THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

On The Benefits of Moving Relay Nodes in Wireless Networks

Yutao Sui

CHALMERS

Communication Systems Group
Department of Signals and Systems
Chalmers University of Technology

Gothenburg, Sweden, 2012

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SUI, YUTAO

Department of Signals and Systems
Technical Report NO. R019/2012
ISSN 1403-266X

Department of Signals and Systems
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Telephone: +46 (0) 31 772 1000

This thesis has been prepared by using LyX and software from Microsoft®.

Printed in Sweden by Chalmers Reproservice,
Gothenburg, Sweden, December 2012

To the one that I love

Abstract

In order to meet the needs of high speed wireless connections, a new generation of cellular network, i.e., Long Term Evolution (LTE) has been standardized and deployed by the 3rd Generation Partnership Project (3GPP). By employing advanced smart antenna techniques, fast channel dependent scheduling, adaptive coding and modulation, etc., LTE offers a very high peak data rate in ideal conditions. However, the capacity of the LTE network is not evenly distributed, i.e., the cell edge users have much worse throughput than cell center users. The successor of LTE, the LTE-Advanced, aims at both further improve the system capacity and improve the cell edge user experiences. In order to extend the coverage for heavily shadowed or remote areas, and guarantee good user experiences at certain capacity demanding hotspot areas, a heterogeneous and small cell networks (HetSNets) design paradigm has been introduced in LTE-Advanced systems.

In this thesis, we study the impacts of the deployment of a new type of relay node (RN), i.e., moving RN (MRN) on current cellular systems. There are several benefits as well as challenges of using MRNs to serve users inside public transportation vehicles. In a noise limited single cell system, the deployment of MRN can significantly lower the end-to-end outage probability (OP) at the user equipment (UE) on board compared to serving the UE by direct or fixed RN (FRN) assisted transmission. The studies have been extended to more practical setups when considering the impact of co-channel interference. In such scenarios, MRN assisted transmission still greatly outperforms direct transmission and FRN assisted transmission in terms of end-to-end OP, when the vehicular penetration loss (VPL) is moderate to high. Moreover, due to the low transmit power nature of an MRN, it generates much less interference to the UEs outside the vehicle, which is very appreciated in a densely deployed urban scenario, since link availabilities are usually dependent on interference rather than on coverage. Hence using MRNs seems very promising for improving the quality-of-service for vehicular users in future mobile communication systems.

Keywords

LTE, LTE-Advanced, Heterogeneous and small cell networks, Fixed relay node, Moving relay node

Acknowledgment

I got lots of help from different people on the way to this thesis and I would like to take this opportunity to express my appreciations. First of all, I would like to thank my supervisors, Prof. Arne Svensson and Prof. Tommy Svensson, for letting me join this research group. During the studies, I got lots help from Tommy, both academically and personally. He is a role model for me in lots of things, especially in living a healthy life. Without the support from you, this thesis would never have been written.

Furthermore, I would like to thank my co-supervisor Dr. Agisilaos Papadogiannis for providing me lots of good research ideas and sensible discussions. He teaches me a good way to present research ideas and encourages me during the whole way of my studies. Moreover, I would like to thank Prof. Erik Ström for his generosity of sharing his knowledge and his great leadership, and thank Wei Yang for his unselfish contributions to our research works. A special thanks to John Eckerdal who teaches me how to use Linux and lots of advanced C++ programming skills. Without you, I could not finish most of my simulations on time. I am really grateful to join the Communication Systems group in the Department of Signals and Systems. I have a really enjoyable working environment here and our secretary Agneta Kinnander is always helpful whenever I have difficulties.

Certainly, the support from different funding agencies can never be forgotten. 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.

I would like to thank all my family, friends, and colleagues for providing support in my life.

List of Publications

Appended papers

This thesis is based on the following papers:

[A] Y. Sui, J. Vihriälä, A. Papadogiannis, M. Sternad, W. Yang, and T. Svensson, "Moving Cells: A Promising Solution to Boost Performance for Vehicular Users", submitted to *Special Issue on Heterogeneous and Small Cell Networks (HetSNets), IEEE Communications Magazine.*

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

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

[D] Y. Sui, A. Papadogiannis, W. Yang, and T. Svensson, "On the Benefits of Fixed and Moving Relays for Vehicular Users under Co-channel Interference", to be submitted to *EURASIP Journal on Wireless Communications and Networking.*

Other publications

The following publications are not appended to this thesis.

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

[B] A. Papadogiannis, Y. Sui and T. Svensson, "The Potential of a Hybrid Fixed/User Relay Architecture–A Performance Analysis", in *Proc. IEEE VTC* 2012-fall.

[C] A. Papadogiannis, M. Färber, A. Saadani, M. Nisar and others, "Advanced Relaying Concepts for Future Wireless Networks", in *Proc. Future Network and Mobile Summit,* July, 2012.

[D] EU FP7 INFSO-ICT-247223 ARTIST4G D3.5c, "Moving Relays and Mobility aspects," Tech. Rep., May 2012.

Available: https://ict-artist4g.eu/projet/deliverables/ accessed Dec. 15th, 2012.

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Part I

Introductory Chapters

Chapter 1

Introduction

When I started to use mobile phones, voice and SMS were the only services that I cared about. My first mobile phone was a Motorola V60. It was sturdy and the voice quality was nice but typing SMS on it was really difficult. After I got my first Nokia mobile phone, I was really fascinated by how easy it was to type SMS with it. On the other hand, at that time, maybe a phone with a good camera could attract me in the store, but when I was considering buying a new phone, I still preferred a phone with good voice quality and an easy to use SMS function. This was simply because sharing photos with others from your mobile was quite painful. The bluetooth connection is slow and the size of MMS at that moment was restricted to 100 KB per message.

