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In-band Relays for Next Generation Communication Systems

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Abstract

Next generation mobile communication systems will operate at high system bandwidths of up to 100MHz and at carrier frequencies beyond 2GHz to provide peak data rates of up to 1Gbit/s with similar average revenues per user as todays cellular networks. High bit rates should be available to all users in a cell which is challenging due to the unfavorable propagation conditions in these bands. In-band relays are a seen as a promising technology for cellular networks to extend the high bit rate coverage and to enable cost efficient network deployments.

The research in this thesis has contributed to the development of the relaying concept within the European research project WINNER. WINNER has designed a next generation radio system concept based on Orthogonal Frequency Division Multiple Access (OFDMA) with the inclusion of relays as one of the major innovations. In our work we have identified the radio resource management as the most important function to exploit the potential benefits of relay based deployments. We develop a flexible radio resource management framework that adapts to a wide range of deployments, whereas our main focus is on metropolitan area deployments. Here we propose to utilize a dynamic resource assignment based on soft frequency reuse. Further, we propose a practical way to integrate cooperative relaying in a relay network. This concept allows the cooperation of multiple radio access points within a relay enhanced cell with low overhead and small delays.

In system simulations we compare the performance of relay deployments to base station only deployments in a metropolitan area network. Our results show that relay deployments are cost efficient and they increase both the network throughput as well as the high bit rate coverage of the network. Further, they show that our proposed soft frequency reuse scheme outperforms competing interference coordination schemes in the studied metropolitan area scenario. Even though the results have been obtained for WINNER system parameters, the conclusions can also be applied to OFDMA based systems such as 3GPP Long Term Evolution and WiMAX.

Preface

The research work for this doctoral thesis was carried out at the Future Cellular Systems group in Nokia Research Center, Helsinki, during the years 2003-2009. The work was done under the supervision of Prof. Risto Wichman, head of the Wireless Signal Processing group at the Department of Signal Processing and Acoustics, Aalto University School of Science and Technology.

First, I would like to thank my supervisor Prof. Risto Wichman for his support and guidance during my studies and research work as well as for providing me with the freedom needed to combine a full-time job with writing a dissertation. Further, I would like to thank my mentors at Nokia Research Center Dr. Ari Hottinen and Dr. Carl Wijting for numerous ideas concerning the work and their significant contribution in many publications and patents. Next, I would like to thank Dr. Kimmo Valkealahti for the fruitful cooperation and his invaluable help in the system simulator development and the IT department of Nokia that provided us with the high performance grid computing resources required to run all these highly complex system simulations. I would also like to thank Dr. Seán Murphy and Prof. Jukka Lempiäinen for reviewing the thesis and for their comments and suggestions.

For two years I had the privilege of being part of the European Research Project WINNER II with the goal to design a next generation communication system. During this time I met great people and excellent researchers. We had numerous discussions on the future of mobile communication systems in general and on relaying in particular which clearly influenced and guided my work. In particular, I would like to thank my colleagues at Nokia Research Center Dr. Carl Wijting, Dr. Antti Sorri, Dr. Kari Kalliojärvi, Dr. Jean-Philippe Kermoal and Xiaoben He and my colleagues in the relaying task and in the concept finalization phase Dr. Simone Redana, Dr. Peter Rost, Dr. Michal Wódczak, Niklas Johansson, Dr. Martin Döttling, Prof. Tommy Svensson, Prof. Mikael Sternad, Dr. Daniel Schulz, Dr. Ralf Pabst, Dr. Afif Osseiran, Dr. Gunter Auer, Dr. Jijun Luo, Magnus Olsson, Dr. Johan Nyström, Dr. Thierry Lestable, Dr. Stephan Pfletschinger, Dr. Mark Naden, Peter Moberg and Prof. Bernhard Walke for the great cooperation and the great spirit in the project.

My colleagues at Nokia Research Center deserve special thanks for their support, delightful lunch discussions, for forming one of the leading wireless research groups and for making it a great place to work. In particular I would like to thank my colleagues in the optimized local access team Dr. Klaus Hugl, Dr. Cassio Ribeiro, Dr. Mika Rinne, Jarkko Kneckt, Dr. Juha Korhonen, Heikki Kokkinen, Elena Virtej, Martti Moisio, Petteri Lunden, Markus Nentwig, Prof. Olav Tirkkonen, our co-creators from Aalto University Pekka Jänis and Chia-Hao Yu and Dr. Yrjö Kaipainen, Dr. Kimmo Kalliola, Dr. Jani Ollikainen, Dr. Terhi Rautiainen, Pasi Pirhonen, Dr. Massimo Bertinelli, Lars Lindh, Heikki Berg, Tero Henttonen and Jussi Ojala for the excellent cooperation and support in my research work. I would especially like to thank my research leaders Dr. Klaus Hugl, Dr. Samuli Visuri, Dr. Juha Laurila and Dr. Hannu Kauppinen for the freedom and time to work on relays for several years and to finalize my thesis.

I am very grateful to my parents for their support in the entire course of my studies. Finally, and most of all I would like to thank Natascha, Sami and Maja for their love, support and patience which has been essential during the past years.

Espoo,
2010,

Klaus Doppler

Contents

List of abbreviations and symbols

Abbreviations

1xEVDO	1x Evolution Data Only
3GPP	Third-generation partnership project
3GPP2	Third-generation partnership project 2
ACK	Acknowledged
AF	Amplify and Forward
ARQ	Automated Repeat Request
AWGN	Additive White Gaussian Noise
B band	Basic band
BC	Broadcast
BCH	Broadcast Channel
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
byRB	By Resource Block
byUser	By User
CAPEX	Capital Expenditure
CCCH	Common Control Channel
CDF	Cumulative Distribution Function
CoopRRM	Cooperative Radio Resource Management
CP	Cyclic Prefix
CSI	Channel State Information
CTS	Clear to Send
D	Destination

