[28] A. Host-Madsen and J. Zhang, "Capacity bounds and power allocation for wireless relay channels," *IEEE Trans. Inf. Theory*, vol. 51, Jun. 2005.

[29] A. Papadogiannis, M. Farber, A. Saadani, M. D. Nisar *et al.*, "Advanced relaying concepts for future wireless networks," in *Proc. Future Network Mobile Summit*, 2012.

[30] J. Hansryd, J. Edstam, B.-E. Olsson, and C. Larsson, "Non-line-of-sight microwave backhaul for small cells," *Ericsson Review*, Feb. 2013, [Online] http://www.ericsson.com/ accessed 2016-07-01.

[31] I. Chlamtac, M. Contib, and J. J.-N. Liuc, "Mobile ad hoc networking: imperatives and challenges," *Ad Hoc Networks*, vol. 1, pp. 13–64, Jul. 2003.

[32] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions," *IEEE Commun. Mag.*, vol. 52, pp. 86–92, May 2014.

[33] L. Lei, Z. Zhong, C. Lin, and X. Shen, "Operator controlled device-to-device communications in LTE-advanced networks," *IEEE Trans. Wireless Commun.*, vol. 19, pp. 96–104, Jul. 2012.

[34] X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, "An overview of 3GPP device-to-device proximity services," *IEEE Commun. Mag.*, pp. 40–48, May 2014.

[35] Z. Ren, S. Stanczak, P. Fertl, and F. Penna, "Energy-aware activation of nomadic relays for performance enhancement in cellular networks," in *Proc. IEEE Int. Conf. on Commun. (ICC)*, Sydney, Jun. 2014.

[36] H. Min, J. Lee, S. Park, and D. Hong, “Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks,” *IEEE Trans. Wireless Commun.*, vol. 10, pp. 3995–4000, Oct. 2011.

[37] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklós, and Z. Turányi, “Design aspects of network assisted device-to-device communications,” *IEEE Commun. Mag.*, vol. 50, pp. 170 –177, Mar. 2012.

[38] A. Papadogiannis, Y. Sui, and T. Svensson, “The potential of a hybrid fixed/user relay architecture-a performance analysis,” in *Proc. IEEE Veh. Tech. Conf. (VTC)*, Québec City, 2012-Fall.

[39] N. L. Pradhan and T. Saadawi, “Power control algorithms for mobile ad hoc networks,” *Journal of Advanced Research*, vol. 2, pp. 199–206, Jul. 2011.

[40] P. Janis, V. Koivunen, C. Ribeiro, J. Korhonen, K. Doppler, and K. Hug, “Interference-aware resource allocation for device-to-device radio underlaying cellular networks,” in *Proc. IEEE Veh. Tech. Conf. (VTC)*, Barcelona, 2009-Spring.

[41] C.-H. Yu, K. Doppler, C. B. Ribeiro, and O. Tirkkonen, “Resource sharing optimization for device-to-device communication underlaying cellular networks,” *IEEE Trans. Wireless Commun.*, vol. 10, pp. 2752–2763, Jun. 2011.

[42] A. F. Molisch, *Wireless Communications*, 2nd ed. West Sussex, UK: John Wiley & Sons Ltd., 2010.

[43] I. Hwang, B. Song, and S. S. Soliman, “A holistic view on hyper-dense heterogeneous and small cell networks,” *IEEE Commun. Mag.*, vol. 51, pp. 20–27, Jun. 2013.

[44] M. Shirakabe, A. Morimoto, and N. Miki, “Performance evaluation of inter-cell interference coordination and cell range expansion in heterogeneous networks for LTE-Advanced downlink,” in *Proc. Int. Symp. on Wireless Commun. Syst. (ISWCS)*, 2011.

[45] P. Bhat, S. Nagata, L. Campoy, I. Berberana, and other, “LTE-Advanced: An operator perspective,” *IEEE Commun. Mag.*, vol. 50, pp. 104–114, Feb. 2012.

[46] T. Q. S. Quek, G. de la Roche, I. Guvenc, and M. Kountouris, Eds., *Small Cell Networks: Deployment, PHY Techniques,and Resource Management.* Cambridge University Press, 2013.