I came to Sweden in 2007 and at that time mobile broadband service was still considered as something of a luxury. Some operators were still hesitant to roll out their 3G networks. One argument that Telia and Tele2 made was simply that due to the high pathloss and penetration loss at the frequency bands allocated to 3G networks, it was impossible to achieve the required coverage ratio in Sweden and they did not foresee a high demand for mobile broadband services at that time. Another company Hi3G, however, held another opinion and aggressively built their 3G network. But the picture has changed dramatically in the last 3 to 4 years worldwide.

One of the most important events, in my opinion, that changed the picture was the launching of the iPhone 3G by Apple in 2008. It brought several brand new smartphone concepts into our daily lives and gradually our lives began to depend on the availability of mobile internet. Nowadays, Facebook, Twitter, Google+, and Spotify has become indispensable parts of our lives, not mention basic services such as email, web browsing, etc. Instantly sharing photos and videos on a social network becomes more and more popular.

In modern society, ubiquitous connectivity is increasingly important due to the ever-growing demand for social and economic interactions. In 2010, it was reported that more than four billion subscribers worldwide were using mobile phones in their daily lives [1]. This unprecedented demand for mobile services has driven the advancement of the information and communications technology

(ICT) field, a fact that has greatly benefited the global economy and society. The high demand of ubiquitous connectivity, however, put unprecedented challenges on the construction of infrastructures. As an example, it is predicted that the number of base station (BS) sites worldwide will be tripled in 2020 compared to 2007 [2].

My research in these 2 years has been focusing on the application of moving relay nodes (MRNs), which in our point of view may bring significant benefits to the existing wireless systems. Currently, a significant number of mobile users are vehicular, i.e., they use wireless broadband services while being in public transportation vehicles, e.g., buses, trams, trains or ferries. In addition, it is expected that the number of vehicular users will greatly rise in the near future due to the high penetration of smartphones and the increasing portability of tablets and laptops [3]. Hence, public transportation vehicles are expected to evolve into wireless hotspots.

A significant problem, however, is that radio signals traveling from the BS into the vehicle can be severely attenuated by the vehicular penetration loss (VPL). Measurements show that VPL can be as high as 25 dB in a minivan at the frequency of 2.4 GHz [4]. It should be noted that higher VPLs are foreseeable in the well-insulated vehicles of our interest. The VPL will be even higher in higher frequency bands [5], e.g. the 3.6 GHz band allocated to next generation mobile communication at the International Telecommunication Union Radio Communication Sector (ITU-R) World Radio Communication Conference, 2007. Consequently, in order to guarantee a certain level of quality-of-service (QoS) for user equipment (UE) inside vehicles, more radio frequency (RF) power needs to be transmitted to compensate for the VPL. As vehicular UEs will represent a significant portion of broadband UEs in future networks, it is crucial to design wireless systems in a way that those UEs on board can be served cost-effectively while maintaining a certain level of QoS. There are several solutions which have been proposed exploiting the current standardized techniques to serve the vehicular UEs, and we will discuss them in more details in Chapter 2. But in our opinion, deploying dedicated MRNs on public transportation vehicles is one of the most efficient ways to serve the vehicular UEs. In the latter part of the thesis, we will discuss the benefits that MRNs can bring to the system in different setups.

The first time that I presented my research of moving relays was in 2012, the 75th Vehicular Technology Conference, Yokohama. On the airport bus to the hotel, my supervisor Tommy suddenly told me there was Wi-Fi available on the bus and it is certainly a "moving relay". He said I should try the service and find out how it works. Somehow, I think I influenced him a bit too much. Before, I was the one who was always looking for different types of BSs when we were traveling together. This is just an example of applying the concepts of moving relays and such services are available in lots of different countries, but mostly for long-distance coaches and trains.

During our stay in Japan, we used public transportation quite extensively. The best thing I have experienced is that you are not allowed to talk on your mobile phone when you are on board. One consequence of such a wonderful habit is that lots of people are just surfing or listening to music with their mobile phones when they are on board. Similar things become more and more common in Sweden, especially the use of Spotify, which makes streaming music simple and easy with smartphones. But it seems that we get spoiled easily and become more demanding of better and better quality of services. For example, reading news with one's mobile phone simply cannot satisfy the needs of lots of people, including me. We want to watch live TV programs or YouTube video clips on our mobile phones when we are traveling. Though there are lots of apps making this possible, it creates a large burden on the mobile network. In our point of view, deploying MRNs on public transportation vehicles, e.g., buses, trams and trains can be an economical solution for the data hungry travelers. Thus, in the rest of the thesis, I would like to discuss about how the use of MRNs can help the users to improve their experiences.

1.1 Heterogeneous and Small Cell Networks

In order to meet the throughput demands and evenly distribute the capacity of a wireless network, a new design paradigm, i.e., the Heterogeneous and Small Cell Networks (HetSNets), was introduced in LTE release 10 [6]. The idea of HetSNets is to deploy several low power nodes within the coverage of macro BSs to either extend the coverage or boost the local capacity in certain hotspot areas. The HetSNets has many advantages. Let us have a look at a simple example as follows. We use the Shannon capacity to approximate the capacity as

$$C = \sum_{i=1}^{k} B_i \log_2 \left(1 + \frac{P_i}{N_0}\right), \tag{1.1}$$

where i is the number of subchannels, B_i is the bandwidth of the ith subchannel, P_i is the allocated transmit power of the ith subchannel and N_0 is the background noise power. As we can see from (1.1), if we would like to increase the capacity of a network, we can either increase the system bandwidth or increase the received signal-to-noise ratio (SNR). Bandwidth is a scarce resource and the available bandwidth of a mobile communication system is always limited. Hence, increasing the received SNR is one of the most practical ways to increase the network capacity. There have been various methods applied in wireless systems to increase the received SNR, ranging from interference mitigation, interference alignment, to sophisticated multi-point coordination schemes, etc. However, pathloss, the basic cause of the power loss during transmission, cannot be easily alleviated. The fundamental idea of HetSNets is to increase the network capacity by using node densifications, which is an effective way to combat the power loss caused by the pathloss. In a HetSNets scenario, as the cell radius becomes smaller, BSs are much closer to the users and the transmit power of BSs can be significantly lowered to achieve the required coverage.[1]

[1] The received power goes down exponentially as the distance between the transmitter and the receiver increases.