DDF	Dynamic Decode and Forward
DF	Decode and Forward
DL	Downlink
DRS	Dynamic Resource Sharing
DVB	Digital Video Broadcasting
DVB-T	Digital Video Broadcasting-Terrestrial
DVB-H	Digital Video Broadcasting-Handheld
E band	Extension Band
E2E	End-to-End
EF	Estimate and Forward
ETP	Equal Throughput
FD	Frequency Domain
FDD	Frequency Division Duplex
FDPS	Frequency Domain Packet Scheduler
FFT	Fast Fourier Transform
FFR	Fractional Frequency Reuse
FIR	Finite Impulse Response
FSS	Fixed Satellite Service
FUSC	Full Usage of Subcarriers
FTP	File Transfer Protocol
GoB	Grid of Beams
HARQ	Hybrid Automated Repeat Request
HPBW	Half Power Beamwidth
HTTP	Hypertext Transfer Protocol
iCAR	Integrated Cellular and Ad-Hoc Relay
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunications
IMT-A	IMT-Advanced
ISD	Inter-Site Distance
ITU	International Telecommunications Union
LoS	Line-of-Sight
LTE	Long-term Evolution

MA	Multiple Access
MAC	Medium Access Control
MBS	Multiband Scheduler
MCN	Multihop Cellular Network
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MT	Mobile Terminal
NACK	Not Acknowledged
NAF	Nonorthogonal Amplify and Forward
NLoS	Non Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
PDU	Packet Data Unit
PER	Packet Error Rate
PF	Proportional Fair
PHY	Physical
PL	Pathloss
PUSC	Partial Usage of Subcarriers
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phased Shift Keying
R	Relay
RACH	Random Access Channel
RAN	Radio Access Network
RAP	Radio Access Point
RB	Resource Block
REC	Relay Enhanced Cell
redFB	Reduced Feedback
RLC	Radio Link Control
RN	Relay Node
RR	Round Robin
RRC	Radio Resource Control

RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time
RTS	Request to Send
Rx	Receive
S	Source
SDMA	Space Division Multiple Access
SFR	Soft-Frequency Reuse
SIMO	Single-Input Multiple-Output
SINR	Signal-to-Interference plus Noise Ratio
SNR	Signal-to-Noise Ratio
TCP/IP	Transmission Control Protocol
TD	Time Domain
TDD	Time-Division Duplex
TDPS	Time Domain Packet Scheduler
Tx	Transmit
UL	Uplink
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
VAA	Virtual Antenna Array
VoIP	Voice over Internet Protocol
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WINNER	Wireless World Initiative New Radio
WRC	World Radiocommunications Conference

Symbols

$\mathbf{x}$	vector, matrix
$(\cdot)^*$	complex conjugate
$(\cdot)^T$	transpose of a matrix
$(\cdot)^H$	Hermitian transpose of a matrix
$(\cdot)^{-1}$	inverse of a matrix
$(\cdot)^{-H}$	inverse Hermitian transpose of a matrix
$(\cdot)_R$	relay
$(\cdot)_S$	source
$(\cdot)_D$	destination
C	Shannon capacity
$\mathbf{F}$	Fast Fourier Transform Matrix
N	number of antennas
N_{tx}	number of Tx antennas
N_{rx}	number of Rx antennas
N_{s}	number of sources
N_{r}	number of relays
N_{d}	number of destinations
N_0	noise variance
x	transmitted signal
y	received signal
E_{SR}	received energy at relay from source
E_{SD}	received energy at destination from source
E_{RD}	received energy at destination from relay
P_{S}	transmitted power from source
P_{R}	transmitted power from relay
h	channel response
h_{SR}	channel response between source and relay
h_{SD}	channel response between source and destination
h_{RD}	channel response between relay and destination
n_{R}	AWGN noise at relay
n_{D}	AWGN noise at destination

α	fraction of time for broadcast phase
β	correlation between source and relay signal
δ	fraction of power used for new information
ρ	signal to noise ratio
λ	wavelength
p	OFDM subcarrier index
ν	penalty value for RN handover targets
ι	queue size threshold

Chapter 1

Introduction

1.1 Motivation of the thesis

Mobile users of next generation communications systems expect seamless coverage with a guaranteed Quality of Service (QoS) to allow for a similar user experience as provided by today's broadband internet connections. To meet these expectations the process to define International Mobile Telecommunications - Advanced (IMT-Advanced) systems has started. IMT-Advanced systems are mobile broadband communication systems that include new capabilities that go significantly beyond those of the IMT-2000 family of systems (WCDMA, CDMA2000, WiMAX, etc.).

One of the key features of IMT-Advanced are enhanced peak data rates to support advanced services and applications (100 Mbit/s for high and 1 Gbit/s for low mobility were established as targets for research [1]). A request for IMT-Advanced technology proposals has been issued by the International Telecommunication Union (ITU) [2], according to which candidate radio interface technologies can be submitted during 2008 and 2009. The submissions should be accompanied by a self-evaluation of the proposal; also evaluations by external evaluation groups will take place. The evaluation phase is scheduled to be finalized in June 2010. In parallel and after the evaluation activities a consensus building and assessment of the evaluations will take place until October 2010. The development of a recommendation with the radio interface specification is scheduled for February 2011 [2].

To support high aggregate data rates of up to 1Gbit/s a high spectrum demand of approximately 100MHz is expected, which will only be available at frequencies higher than 2GHz. The high carrier frequencies together with regulatory constraints on the transmission power will limit the range for broadband services. Thus, many small cells are required for contiguous coverage of areas with high traffic density. A traditional approach would be to increase the base station (BS) density. However, the network costs scale linearly with the amount of deployed BSs [3] whereas the amount of users and the average revenue per user will not increase accordingly. Therefore, cost efficient alternative deployment concepts are needed.

One promising alternative deployment is based on in-band relays to extend the high throughput coverage of next generation mobile networks. In [4] it was shown that deployments based on in-band relays can increase the high bit rate coverage at the cell border; thereby provide the means to balance the capacity within the cell and increase the coverage area of a single BS. Not surprisingly relays as part of infrastructure based networks have been standardised in the Technical Specification Group j (TSG j) of IEEE802.16j [5] and a study item on relaying has been formed in 3GPP.