[47] A. Anpalagan, M. Bennis, and R. Vannithamby, Eds., *Time and Frequency Domain e-ICIC with Carrier Aggregation in HetNets.* Cambridge University Press, 2014.

[48] Y. Sui, I. Guvenc, and T. Svensson, “Interference management for moving networks in ultra-dense urban scenarios,” *EURASIP Journal on Wireless Communications and Networking (2015) 2015:111. Topical collection on 5G Wireless Mobile Technologies, ISSN: 1687-1499*, 2015.

[49] O. Alani and H. Ali, “Power control scheme to combat cell breathing phenomenon in 3G mobile systems,” *International Journal of Mobile Network Design and Innovation*, vol. 1, pp. 234–239, Jan. 2006.

[50] Y. Wang, W. Zhang, F. Peng, and Y. Yuan, “RNTP-Based resource block allocation in LTE downlink indoor scenarios,” in *Proc. IEEE Conf. Wireless Commun. and Netw. (WCNC)*, Apr. 2013.

[51] Ericsson, ST-Ericsson, “R1-105335: Details of almost blank subframes,” Tech. Rep., Oct. 2010, [Online] http://www.3gpp.org/ accessed 2016-07-01.

[52] S. Deb, P. Monogioudis, J. Miernik, and J. P. Seymour, “Algorithms for enhanced inter-cell interference coordination (eICIC) in LTE HetNets,” *IEEE/ACM Trans. Netw.*, vol. 22, pp. 137–150, Feb. 2014.

[53] NTT DOCOMO, “R1-103264: Performance of eICIC with control channel coverage limitation,” Tech. Rep., May 2010, [Online] http://www.3gpp.org/ accessed 2016-07-01.

[54] Rohde & Schwarz GmbH & Co KG, “LTE- Advanced (3GPP Rel.11) technology introduction,” Tech. Rep., 2013, [Online] http://www.rohde-schwarz.com/ accessed 2016-07-01.

[55] D. G. Brennan, “Linear diversity combining techniques,” *Proceedings of the IEEE*, vol. 47, pp. 1075–1102, Jun. 1959.

[56] J. Zhang, J. Olivier, A. Sayeed, and B. V. Veen, “Low complexity MIMO receiver via maximum SINR interference cancellation,” in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2002-Spring.

[57] P. Marsch and G. P. Fettweis, Eds., *Coordinated Multi-Point in Mobile Communications From Theory to Practice.* Cambridge University Press, 2011.

[58] 3GPP TR 36.836, “Technical Specification Group Radio Access Network; Mobile Relay for Evolved Universal Terrestrial Radio Access (E-UTRA),” Tech. Rep., [Online] http://www.3gpp.org/ accessed 2016-07-01.

[59] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. New Jersey, USA: Prentice Hall, 2002.

[60] L. Norell, A. Lundström, D. Nilsson, H. Österlund *et al.*, “Wi-Fi calling - extending the reach of VoLTE to Wi-Fi,” *Ericsson Review*, vol. 92, Jan. 2015.

[61] Cisco Systems, "Wi-Fi calling and the support of ims services over carrier Wi-Fi networks," Tech. Rep., 2014, [Online] http://www.cisco.com/ accessed 2016-07-01.

[62] J. Hare, L. Hartung, and S. Banerjee, "Beyond deployments and testbeds: experiences with public usage on vehicular WiFi hotspots," in *Proc. Int. Conf. on mobile syst., applications, and services (MobiSys)*, Jun. 2012.

[63] V. V. Phan, K. Horneman, L. Yu, and J. Vihriala, "Providing enhanced cellular coverage in public transportation with smart relay systems," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, 2010.

[64] Y. Chen and X. Lagrange, "Downlink data rate gain provided by a mobile relay for LTE-advanced," in *The 16th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, 2013.

[65] ——, "Downlink capacity gain analysis of mobile relay in LTE-Advanced network," in *IEEE Consumer Communications and Networking Conference (CCNC)*, 2014.

[66] D.-T. Phan-Huy, M. Sternad, and T. Svensson, "Adaptive large MISO downlink with predictor antennas array for very fast moving vehicles," in *Proc. IEEE Int. Conf. on Connected Veh. and Expo (ICCVE)*, 2013.