With proper inter-cell interference coordination (ICIC) schemes, gains from frequency spatial reuse can be expected, since the same frequency resources can reused within much shorter distances compared to the traditional macro cell deployment.

In a HetSNets deployment, several different kinds of low power nodes can be deployed underlying high power macro BSs. If there is a possibility to build dedicated backhaul connections, either wired or line-of-sight (LOS) microwave links, pico BSs or remote radio heads (RRHs) can be deployed in densely populated areas,[2] e.g., shopping malls, train stations, etc., to locally improve the capacity; home BSs are randomly deployed in residence areas or office buildings to formulate femtocells and offload the data traffic when users are at home or at work. If it is challenging to obtain dedicated backhaul links, different types of in-band RNs can be used to meet different needs. We will discuss more about different types of RNs in section 1.2.

In this thesis, we focus on a new type of RN, i.e., the MRN, and its impacts on the system. As mentioned before, VPL is one of the challenges faced by serving the vehicular UEs efficiently. There are several solutions that are discussed in 3GPP to serve vehicular UEs, and we will review these solutions in Chapter 2. But in our opinion, an effective way to combat VPL is through the deployment of MRNs on top of public transportation vehicles. MRNs consist of outdoor and indoor antenna units which are connected via a cable that introduces negligible losses. The indoor antenna is inside the vehicle communicating with the vehicular UEs, while the outdoor antenna is outside the vehicle communicating with the BS, hence the VPL is circumvented. Similar to the standardized type-1 FRNs of the LTE release 10, the MRN can create its own cell within the vehicle, and provides very high data rates to the connected vehicular UEs. Furthermore, MRNs can provide other benefits such as group handover (HO), which reduces the HO failure probabilities for vehicular UEs [7], and collective channel state information (CSI) feedback for advanced backhaul design [8]. It should be noted that the existing UEs can take advantage of MRNs without significant hardware modifications.

1.2 RN assisted transmission

The use of RNs to assist passing messages has a long history. For example, beacon towers built on the Chinese great wall were designed for relaying defensive communication signals from the frontier to headquarters located thousands of miles away when enemy troops were approaching. Similar systems were also found in lots of other countries, such as in Scandinavian countries, the Great Britain, etc. Nowadays, RNs are playing indispensable roles in modern wireless communication systems, ranging from sophisticated space exploration to daily mobile communication systems. For example, if the Curiosity rover communi-

[2]The difference between a pico BS and a RRH is that a pico BS is a low power BS that can formulate its own cell, whereas an RRH is part of the macro BS, deployed distributively to either extend the coverage or improve the local capacity.

cates with the earth station directly from Mars, only a data rate of 32 kbit/s can be achieved, but with the relaying of Mars Reconnaissance Orbiter, a data rate may reach 2 Mbit/s [9]. Another example would be the use of RNs in the cellular communication systems in our daily lives. The use of repeaters can be dated back to the beginning of the GSM systems in the 1980s and more advanced RNs are standardized in the release 10 of the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) standards [10, Ch 10]. Together with other low power nodes, such as pico and femto nodes, RNs are key components in HetSNets. Thus, in this section, we briefly introduce the different types of RN techniques.

1.2.1 Amplify and forward RN

As the name suggests, this type of RN simply amplifies the signal, and then forwards it to the destination. This type of RN is easy to implement and has been widely used in the current wireless systems, e.g., repeaters in the GSM network. The signals received at the RN and the destination from the source can be expressed as

$$y_{\mathrm{R}}^{(\mathrm{S})} = h_{\mathrm{R}}^{(\mathrm{S})}\, x + n_{\mathrm{S}}, \tag{1.2}$$

$$y_{\mathrm{D}}^{(\mathrm{S})} = h_{\mathrm{D}}^{(\mathrm{S})}\, x + n_{\mathrm{D}}, \tag{1.3}$$

where x represents the signal sent from the source; $h_{\mathrm{R}}^{(\mathrm{S})}$ and $h_{\mathrm{D}}^{(\mathrm{S})}$ are channel gain between the source and the RN, the source and the destination, respectively; n_{S} and n_{D} represent the noise affecting the communication. After receiving the signal from the source, the RN amplifies the received signal and forwards it to the destination. If we denote the gain of the RN as G, and a channel gain of $h_{\mathrm{D}}^{(\mathrm{R})}$ is assumed between the RN and the destination, then the signal received at the destination from the RN is given as

$$y_{\mathrm{D}}^{(\mathrm{R})} = G\, h_{\mathrm{D}}^{(\mathrm{R})}\, y_{\mathrm{R}}^{(\mathrm{S})} + n_{\mathrm{D}}. \tag{1.4}$$

If there is no direct link between source and destination, from (1.3) and (1.4) we can see that a drawback of amplify and forward (AF) RN is that it both amplifies the signal and the noise. In the presence of interference, the AF RN also amplifies the interference. Thus, the deployment of AF RN must be at a place with SNR or SINR advantages, otherwise little gains can be expected from such RNs.

1.2.2 Decode and forward RN

In a decode and forward (DF) RN assisted transmission, in the first step the RN decodes part or all of the received signal. In the second step, the RN re-encodes the decoded message and forwards it to the destination. DF RNs do not suffer from the problem of noise or interference amplification as AF RNs, but it may have the risk of error propagation if the RN fails to decode the message from the source correctly. Thus, in practical systems, e.g., the fixed RN (FRN) in the LTE-Advanced system, a cyclic redundancy check (CRC) may be used to spot the wrongly decoded message, and if an error is detected, the RN stops to forward the message and requests a re-transmit of the message from the source.