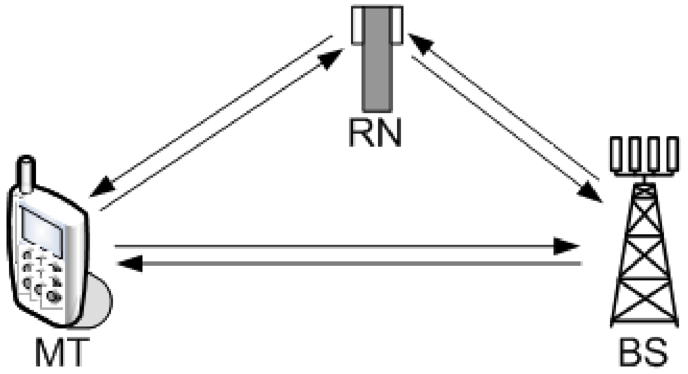


Figure 1.1: The relay node receives a signal from a source (BS or MT) and forwards it to the destination (MT or BS). The destination may also receive a direct signal from the source.

Wireless relays are devices that receive a wireless signal from a source and forward it to a destination, as depicted in Figure 1.1. In a cellular network the source and destination can be a BS, a mobile terminal (MT) or another relay node (RN). The relay is placed between the source and the destination and the link budget for both the link to the source and the destination is higher than for the direct link between the source and the destination. As a consequence both links have a higher throughput than the direct link and the overall throughput can increase even if the relay operates in half-duplex, i.e. receiving in a first time slot and forwarding in a second time slot. Depending on the signal processing performed on the received signal the following operation modes of a relay can be distinguished

- Amplify and Forward
- Decode and Forward
- Estimate and Forward

The destination may be able to receive both the signal from the source and from the relay and gains from a cooperation between the source and the relay may be achieved. We refer to this mode of operation as cooperative relaying.

The information theoretical properties of the Gaussian relay channel have already been studied in the 1970s for example by Cover [6]. However the integration of relays into a cellular system has only gained attention around the year 2000 for example in [7].

Many details have to be solved to exploit the potential benefits of relays in cellular networks. These details have been addressed in the relaying task of the European research project WINNER (Wireless World Initiative New Radio). The WINNER project started in January 2004 and ended in December 2007. WINNER has been funded by the Sixth Framework Program of the European Commission, aiming at the identification and assessment of key technologies for IMT-Advanced mobile communication systems [8]. The 42 project partners included the major industrial and academic players in mobile communications and the project volume was about 43 Mio EUR [9] with more than 4000 person months of effort. The main outcome of the project was the definition of the WINNER system concept [10] and [11]. The system concept meets the IMT-Advanced requirements and it was backed up by proof-of-concept simulations in network deployments foreseen to be representative for IMT-Advanced communication systems.

The WINNER Radio Access Network (RAN) has been designed to fulfill the IMT-Advanced performance requirements and enable a cost efficient deployment. Within WINNER, relaying has been identified as the key technology to enable cost efficient deployments. The relaying task of WINNER had the goal to define a relaying concept that integrates relays into the overall WINNER RAN and to show that this concept is cost efficient. Next to the IMT-Advanced requirements additional requirements have been derived from the services that the WINNER RAN has to support [12], e.g. a minimum delay of 1 ms in downlink and 2 ms in uplink over the radio interface. The short delays enable a relay based deployment to fulfill even the stringent end-to-end delay requirements of 20ms (less than 10ms for the air interface) of highly interactive services [12].

The relaying concept should allow a flexible deployment of relays to

- Extend the coverage of a BS
- Distribute the capacity available from a BS more evenly in the cell
- Cover otherwise shadowed area

Further, it should take limitations of real cellular systems into account, e.g. the forwarding of feedback information, control overhead, etc. Finally, proof-of-concept simulations should show that the relaying concept outperforms a deployment based on BS only and that it is cost efficient. The simulations should be performed for three typical deployments of IMT-Advanced communication systems: a wide area scenario that provides base urban coverage, a metropolitan area scenario based on micro-cells and a local area office scenario.

The main focus of this thesis is on the metropolitan area scenario based on a micro-cell deployment. Urban areas are characterized by a high population density. Typically its inhabitants have a higher income level and adopt new technologies faster than people living on the countryside. The resulting high traffic density will not be achieved by macro-cell deployments but micro-cell deployments will be required. Thus, we expect this scenario to be the most interesting for IMT-Advanced broadband mobile communication systems.

Since the WINNER system concept is based on Orthogonal Frequency Division Multiple Access (OFDMA) the key technology components and assessment results provide relevant input to the future evolution towards IMT-Advanced of other OFDMA based systems such as WiMAX [13] and 3GPP Long Term Evolution [14].

1.2 Scope of the thesis

The scope of this thesis is to outline how wireless in-band relays can be integrated in an OFDMA based IMT-Advanced broadband mobile communication system. In particular this thesis contributes to the following important aspects of cellular relay networks

- Radio resource management
- Relays to support multiband operation

- Cooperative relaying

We have identified the Radio Resource Management (RRM) as the most important function to exploit the potential benefits of relay based deployments. The RRM framework that we have developed within the relaying task in WINNER adapts to different deployments in a wide area, a metropolitan area and a local area indoor office scenario whereas the main focus of this thesis is on metropolitan area networks.

Next to performance targets, IMT-Advanced mobile communication systems have to significantly reduce the cost per transmitted bit in order to be successful. Within the WINNER project, relay based deployments have been identified as the key technology to reduce the deployment costs of a system when providing initial coverage and/or to achieve a given performance target. Therefore, we investigate the BS to RN cost ratio for which a relay based deployment offers a cost advantage compared to a BS only deployment for a metropolitan area test scenario.

The spectrum which is currently allocated to IMT systems is very fragmented. It is likely that next generation mobile communications system will operate on multiple bands to achieve the required high aggregate data rates. In multiband operation, we study the potential of relays to balance the coverage areas of bands with different propagation properties.

Cooperative relaying has been identified as a promising technology to increase the capacity of a relay network and a vast amount of cooperative relaying protocols have been proposed in literature. However, the integration of cooperative relaying into a cellular relay network received only little attention. In this thesis we present a concept that integrates cooperative relaying into the WINNER system.

1.3 Contributions of the thesis

The work presented in this thesis has mostly been carried out within the relaying task of the European research project WINNER. It has actively contributed to the development of the WINNER relaying concept and to the overall WINNER system concept.

The WINNER relaying concept has solved many details on how to integrate relays into a cellular system and proof-of-concept simulation have shown that it outperforms a deployment without relays.