[67] A. Saadani, G. Liebl *et al.*, "D3.4 relay configurations," Tech. Rep., Artist4G deliverable, Jul. 2011, [Online] https://ict-artist4g.eu/projet/deliverables accessed 2012-06-12.

[68] Y. Chen and X. Lagrange, "Analysis and improvement of mobility procedures for mobile relays in LTE networks," in *Proc. IEEE Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2015.

[69] Y. Sui, A. Papadogiannis, and T. Svensson, "The potential of moving relays—a performance analysis," in *Proc. IEEE Conf. Veh. Tech. (VTC)*, 2012-Spring.

[70] Y. Sui, A. Papadogiannis, W. Yang, and T. Svensson, "Performance comparison of fixed and moving relays under co-channel interference," in *Proc. IEEE Global Commun. Conf. (GLOBECOM) Workshops*, 2012.

[71] Y. Sui, Z. Ren, W. Sun, P. Fertl, and T. Svensson, "Performance analysis of fixed and moving relays for vehicular users under co-channel interference and multi-node handover," *submitted to IEEE Trans. Veh. Technol.*, 2016.

[72] D. C. Mur, A. Garcia, and P. Serrano, "Device to device communications with Wi-Fi Direct : overview and experimentation," *IEEE Commun. Mag.*, to appear.

[73] Ericsson, “RWS-120003 LTE Release 12 and Beyond,” 3GPP Radio Access Network Workshop on Release 12 and Onwards, Ljubljana, Slovenia, Tech. Rep., Jun. 2012, [Online]: http://www.3gpp.org/ accessed 2016-07-01.

[74] P. Popovski, V. Braun, G. Mange, P. Fertl *et al.*, “ICT-317669-METIS/D6.2 Initial report on horizontal topics, first results and 5G system concept,” Tech. Rep., 2014, [Online]: https://www.metis2020.com accessed 2016-07-01.

[75] Y. Sui and T. Svensson, “Uplink enhancement of vehicular users by using d2d communications,” in *Proc. IEEE Global Commun. Conf. (GLOBECOM) Workshops*, 2013.

[76] A. Chen, *Location- and Context-Awareness.* Springer Berlin Heidelberg, 2005, ch. Context-Aware Collaborative Filtering System: Predicting the User’s Preference in the Ubiquitous Computing Environment, pp. 244–253.

[77] S. Barmpounakis, A. Kaloxylos, P. Spapis, and N. Alonistioti, “COmpAsS: A Context-Aware, user-oriented RAT selection mechanism in heterogeneous wireless networks,” in *Proc. Int. Conf. on Advanced Commun. and Computation (INFOCOMP)*, 2014.

[78] P. Lungaro, Z. Segall, and J. Zander, “ContextShift: a model for efficient delivery of content in mobile networks,” in *Proc. IEEE Conf. Wireless Commun. and Netw. (WCNC)*, 2010.

[79] D.-T. Phan-Huy, T. Svensson, M. Sternad, W. Zirwas *et al.*, “Connected vehicles that use channel prediction will fully take advantage of 5G,” in *The 22nd ITS World Congress*, 5 - 9 Oct. 2015.

[80] N. Jamaly, R. Apelfröjd, A. B. Martinez, M. Grieger *et al.*, “Analysis and measurement of multiple antenna systems for fading channel prediction in moving relays,” in *The 8th European Conference on Antennas and Propagation (EuCAP)*, Apr. 2014, pp. 2015 – 2019.

[81] P. Lioliou, M. Viberg, M. Coldrey, and F. Athley, “Self-interference suppression in full-duplex MIMO relays,” in *Proc. Conference Record of the Forty Fourth Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, 7 - 10 Nov. 2010, pp. 658 – 662.

[82] T. Rappaport, S. Sun, R. Mayzus, H. Zhao *et al.*, “Millimeter wave mobile communications for 5G cellular: It will work!” *IEEE Access*, vol. 1, pp. 335 – 349, May 2013.

[83] R. Baldemair, T. Irnich, K. Balachandran, E. Dahlman *et al.*, “Ultra-dense networks in millimeter-wave frequencies,” *IEEE Commun. Mag.*, vol. 53, pp. 202 – 208, Jan. 2015.