The end-to-end SNR or SINR expression of the DF RN is generally unknown. Instead, the outage probability (OP) is used as a measure of its performance. Since the DF RN has to decode the message from the source first and then forwards the message to the destination, as long as one of the hops is in outage then an outage can be declared for the end-to-end communication. As will be pointed out in Section 1.3, the QoS requirements can be mapped to a minimum SNR or SINR requirement. Thus, if either of the two links falls below a certain SNR or SINR threshold, an outage occurs. Defining the minimum required SNR or SINR threshold as $\gamma_{\mathrm{th_R}}$, the end-to-end OP for DF RN can be expressed as

$$P_{\mathrm{out_R}}\left(\gamma_{\mathrm{th_R}}\right) = \Pr\left(\min\left(\gamma_{\mathrm{R}},\, \gamma_{\mathrm{D}}\right) < \gamma_{\mathrm{th_R}}\right), \tag{1.5}$$

where γ_{R} and γ_{D} are the SNR or SINR at the RN and the destination, respectively. Expression (1.5) will be used as the metric throughout this thesis to characterize the performance of DF RNs.

1.2.3 Other types of RNs

There are lots of other types of RNs being widely studied both academically and during industrial standardization processes, and they all show their advantages in certain scenarios. Those types of RNs include but not limited to compress-and-forward (CF), estimate-and-forward (EF) and hybrid AF/DF RNs. In this thesis we will not focus on these schemes but a good survey of recently developed RNs schemes can be found in [11].

1.2.4 Half-duplex versus full-duplex

A half-duplex RN is the type of RNs that cannot simultaneously transmit and receive in both directions. This means that a transmission of one symbol takes two channel uses. In contrast, a full-duplex RN can provide connection in both directions at the same time. Certainly, a full duplex RN can achieve higher rate than a half-duplex RN but the implementation of a full-duplex RN requires well isolation between the transmitter and receiver RF modules. In the recent standardized FRN in LTE release 10, a half-duplex RN protocol is employed.

1.2.5 In-band versus out-band

An RN is said to be "in-band" if the same carrier frequency is used to communicate both with the source and destination nodes. An out-band RN, on the other hand, use different carrier frequencies to communicate with the source and destination nodes, respectively. The advantage of out-band RN is that they have the potential to work in a full duplex mode, whereas it is challenging to build a full-duplex in-band RN due to self-interference between transmit and receive RF modules.

In LTE, the difference between a full duplex out-band RN compared to a pico BS with wireless backhaul is that the RN can re-use the radio interference defined for the BS to UE communications, and it works in both LOS and non-line-of-sight (NLOS) propagation conditions, whereas a pico BS with wireless backhaul requires dedicated LOS microwave connection and the communication protocols between the core network and the pico BS are usually manufacture specified. Hence, high compatibilities can be expected between macro BSs and RNs from different manufactures.

1.2.6 RN techniques in 3GPP LTE systems

The application of RNs in practical cellular systems has a long history. Repeaters have been used in the age of the GSM system and more advanced FRNs are standardized in LTE release 10. During the initial study of 3GPP LTE systems, two types of RNs have been defined, type-1 RN and type-2 RN. Type-1 RNs are non-transparent, both to the BS and the UE. From the UE viewpoint, type-1 RN appears as a regular BS, and terminates all the layer-2 and layer-3 communication protocols. It has its own cell ID, control channel, reference and synchronization signals as well as support re-transmission processes [10, Ch 30]. Thus, type-1 RNs can be used for both capacity boosting and coverage extension. The FRN in LTE re-use most of the radio interface standardized for the UEs for the the initial attachment to the serving BS (also known as Donor eNB or DeNB in LTE[3]), and then identifies itself as an RN. Three classes of type-1 RNs were discussed during the studies of 3GPP, i.e., in-band half duplex, out-band full duplex and in-band full duplex RNs but only the in-band half duplex type-1 RNs are standardized in 3GPP LTE release 10.

In contrast, type-2 RNs have not been standardized yet and only received a functional description from 3GPP. Type-2 RNs do not have their own cell ID, and thereby are transparent to UEs. Rather to be used for coverage extension, this type of RNs are designed to cooperate with BSs to improve the capacity for certain hotspot areas. Type-2 RNs are not standardized yet but it opens the window for technologies such as CF, EF and hybrid AF/DF RNs in future release of the LTE standards. As type 2 RNs require cooperation with BSs, new air interfaces need to be defined between BSs and RNs. Hence, type-2 RNs may bring much bigger impacts to the existing system than type-1 RNs.

1.3 Outage probability and QoS aspects

Compared to other low power nodes, such as pico or femto nodes, an RN has its advantages. One may argue that a pico BS with microwave backhaul may very well serve the users better than an RN node, since it has dedicated backhaul and no half duplex loss. But the deployment of microwave backhaul requires an LOS connection between the transmitter (TX) and the receiver (RX), which is

[3]eNB refers to evolved UMTS Terrestrial Radio Access (E-UTRA) Node B or Evolved Node B and is the special name of a BS in the E-UTRA of LTE.

difficult to achieve in many locations. RNs standardized in LTE, on the other hand, do not require LOS connections, which is a huge advantage in very dense cities or in rural areas. Of course, the disadvantages of RNs are that they may consume resources that can be used to serve UEs directly and they may introduce half-duplex loss as the way they are standardized at this moment. If we do not deploy the FRNs carefully, it may even downgrade the QoS at the target UEs compared to serve them directly from the BS. Hence, certain metrics must be taken into consideration when deploying a new type of node into an existing network. In the next section, we briefly discuss on one of the most important metrics, outage probability, which is usually used to measure the QoS at a UE.