The contribution of this thesis concentrates on four important aspects of the WINNER relaying concept.

1. WINNER radio resource management framework
2. Multiband operation with relay support
3. Integration of cooperative relaying into a cellular network
4. Evaluation of relay deployment strategies in a metropolitan area

First, this work has contributed to the development of the WINNER radio resource management (RRM) framework. The WINNER RRM framework proposes that the BS flexibly assigns resources to itself and the relays within the relay enhanced cell. In contrast to a centralized solutions it does not require extensive feedback and resource allocation signaling between the BS and the relays. The work presented in this thesis has mainly contributed to the RRM in a metropolitan area relay network where the author proposes to utilize soft frequency reuse. Soft frequency reuse enables reuse one and introduces signal to interference plus noise ratio (SINR) variations that can be exploited by the packet scheduler. The author presents an interference aware scheduling algorithm that exploits these variations and allocates high SINR resources preferably to users at the cell border. Performance assessment results for the metropolitan area test scenario show that the proposed solution outperforms a deployment without relays and that soft-frequency reuse together with the proposed interference aware scheduling algorithm is an effective way to coordinate the interference. Further, the author proposes a local power mask adaptation to adjust the RRM based on local traffic variations.

Second, in a network with multiband operation, the author shows how relays can be utilized to balance the coverage area of different frequency bands. Bands with lower center frequency have better propagation properties (larger ranges) than higher frequency bands, and RNs are a cost efficient way to extend the coverage area of the higher bands. Performance assessment results show that the relays effectively extend the coverage area of the higher frequency band and significantly increase the capacity of the network. Further, the author introduces the multiband scheduler, a concept which he has developed together with Dr. Carl Wijting and Dr. Jean Philippe Kermoal. The multiband scheduler allows a fast and seamless switch between different bands to meet the stringent delay requirements of IMT-Advanced systems.

Third, the author outlines how cooperative relaying can be integrated into a cellular network. In particular he describes a resource allocation strategy for cooperatively served mobile terminals (MT). The first common node in the tree topology within the relay enhanced cell (the BS in a two hop deployment) allocates the resources to the cooperatively served MT. The author introduces the concept of a serving radio access point (RAP) for cooperative connections. The serving RAP will signal the resource allocation and perform retransmissions. The retransmissions are not cooperatively transmitted and do not need to be coordinated, which reduces the delay.

Fourth, the author has evaluated multiple deployment strategies in a metropolitan area scenario, modeled by the Manhattan grid. He compares the different deployments and determines the cost ratio of a micro BS to a relay node (RN) for which RNs will be cost efficient. Based on these results he suggests and motivates a relay deployment which can serve as a reference scenario for research and standardization bodies.

Next to the contribution to the WINNER relaying concept this thesis proposes the use of amplify and forward (AF) within the cyclic prefix (CP) relays. The author studies the potential gains from this operation mode in a metropolitan area network and shows in link results that it outperforms half-duplex decode and forward (DF) relaying also in a multiple-input multiple-output (MIMO) system. Relays utilizing AF within the CP are a promising solution for OFDM based networks such as Digital Video Broadcast (DVB) networks but they are not well suited for OFDMA networks since they cannot forward data selectively only to mobile terminals in their coverage area.

1.4 Summary of the publications and contribution of the author

This thesis is based on 14 original publications which are listed in Appendix A.

The author has been an active contributor to the WINNER relaying task. He has been one of the main contributors to all deliverables of the WINNER relaying task [15], [16] and [17]. He has been the editor of D3.5.2 [16] and the main author of the section on the radio resource management framework based on dynamic resource assignment. Within this framework the author has proposed to utilize soft frequency reuse in metropolitan area deployments. In addition he has proposed an interference aware scheduling scheme [18] and a power mask adaptation scheme [19] to exploit the benefits of soft frequency reuse.

He has been leading and driving the spatial temporal processing and relays subtask responsible for the integration of cooperative relaying into the WINNER relaying concept. The concept of the serving access point, the resource allocation strategy and the handling of retransmissions have been proposed by the author. In [20] the intermediate concept of the integration of cooperative relaying into the WINNER system concept has been presented together with performance assessment results for different cooperative relaying protocols. The author has contributed the sections describing the concept while the assessment results have been obtained by the other authors of the paper.

The author has been the proof-of-concept subtask leader in the WINNER relaying task which was responsible to provide assessment results of the relaying concept in the different test scenarios. The author has contributed the majority of the assessment results in the metropolitan area test scenario, which have been published in [21, 22, 19, 18]. In [21] we investigate the performance gains from relays and we derive the BS to RN cost ratio for which relay deployments are cost efficient compared to BS only deployments. In [22] we compare the performance of different interference coordination strategies, including soft frequency reuse in a metropolitan area network. In [19] we present the power mask adaptation scheme and in [18] the interference aware scheduling scheme for soft frequency reuse. The simulation software used to obtain the aforementioned results and the results for metropolitan area relay deployments in [11, 23, 24, 25, 26] built on top of an existing dynamic system simulator platform. The author has together with Dr. Kimmo Valkealahti implemented all relaying related functionalities to the simulator. All simulations and post processing of the results have been carried out by the author.

The author was the main contributor from the relaying task in the concept finalization meetings and to the deliverable containing the WINNER II system concept description [10]. In [11] and [24] we present the main parts of the WINNER II system concept together with selected assessment results. The author has been responsible for the sections on relaying in both publications and together with the first and third author he has written the introduction, the conclusions and has edited the publications. [26] introduces the WINNER II relaying concept in a book on the WINNER II system concept. The author was the main contributor to the sections on the WINNER relay test scenarios, the cost efficiency of RNs, the design choices for relay based cellular networks, the radio resource partitioning, relay ARQ and he has contributed simulation results for metropolitan area relay deployments and for an optimum resource partitioning in the wide area test scenario.

Further, the author has had a significant contribution to the overall editing of the book chapter.

In [23] and [27] the multiband scheduler concept is presented. Numerical results in [23] show the benefits of the multiband operation in relay networks. The concept of the multiband scheduler and the integration of relays has been developed by the author together with the co-authors. The simulations and post processing of the results have been carried out by the author.

[28] and [29] address the integration of relays into an OFDM system. In [28] the use of the amplify and forward within the cyclic prefix protocol for cellular OFDM networks is proposed and potential performance gains from relays in that scenario are studied. In [29] the performance of this protocol in a multi-antenna system is compared to a half-duplex amplify and forward and a decode and forward protocol. The idea of using the amplify and forward within the cyclic prefix protocol has been proposed by the author. The simulation software for obtaining the results built on top of an existing link simulator where the author has implemented the different relaying protocols, the relay channel and the subcarrier allocation procedure. All simulations and post processing of the results have been carried out by the author.

In [30] a general weighted relaying protocol for interference relay networks is proposed which generalizes the protocols earlier presented in literature. Further, the performance of spatially separated interference relay networks is studied for selected network topologies. The author has contributed to the development of the general weighted relaying protocol and to the definition of the scenarios to be studied. The main work of writing the paper and obtaining the assessment results have been carried out by the first author.

The author has been the main contributor to the following novel concepts: the concept on how to integrate cooperative relaying into the WINNER system, the multiband scheduler, the idea to utilize soft frequency reuse in metropolitan area networks, the interference aware scheduler for soft frequency reuse, the adaptive soft reuse scheme and the proposed end-to-end relay ARQ scheme. Several patent applications have been filed on novel aspects of the work presented in this thesis [31, 32, 33, 34, 35, 36, 37, 38, 39, 40]. Some of these patent applications are related to resource assignment in relay networks with more than two hops which has not been presented in any of the aforementioned conference and journal articles.

1.5 Structure of the thesis

This thesis is organized as follows. In Chapter 2 we give a brief overview of the main information theoretic results found in literature on the relay channel with and without cooperation. Then we show the potential link level gains from the AF within the CP relaying protocol using a metropolitan area propagation model. Further, we discuss some performance bounds that have been derived for relay networks.

In Chapter 3 we present selected protocol aspects and functional elements that are required when integrating relays into cellular networks. We outline the WINNER radio resource assignment solution for relay networks and show how it can be applied to a metropolitan area deployment. The main focus here is on dynamic resource assignment based on soft frequency reuse for the metropolitan area. Further, we illustrate how cooperative relaying can be integrated into the relaying concept and finally we outline how relays can be utilized in a network with multiband operation.

In Chapter 4 we first give a short overview of different system simulator used to evaluate the performance of cellular networks. Then we introduce the system simulation tool that has been used in our work. Thereafter we present the metropolitan area test scenario. We present an extensive amount of performance results for the metropolitan area scenario including results on soft frequency reuse and dynamic resource assignment for relay deployments as well as a cost comparison between BS only and relay deployments. Further, we present results on relays in networks with multiband operation in a wide area test scenario. We then compare our results on dynamic resource assignment to system simulation results of other research groups, available in literature. Please note that in Chapter 2 the focus is on link level results whereas the results in Chapter 4 have been obtained in system simulations, which should give an indication on the expected performance of relays deployed in a cellular network.

Chapter 5 concludes the thesis.

Chapter 2

Wireless Relays

In this chapter we give a brief overview of information theoretic aspects of relay networks. In Section 2.1 we introduce the different operation modes and the signal model commonly used in relaying literature. In Section 2.2 we briefly review some of the most important information theoretic results on the relay channel that can be found in literature. In Section 2.3 we give a short overview and discuss selected cooperative relaying strategies proposed in literature. In Section 2.4 we outline the integration of relays into an Orthogonal Frequency Division Multiplexing (OFDM) system. Further, we give some intuition on the potential gains of relays in a metropolitan area OFDM network. In Section 2.6 we review some information theoretic results for large relay networks. We conclude with a summary and discussion in Section 2.7.

2.1 Introduction

Figure 2.1 illustrates the simplest possible relay network. It consists of 3 nodes, the source S, the relay R and the destination D.

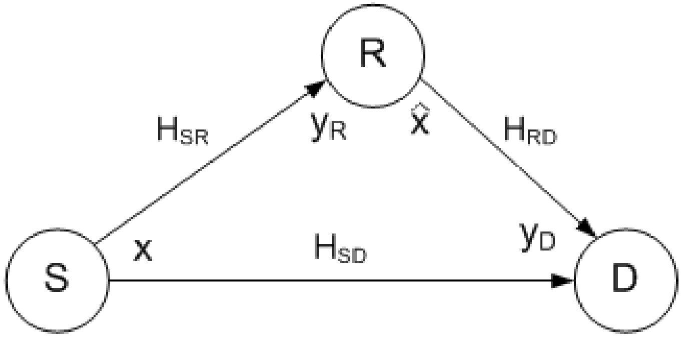


Figure 2.1: Relay Channel Model

The source transmits the signal x and the received signal at the relay y_r can be found as

$$y_r = \sqrt{E_{\mathrm{SR}}} h_{\mathrm{SR}} x + n_{\mathrm{R}} \tag{2.1}$$

where E_{SR} denotes the average signal energy received from the source and h_{SR} the radio channel between source and relay. x is normalized to have unit average energy. E_{SR} captures effects of slow fading, shadowing, path-loss and transmit power; h_{SR} captures fast fading effects of the radio channel and is normalized to have unit average energy. n_{R} is the additive white Gaussian noise at the relay with zero mean and variance $\sigma^2_{n_{\mathrm{R}}}$.

Depending on the signal processing performed by the relay the different relay operation modes can be distinguished. In *amplify and forward* mode the relay amplifies the received signal and forwards it to the destination. The received signal at the destination can be found as

$$y_{\mathrm{D}} = \sqrt{\frac{E_{\mathrm{SR}} E_{\mathrm{RD}}}{E_{\mathrm{SR}} + \sigma^2_{n_{\mathrm{R}}}}} h_{\mathrm{RD}} h_{\mathrm{SR}} x + \tilde{n}_D \tag{2.2}$$

where E_{RD} denotes the average of the signal energy received from the relay and $\sqrt{\frac{1}{E_{\mathrm{SR}} + \sigma^2_{n_{\mathrm{R}}}}}$ is a power normalization term used at the relay. h_{RD} denotes the radio channel between the relay and the destination, has unit average energy and captures the fast fading effects. $\tilde{n}_D$ denotes the effective noise contained in the received signal, which consists of the noise at the relay, amplified by $\sqrt{\frac{E_{\mathrm{RD}}}{E_{\mathrm{SR}} + \sigma^2_{n_{\mathrm{R}}}}}$ and filtered by h_{RD}, as well as the additive white Gaussian noise n_{D} with zero mean and variance $\sigma^2_{n_{\mathrm{D}}}$ at the destination:

$$\tilde{n}_D = \sqrt{\frac{E_{\mathrm{RD}}}{E_{\mathrm{SR}} + N_0}} h_{\mathrm{RD}} n_{\mathrm{R}} + n_{\mathrm{D}} \tag{2.3}$$

One important property of amplify and forward relays is the amplification of the receiver noise at the relay which can be seen in the first term of equation (2.3). Relays in amplify and forward operation are also known as non-regenerative relays, repeaters or signal boosters.