From a QoS point of view, all kinds of services have minimum bit error rate (BER) or code word error rate (CWER) requirements. If these requirements cannot be fulfilled during a certain time period, the service may be interrupted and an outage occurs. Certainly, different people have different tolerances of such disturbances, and this can be well exploited in some communication systems. One classic example is the GSM system. During a voice call, if a data packet gets lost, it will just be replaced by the previous one. This of course will lower the voice quality but as long as it does not happen too often, most people can go along with it. The meaning will get through sooner or later, as the conversation continues. On the other hand, if the call drops too often due to poor reception, then most people would easily get very upset.

Furthermore, the frequencies and durations of the disturbances are also important factors when it comes to the satisfaction of services and it seems that customers tend to remember the bad quality of a service (just like people remember bad weather and not good weather). Even if the OP is low on the average of a long time period, customers may have different perceptions on the QoS. Studies show, in a fully loaded cellular system, customers tend to be more annoyed by frequent call dropping rather than denial of access [12]. The reason is that if a call is dropped, customers will try to call back immediately to continue the conversation, but if there is a denial of access, most people tend to learn to wait a bit more and try again later. Certainly, the argument of how to provide economical satisfactory services will never end, especially for “bad” operators in front of smarter customers. Nevertheless in this thesis, we just focus on the error probabilities, which can be quantified mathematically.

The BER or the CWER requirements can be translated into a required average minimum received SNR or SINR at the UE side. In such way, the calculation of OP becomes much simpler, since a maximum BER or CWER requirement can be mapped to a corresponding minimum received SNR or SINR [13, Ch 12]. We can express the OP as

$$P_{\text{out}} = \Pr\left(\gamma < \gamma_{\text{th}}\right) = \int_{0}^{\gamma_{\text{th}}} f_{\gamma}\left(\gamma\right) d\gamma, \tag{1.6}$$

where γ represents the instantaneous received SNR or SINR, γ_{th} is a minimum required threshold of the received SNR or SINR, and $f_{\gamma}\left(\gamma\right)$ is the probability density function (pdf) of γ. The difficult part of determining the OP is to determine the pdf of γ. OP can also be used to find the average SNR or SINR that guarantee a certain QoS, which is also referred as a fading margin [13, Ch 12].

1.4 Motivation of the thesis work

We focus on the application of MRNs in different scenarios. In order to understand whether there is a potential benefit to add a new type of node to the existing system, transmission assisted by FRN is employed as a reference scheme and conventional BS to UE direct transmission is used as the base line. In all the studies, in order achieve a fair comparison, we employed different ways, i.e., by analytical analysis, numerical methods or by simulation, to optimize the FRN position which minimize the overall OP at the UE on average. Furthermore, MRNs can also help to lower the UE transmit power, which may potentially save the energy used to operate the communication network.

We begin our study in a noise limited system in the presence of flat Rayleigh fading. In order to achieve a fair comparison, an OP lower bound is derived when assuming that we know the exact UE position. Furthermore, an optimal FRN position that minimizes the overall OP at the UE when knowing only the UE position distribution is obtained numerically. We notice that as the VPL increases, the use of an MRN can significantly lower the end-to-end OP at a vehicular UE. We continue our studies to a system where the communication is corrupted by co-channel interference (CCI). A 2-cell setup is studied and both the effects of small scale fading and shadowing are considered. In a system with or without handover possibilities, MRN shows its advantages compared to both FRN assisted transmission and direct transmission. Those details are presented in Chapter 3.

1.5 Outline of the thesis

The thesis is divided into two parts. The first part provides an overview and background information needed for those who are not familiar with the topics and the author's work. The second part includes the contribution of the author's work in the form of papers. The outline of the first part is as follows. After the an overview of the studied topics in the paragraphs above, Chapter 2 reviews the solutions based on using the existing techniques to serve vehicular UEs. In Chapter 3, the application of MRNs in three types of application scenarios are discussed. The conclusions, future research direction are given in Chapter 4.

Chapter 2

Review of Current Solutions

As mentioned before, a noticeable amount of wireless data hungry vehicular UEs are expected in the near future and how to serve them effectively will be a big challenge for cellular networks. As vehicles of our interest usually move at a moderate to high speed as well as with high VPL, it is difficult to serve the data hungry UEs on board without consuming more resources. Solutions based on using the existing system elements, such as optimizing the deployment of macro cells, using layer-1 repeaters or Wi-Fi access points (APs) to serve vehicular UEs, have been discussed in 3GPP [14]. But in our opinion, the dedicated deployment of MRNs is one of the best solutions. In this chapter, we review solutions based on using the existing system elements to serve vehicular UEs and compare their pros and cons. In Chapter 3, we discuss the benefits as well as challenges of deploying dedicated MRNs to service vehicular UEs. All layer-1 repeaters, Wi-Fi APs as well as MRNs communicate with macro BS via radio interfaces, but the differences between MRNs and other two schemes are: 1) MRNs also act as regular BSs to communicate with the UEs they serve; 2) MRNs may potentially support multi-RAT, e.g., LTE, HSPA, GPRS, Wi-Fi, etc.

2.1 Dedicated deployment of macro BS

One of the solutions that is fully compatible with the current standards is to deploy dedicated macro BSs to serve vehicular UEs. This solution is motivated by the fact that the routes of public transportation vehicles are usually known, especially for high speed trains and coaches. Hence, in principle, by proper site planning, the coverage of macro BSs can be optimized towards train lines or highways by employing directive antennas. Moreover, a HetSNets solution can be applied here. High-power BSs can be used to handle the control signaling, and offer basic coverage for low data rate services, e.g., voice, SMS, E-mail, etc., while low-power nodes can be deployed to boost the capacity. For example, with carrier aggregation (CA)[1], primary component carriers (PCCs) are transmitted by high-power BSs and secondary component carrier (SCCs) are transmitted by the low-power nodes. By using sophisticated cross-carrier scheduling schemes, the control signals can be handled by high-power BSs and the data can be transmitted by low-power SCCs. If CA is not possible, then RRHs can be considered. Since the RRHs have the same cell ID as the macro BS, the closest RRH can serve the high speed vehicle without HO being triggered.