In *decode and forward* mode the relay decodes the signal received from the source and forwards it to the destination. The received signal at the destination can be found as

$$y_{\mathrm{D}} = \sqrt{E_{\mathrm{RD}}} h_{\mathrm{RD}} \hat{x} + n_{\mathrm{D}} \tag{2.4}$$

where $\hat{x}$ denotes the signal transmitted by the relay. Please note that the relay does not forward the same signal x to the destination. The relay may change the modulation and coding scheme when forwarding the signal, sometimes referred to as decode and re-encode or it might not be able to decode the signal correctly. These are two important properties of decode and forward relaying. The flexibility to change the modulation and coding scheme allows the relay network to adapt to different channel qualities on the links to the source and to the destination. Secondly, decoding errors at the relay will also propagate to the destination. Decode and forward relays are also known as regenerative relays.

In general the destination may be able to receive both the signal from the source and from the relay. The relay may operate in *half-duplex* or in *full-duplex* mode. In half-duplex mode the relay transmits on resources orthogonal to the resources used by the source. Assuming that the source does not transmit while the relay transmits the received signal at the destination can be found as

$$\begin{aligned} y_{\mathrm{D}}^{(1)} &= \sqrt{E_{\mathrm{SD}}}h_{\mathrm{SD}}x + n_{\mathrm{D}}^{(1)} && (2.5) \\ y_{\mathrm{D}}^{(2)} &= \sqrt{E_{\mathrm{RD}}}h_{\mathrm{RD}}\hat{x} + n_{\mathrm{D}}^{(2)} && (2.6) \end{aligned}$$

where E_{SD} denotes the average of the signal energy received from the source and h_{SD} denotes the radio channel between the source and the destination which has unit average energy and captures the fast fading effects. $y_{\mathrm{D}}^{(1)}$ and $y_{\mathrm{D}}^{(2)}$ might be received for example in different time slots, on different frequency channels or using orthogonal spreading codes. In *estimate and forward* mode the relay network can exploit that the destination receives both the signal from source and the relay. In this case the relay transmits an estimate of x to the destination

$$\hat{x} = f(x) \qquad (2.7)$$

The destination uses the estimate as a side information when decoding the signal received from the source. This mode of operation is also known as compress and forward, observe and forward and quantize and forward.

In general for half-duplex relays we can distinguish two phases as illustrated in Figure 2.2. In the first phase, the *broadcast phase* (BC), the source broadcasts the signal

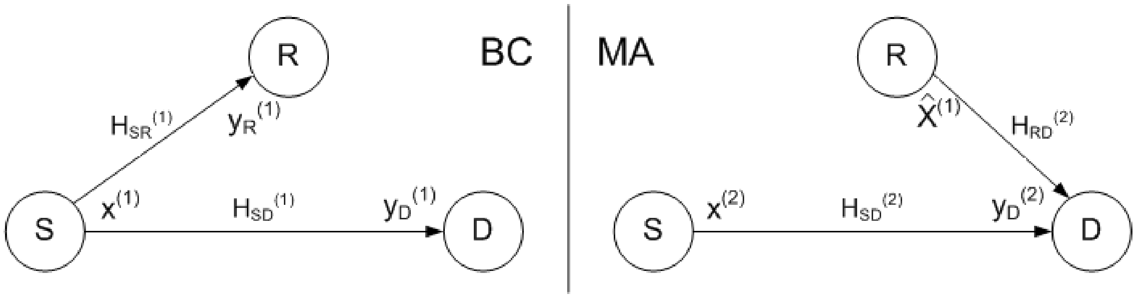


Figure 2.2: Half-Duplex relay operation. In the broadcast phase (BC) both the relay (R) and the destination (D) receive the signal from the source (S). In the multiple access (MA) phase the destination receives both the signal from the source and the relay.

which both the relay and the destination receive. In the second phase, the *multiple access phase* (MA), the destination receives the signal from both the source and the relay.

In the broadcast phase the relay and the destination receive

$$\begin{aligned} y_{\mathrm{R}}^{(1)} &= \sqrt{E_{\mathrm{SR}}^{(1)}} h_{\mathrm{SR}}^{(1)} x^{(1)} + n_{\mathrm{R}}^{(1)} \quad (2.8) \\ y_{\mathrm{D}}^{(1)} &= \sqrt{E_{\mathrm{SD}}^{(1)}} h_{\mathrm{SD}}^{(1)} x^{(1)} + n_{\mathrm{D}}^{(1)} \quad (2.9) \end{aligned}$$

and in the multiple access phase the received signal at the destination can be found as

$$y_{\mathrm{D}}^{(2)} = \sqrt{E_{\mathrm{SD}}^{(2)}} h_{\mathrm{SD}}^{(2)} x^{(2)} + \sqrt{E_{\mathrm{RD}}^{(2)}} h_{\mathrm{RD}}^{(2)} \hat{x}^{(1)} + n_{\mathrm{D}}^{(2)} \quad (2.10)$$

where $(.)^{(1)}$ and $(.)^{(2)}$ denote the broadcast and multiple access phase, respectively.

The destination can benefit from a cooperation between source and relay node and a large set of *cooperative relaying* protocols have been developed. Cooperative diversity protocols utilize the broadcast phase and the inherent spatial diversity [41]. The destination combines the signals received from the source in the broadcast phase and from the relay in the multiple access phase. In the multiple access phase the destination may also benefit from a cooperation between source and relay. As can be seen from 2.10 the destination receives the signal from multiple transmitters (antennas) which can form a virtual antenna array [42]. Further, multiple sources can cooperate by overhearing each others signal in the respective broadcast phases and forwarding it in a joint multiple access phase. Since this mode of cooperation is best applicable to the uplink of a cellular network it is referred to as user cooperation [43].

In full-duplex operation the relay receives and transmits on the same resources. This requires separate receive and transmit antennas and sufficient isolation between these antennas due to differences of up to 120dB in the received and the transmitted signal levels. Therefore, relays are generally assumed to operate in half-duplex operation. Nevertheless, there are important applications of full-duplex relays where a sufficient isolation can be achieved, for example as cellular repeaters in tunnels and underground car parks or as gap fillers in broadcast networks.

2.2 Information-theoretic Aspects of Relaying

In the following we will present key information theoretic results for the relay channel and different relaying protocols to get some understanding of its properties. In particular we state the upper bounds and achievable rates for fixed channel gains. Then we will discuss the impact of different parameters on the upper bounds and achievable rates and compare the results for a simple relay network, where the source the relay and the destination are placed on a line.

It should be noted that there is a vast amount of information theoretic results on the achievable rates for different relay protocols available and we do not review all of it.

The relay channel has been introduced already in the beginning of the 70s [44] and first information theoretic properties have been derived for a degraded relay channel. This work has been extended in [6] which derives capacity equations for the degraded relay channel and bounds for the general Gaussian relay channel.

In general the capacity of the relay channel is not known, except for the degraded relay channel, where the noise at the relay is also added to the signal transmitted by the source to the destination. However, upper bounds have been derived in literature. Secondly, an achievable rate can be calculated which gives a lower bound. If the upper and lower bounds coincide the capacity has been found. This is generally not the case and the goal is to derive upper bounds and achievable rates that are close to each other.

The following upper bounds and achievable rates for fixed channel gains have been derived in [45] if not otherwise stated. For all the equations we assume an independent additive white Gaussian noise with unit variance at both the relay and the destination, i.e. $\sigma^2_{n_\mathrm{R}} = \sigma^2_{n_\mathrm{D}} = 1$.

The upper bound for the full-duplex relay channel can be derived by applying the maximum flow minimum cut theorem to relay networks as suggested by Theorem 4 in [6]. The relay network in Figure 2.1 has two possible cuts, around the source (broadcast)

$(\{S\},\{R,D\})$ and around the destination (multiple access) $(\{S,R\},\{D\})$. Clearly the capacity cannot be greater than the maximum flow through either of these cuts. The upper bound for the full-duplex relay channel can be found as [6]

$$\begin{aligned} C^{+} = \max_{0\leq\beta\leq 1} \min\{ & \frac{1}{2}\log(1+(1-\beta)(h_{\mathrm{SR}}^2 E_{\mathrm{SR}} + h_{\mathrm{SD}}^2 E_{\mathrm{SD}})), \\ & \frac{1}{2}\log(1+h_{\mathrm{SD}}^2 E_{\mathrm{SD}} + h_{\mathrm{RD}}^2 E_{\mathrm{RD}} + 2\sqrt{\beta h_{\mathrm{SD}}^2 h_{\mathrm{RD}}^2 E_{\mathrm{SD}} E_{\mathrm{RD}}})\} \end{aligned} \tag{2.11}$$

where the first term limits the maximum information transfer from the source to the relay and the destination. The second term limits the maximum information transfer from the source and relay to the destination. The codebook for each block used by the source and the relay is assumed to be Gaussian transmitted with powers P_{S} and P_{R} and $E[X_1X_2] = \sqrt{\beta P_1 P_2}$. Please note that for the first block transmitted by the source no cooperation between source and relay is possible but by assuming that $n \to \infty$ blocks are transmitted the resulting loss can be neglected.

An achievable rate for decode and forward relaying can be found as in [6] and in [45]

$$\begin{aligned} R &= max\{R_1, R_2\} \qquad (2.12) \\ R_1 &= \max_{0\leq\beta\leq 1} \min\{\frac{1}{2}\log(1+(1-\beta)h_{\mathrm{SR}}^2 E_{\mathrm{SR}}), \\ &\quad \frac{1}{2}\log(1+h_{\mathrm{SD}}^2 E_{\mathrm{SD}} + h_{\mathrm{RD}}^2 E_{\mathrm{RD}} + 2\sqrt{\beta h_{\mathrm{SD}}^2 h_{\mathrm{RD}}^2 E_{\mathrm{SD}} E_{\mathrm{RD}}})\}, \\ R_2 &= \frac{1}{2}\log(1+h_{\mathrm{SD}}^2 E_{\mathrm{SD}} + \frac{h_{\mathrm{SR}}^2 E_{\mathrm{SR}}}{1+\frac{h_{\mathrm{SD}}^2 E_{\mathrm{SD}} + h_{\mathrm{SR}}^2 E_{\mathrm{SR}} + 1}{h_{\mathrm{RD}}^2 E_{\mathrm{RD}}}}), \end{aligned}$$

where Block Markov encoding is assumed, i.e. the destination is only able to decode the signal after receiving all the encoded blocks. For a better signal quality of the source signal at the relay compared to the destination the relay will cooperate with the source, i.e. β will be close to one. For a worse quality of the source signal received at the relay than at the destination the relay will only have a limited contribution to the signal transmitted by the source and β will be close to zero.