However, this solution cannot effectively combat the signal power loss caused by the VPL. In addition, site acquisition and maintenance are also big challenges for the operators, since it requires the operator to build dedicated backhaul connections, power supplies, cell towers, etc. Furthermore, since this solution is dedicated for trains and long range coaches, it cannot be easily extended to urban scenarios, i.e., to serve vehicular UEs on buses, trams, etc.

2.2 Layer-1 repeaters on the vehicle

Layer-1 repeaters are analog repeaters, which amplify and forward signals in a given frequency band. Compared to the advanced RNs in LTE, repeaters are relatively of low cost, since little signal processing is required. On the vehicles of interest, the indoor and outdoor antennas can be well separated and a sufficient isolation between the TX and the RX antennas could be achieved. Hence, repeaters can possibly work in a full duplex mode. This is an advantage compared to the half-duplex RNs standardized in LTE. Furthermore, Layer-1 repeaters can overcome the VPL caused by the well-isolated vehicles, and thereby lower the UE transmit power.

However, the disadvantages of using layer-1 repeaters are also very obvious. The SINR cannot be improved at layer-1 repeaters, since they just amplify and forward the received signal rather than re-generate it. Thus, they can only be deployed at positions with SINR advantages. This certainly cannot easily be achieved on vehicles with high mobility as well as in urban areas with complicated interference patterns. Furthermore, since repeaters just simply amplify and forward the signal, no advanced signal processing techniques can be exploited and the HO of vehicular UEs between different BSs still needs to be done on an individual basis.

2.3 LTE as backhaul, Wi-Fi as access link on board

As mentioned before, using Wi-Fi to provide internet access to mobile users on board is fairly common and there are several companies providing such solutions on high speed trains or coaches. As most of the smartphones, not mention laptops, are Wi-Fi-capable, the existing Wi-Fi technology can be very well

[1] CA is a technique introduced in LTE-Advanced system to aggregate several component carriers, and thereby increases the network capacity.

exploited. Similar to the Layer-1 repeater, a wireless backhaul node can be mounted on the roof of a vehicle with antenna deployed outside communicating with the cellular network as a regular UE, while provides wireless data coverages inside the vehicle with Wi-Fi APs. The UEs on board can use the Wi-Fi service for data and voice over IP (VoIP) connections, and regular voice calls can be handled directly by the cellular network. In this way, the VPL can be easily circumvented and group HO of data users can also be achieved. In additions, this solution also enables Wi-Fi only devices, e.g., laptops, tablets, to use the cellular network, which may bring extra income for the service providers.

However, integrating Wi-Fi technology to the current cellular network to provide UEs with a seamless experience is a challenge [15]. Although the current 802.11x extension of Wi-Fi, makes roaming possible within Wi-Fi networks, functions such as charging, authentication, security, etc., still require both software and hardware upgrades for the Wi-Fi module to access the universal subscriber identity module (USIM) on the phone. Furthermore, although the 802.11e amendment of the Wi-Fi standard has QoS support, it only functions within the APs which belong to the same Wi-Fi network [16]. Since Wi-Fi is operating on open industrial, scientific and medical (ISM) bands, the interference condition is not controlled in the same ways as in the dedicated frequency bands owned by the operators. In trains or coaches outside the city, the interference power from other Wi-Fi networks can be low, but in densely populated cities, where Wi-Fi APs are randomly deployed almost everywhere, it will be really difficult for the operators to offer a the same QoS guarantee as in their own network.

Chapter 3

Dedicated MRN deployment

A new solution that is under investigation is to deploy dedicated MRNs on top of public transportation vehicles to serve the UEs on board, as shown on Fig. 3.1. MRNs are low power BSs mounted on the vehicles where MRNs connect to macro BSs via radio interface. The advantages of deploying a dedicated MRN is not only due to its ability to eliminate the VPL. As MRNs are not limited by size and power as regular UEs, it can better exploit various smart antenna techniques as well as more advanced signal processing schemes to further boost the performance. For example, in a train, several backhaul antennas can be interconnected and form a cooperative and coordinated relay system (CCRS) [17], which strengthens the backhaul link by using antenna selection techniques. In a bus or tram, prediction antennas can be exploited. Thus more reliable CSI can be obtained; hence, facilitates the channel dependent scheduling of the backhaul link [8].

Moreover, most FRN physical layer interfaces standardized in 3GPP LTE release 10 can be reused by MRNs. An MRN can create its own cell and terminates all the layer-2 and layer-3 communication protocols, and thereby serves the UEs on board as a regular BS. MRN may also have the potential to support

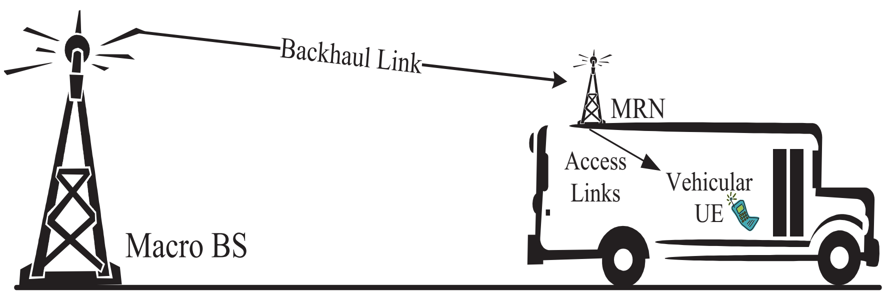

Figure 3.1: Using MRN to serve vehicular UE

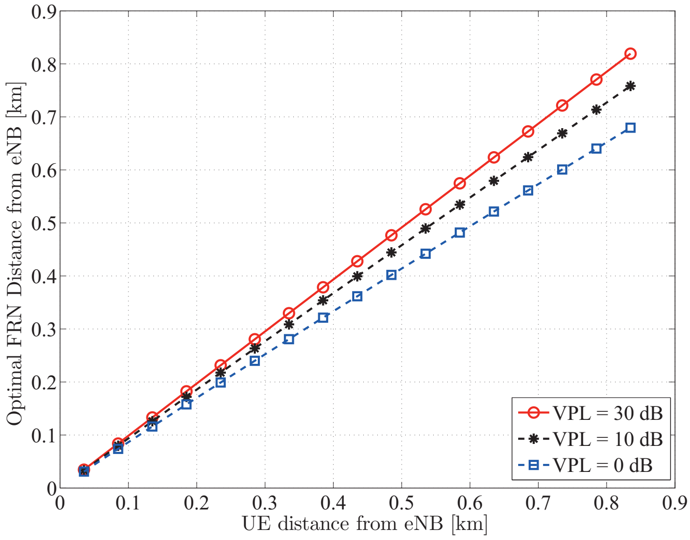

Figure 3.2: Optimal FRN position when UE position is known

multi-RAT functionalists, i.e., LTE, HSPA, GPRS, Wi-Fi, etc.,[1] as its access link to the vehicular UEs. In addition, group HO can be performed by regarding the UEs served by the same MRN as a super-user group. This is very beneficial from a system architecture point of view, as the probabilities of handover failure can be lowered [7]. We are going to discuss the benefits of deploying dedicated MRNs in details in the later part of this thesis.

In order to understand the benefits of deploying MRNs on top of public transportation vehicles, we begin our studies in a noise limited, single cell set up. This setup was discussed in details in [18] and the end-to-end OP was used as a metric to evaluate the performance. A half-duplex DF FRN assisted transmission was used as a reference, and the direct transmission was used as the baseline. In [18], we showed that if the UE position is known, then the optimal FRN position which minimized the end-to-end OP can be expressed as a function of VPL, the ratio between the BS transmit power and FRN transmit power. In Fig. 3.2, we plot the optimal FRN position as a function of VPL by assuming a typical urban propagation condition. The plot indicates that if we know that the UE is on board and the communication is affected by high VPL, the best solution is to place an RN as close as possible to the vehicle to compensate the loss caused by VPL. This motivates the use of MRN to serve UEs affected by high VPL.

In an interference limited system, the deployment of MRNs has more advantages than just eliminating the VPL. In [19], we investigated the performance

[1]RAT refers to Radio Access Technology; HSPA refers to High Speed Packet Access; GPRS refers to General Packet Radio Service

of an MRN in the presence of co-channel interference (CCI). A two cell setup was considered and more practical channel models were employed. In the presence of only small scale fading, the studies showed that MRN can significantly lower the end-to-end OP at the vehicular UE compared to direct transmission when the VPL was moderate to high. For example, when the VPL is 30 dB, a half-duplex MRN can lower the end-to-end OP by 65% compared to direct transmission, and better performance is expected from a full-duplex MRN.

The studies have been further extended to a more comprehensive setup in [20]. We considered impacts of pathloss, shadowing as well as small scale fading on the end-to-end OP performance of the MRN assisted transmission. In addition, the effect of HO between the BS and the RN on the end-to-end OP was also studied. Figs. 3.3 and 3.4 show the end-to-end OP of the considered schemes, where the FRN position was optimized numerically to minimize the average end-to-end OP at the vehicular UE. The MRN worst case represents the case in which the MRN experiences the highest interference.

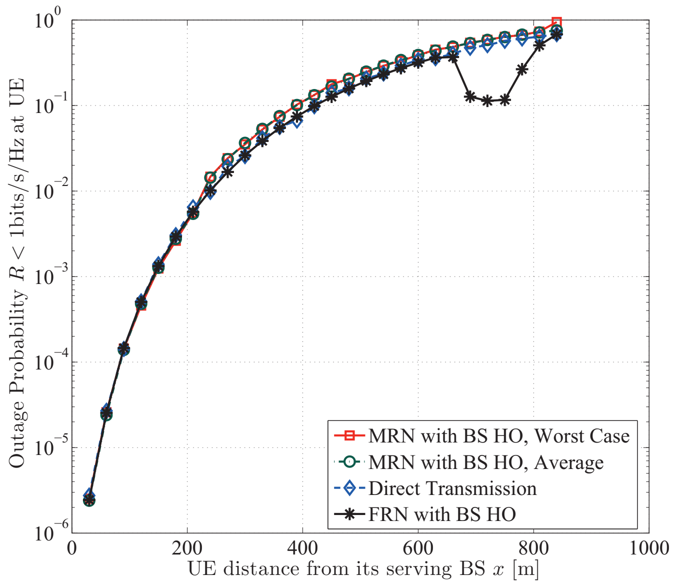

Figure 3.3: OP performance in a system with HO capability at VPL = 10 dB

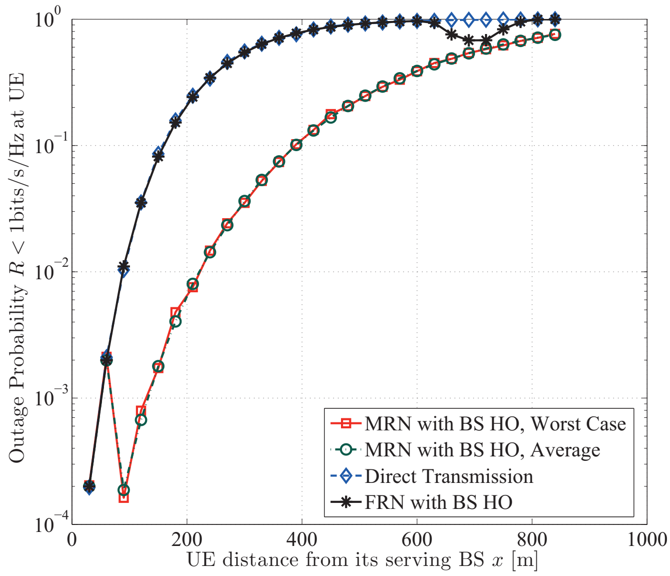

Figure 3.4: OP performance in a system with HO capability at VPL = 30 dB

From the plots, we can observe that when the VPL is low, i.e., 10 dB, the MRN and direct transmission show almost the same performance, and the FRN can help to lower the end-to-end OP locally when the UE is handed over to it. But as the VPL increases to 30 dB, the advantages of using MRN is very obvious compared to both direct transmission and FRN assisted transmission. Another thing we should notice is that the MRN can be operated at a much lower transmit power compared to macro BSs or other low power nodes but achieve similar or even better performance. Thus MRNs can generate less interference to UEs outside the vehicles from its access link. This is much appreciated in a densely deployed urban scenario where link availabilities usually dependent on interference rather than on coverage. More detailed results and analysis are presented in [20] and system level evaluation results in a multiple cell setup from our partner is presented in [21].

Chapter 4

Contributions and Future Work

The purpose of this thesis is to show initial understandings of deploying a new type of node, i.e., the MRN, to the network. The analysis begins with simple setups and both FRN assisted transmission and direct transmission are used as references. In this chapter, we summarize the publications that lead to this thesis and path for future works.

4.1 List of Contributions

The four main contributions included in Part II of the thesis are listed as follows.

- **Paper A** *Moving Cells: A Promising Solution to Boost Performance for Vehicular Users*

This is an overview article which summarizes the solutions discussed in 3GPP studies to serve vehicular UEs. Furthermore, initial system level evaluation results of MRN assisted transmission done by our partner is presented. A prediction antenna solution to improve the backhaul link reliability is also summarized in this paper.

- **Paper B** *The Potential of Moving Relays—A Performance Analysis*

This paper was an initial study of the benefit of deploying an MRN in a single cell noise limited scenario. In this paper, the end-to-end OP was considered as the metric to evaluate the performance. Both FRN assisted transmission and direct transmission were used as references. An FRN performance lower bound was derived when the UE position was known. In order to achieve a fair comparison, the optimal FRN position that minimized the average OP was obtained numerically when only knowing the UE position distribution. From the results we can see that when the VPL is moderate to high, the MRN can significantly lower the end-to-end OP at the vehicular UE.

- **Paper C** *Performance Comparison of Fixed and Moving Relays under Co-channel Interference*

In this paper, we investigated the end-to-end OP performance of an MRN in the presence of CCI when only considering the effect of pathloss and small scale fading. A two cell setup was considered, and the FRN assisted transmission and direct transmission were used as reference cases. We did not consider any ICIC schemes, and hence the results could be seen as a worst case study. Better performance could be possible when we consider different ICIC schemes. In this study, we also employed more practical channel models for pathloss and small scale fading, and the optimal FRN position that minimized the average OP was obtained numerically. The results showed that MRN assisted transmission had similar performance to direct transmission when the VPL is 10 dB and as we increased the VPL, MRN assisted transmission greatly outperformed direct transmission as well as FRN assisted transmission. Furthermore, the MRN was operated at a much lower transmit power than the FRN. Hence, the use of MRN also has the potential to improve the energy efficiency of the network.

- **Paper D** *On the Benefits of Fixed and Moving Relays for Vehicular Users under Co-channel Interference*

In this paper, we extended our study to a more practical scenario compared to Paper C. Similarly a two cell setup was considered, and the FRN assisted transmission and direct transmission were used as reference cases. In addition, the effect of shadowing and HO between macro BS and RNs were also considered together with pathloss and small scale fading. In the presence of both shadowing and small scale fading, it was difficult, both numerically or even by simulations, to obtain the optimal FRN position that lower the average OP when only knowing the UE position distribution. Thus, we introduced the concept of fading margin to obtain the FRN position for a fair comparison. When HO was not considered, compared to Paper C, similar behavior for the considered schemes were observed. When HO between macro BS and RNs were considered, in low VPL cases, we observed that FRN could locally lower the end-to-end OP when the vehicular UE was handed over to it. As VPL increased to 30 dB, compared to direct transmission and FRN assisted transmission, MRN could significantly lower the end-to-end OP at the vehicular UE.

4.2 Future work

So far, our studies were only limited to simple scenarios where analytical analysis can be performed. We gained quite a few understandings of the benefits of deploying MRNs as well as the challenges. In order to gain more comprehensive understandings of how this type of new nodes will impact on the mobile networks, system level evaluations need to be conducted; however, this needs to be done by simulations. With the help of more advanced simulations, more practical scenarios, e.g., multiple vehicles moving through multiple cells, can be studied.

Furthermore, ICIC schemes also need to be considered. Although the vehicle can isolate most of the interference generated by MRNs within the vehicle, it may still affect the UEs that are quite close to it, e.g., in a bus stop. The LTE release 10 provides an advanced flexible framework for the implementation of various ICIC schemes, and further enhancement of the ICIC framework is under investigation during the studies of LTE release 11 and release 12. Thus, it is also useful to see whether the current ICIC framework is enough for the operations of MRNs. Otherwise, new ICIC schemes need to be considered.

Another interesting direction for the research would be cooperative communications between MRNs and their donor BSs. At this moment, we only assume that MRNs can serve the UEs inside the vehicle, but with certain modifications, it is possible to use the MRNs to serve the UEs outside the vehicle. Then, the cooperation between MRNs and their donor BSs can be considered to help the UEs around the MRNs. Certainly, this is more challenging, since the transmit power of the MRN is very low, which means that the coverage of the MRN could be very limited. But some of the schemes developed for type-2 RNs can still function and be beneficial. For example, MRNs can help the re-transmission when the initial transmission from the macro BS to the macro UE fails.

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