The achievable rate for amplify and forward relaying using the same power normalization as in equation (2.2) can be found by using the signal-to-noise ratio of the received signal ρ as given by

$$R = \frac{1}{2}\log(1+\rho) = \frac{1}{2}\log(1+\frac{h_{\mathrm{SD}}^2 E_{\mathrm{SD}}(1+h_{\mathrm{SR}}^2 E_{\mathrm{SR}}) + h_{\mathrm{SR}}^2 E_{\mathrm{SR}} h_{\mathrm{RD}}^2 E_{\mathrm{RD}}}{1+h_{\mathrm{SR}}^2 E_{\mathrm{SR}} + h_{\mathrm{RD}}^2 E_{\mathrm{RD}}}) \tag{2.13}$$

The upper bound for the half-duplex relay channel can be found by again applying the max-flow-min-cut theorem as [45]

$$\begin{aligned}
C^{+} &= \max_{0\leq\beta\leq 1} \min\{C_1^{+}(\beta), C_2^{+}(\beta)\} \qquad (2.14)\\
C_1^{+} &= \frac{\alpha}{2}\log(1+h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(1)}+h_{\mathrm{SR}}^2E_{\mathrm{SR}}^{(1)})+\frac{1-\alpha}{2}\log(1+(1-\beta)h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(2)}),\\
C_2^{+} &= \frac{\alpha}{2}\log(1+h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(1)})+,\\
&\frac{1-\alpha}{2}\log(1+h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(2)}+h_{\mathrm{RD}}^2\frac{E_{\mathrm{RD}}}{1-\alpha}+2\sqrt{\beta h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(2)}h_{\mathrm{RD}}^2E_{\mathrm{RD}}\frac{E_{\mathrm{RD}}}{1-\alpha}}),
\end{aligned}$$

where α denotes the time the relay receives from the source and $1-\alpha$ the time where both the source and the relay transmit. Different to [45] we let the relay increase its power to $\frac{E_{\mathrm{RD}}}{1-\alpha}$ in the half duplex case in order to get the same average power for different α values.

An achievable rate for half-duplex decode and forward relaying when assuming that the relay successfully decoded the signal can be found as [45]

$$\begin{aligned}
R &= \max_{0\leq\delta\leq 1} \min\{R_1(\delta), R_2(\delta)\}, \qquad (2.15)\\
R_1 &= \frac{\alpha}{2}\log(1+h_{\mathrm{SR}}^2E_{\mathrm{SR}}^{(1)})+\frac{1-\alpha}{2}\log(1+(1-\delta)h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(2)}),\\
R_2 &= \frac{\alpha}{2}\log(1+h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(1)})+,\\
&\frac{1-\alpha}{2}\log(1+h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(2)}+h_{\mathrm{RD}}^2\frac{E_{\mathrm{RD}}}{1-\alpha}+2\sqrt{(\delta h_{\mathrm{SD}}^2E_{\mathrm{SD}}^{(2)}h_{\mathrm{RD}}^2\frac{E_{\mathrm{RD}}}{1-\alpha}}),
\end{aligned}$$

In this case Block Markov encoding is not required to achieve this rate but a parallel Gaussian channel argument for the receiving and transmitting phase of the relay can be used. In the second phase with duration $1-\alpha$ the source transmits both the information from the first phase using a different codebook with power δP_{S} and new information with power $(1-\delta)P_{\mathrm{S}}$. The destination treats the new information as noise and after decoding the information from the first phase it subtracts it from the signal and decodes the new information. Please note that the rate during the relay receive period has to be lower than $\frac{\alpha}{2}\log(1+h_{\mathrm{SR}}^2E_{\mathrm{SR}}^{(1)})$.

The achievable rate for half-duplex amplify and forward relaying can be found as in the Appendix II of [46]

$$R=\{\frac{1}{4}\log(1+2h_{\mathrm{SD}}^2E_{\mathrm{SD}}+\frac{4h_{\mathrm{SR}}^2E_{\mathrm{SR}}h_{\mathrm{RD}}^2E_{\mathrm{RD}}}{1+2h_{\mathrm{SR}}^2E_{\mathrm{SR}}+2h_{\mathrm{RD}}^2E_{\mathrm{RD}}}) \qquad (2.16)$$

We use the same normalization term $\sqrt{\frac{1}{E_{\mathrm{SR}}+1}}$ as in (2.2). It is derived by using the vector results in [47] after writing the equations for the two phases in matrix equation form $\mathbf{y}_{\mathrm{D}} = \mathbf{A}x_{\mathrm{S}} + \mathbf{B}\mathbf{N}$ where $\mathbf{N}$ comprises both the noise at the relay and the destination.

The achievable rate for estimate and forward can be found for example by using Wyner-Ziv lossy source coding [48] as in [45]

$$\begin{aligned} R &= \frac{\alpha}{2} log(1 + h_{\mathrm{SD}}^2 E_{\mathrm{SD}}^{(1)} + \frac{h_{\mathrm{SR}}^2 E_{\mathrm{SR}}^{(1)}}{1+\sigma_\omega^2}) + \frac{1-\alpha}{2} log(1 + h_{\mathrm{SD}}^2 E_{\mathrm{SD}}^{(2)}) \qquad (2.17) \\ \sigma_\omega^2 &= \frac{h_{\mathrm{SR}}^2 E_{\mathrm{SR}}^{(1)} + h_{\mathrm{SD}}^2 E_{\mathrm{SD}}^{(1)} + 1}{((1 + \frac{h_{\mathrm{RD}}^2 \frac{E_{\mathrm{RD}}}{1-alpha}}{1+h_{\mathrm{SD}}^2 E_{\mathrm{SD}}^{(2)}})^{(1-\alpha)/\alpha} - 1)(h_{\mathrm{SD}}^2 E_{\mathrm{SD}}^{(1)} + 1)}, \qquad (2.18) \end{aligned}$$

Please note that the factor $\frac{1}{2}$ in equation (2.11) to (2.17) is not due to the half duplex constraint but due to the assumption of real channel and hence can also be found in the full duplex case. In the half duplex relaying case α specifies the share of resources used for the broadcast and the multiple access phase. Especially for the case of different channel qualities in the relay network, the choice of α will greatly affect the achievable throughput. For cellular relay networks with fixed relays the channel quality between the BS and the relay will be quite stable but the quality of the access links can have significant variations. Thus, a fixed α might degrade the performance of the network and should be avoided. In the half-duplex case for amplify and forward the relay repeats exactly the same signal as it has received in the broadcast phase and thus $\alpha = 0.5$. Here we assume a protocol where the source transmits in a first time slot and the relay in the second. We allow both the source and the relay to use double the power compared to the full duplex case. The superscripts $(.)^{(1)}$ and $(.)^{(2)}$ denote the broadcast phase and the multiple access phase, respectively. The transmit power of the source can be chosen differently in both phases but has to satisfy a set power constraint.

β is a measure of the correlation between the signals transmitted by the relay and the destination. The optimal correlation depends on the different channel gains in the network. In general, if the signal-to-noise ratio (SNR) between source and relay is very good, the correlation should be high. This is a typical assumption for the downlink of a cellular relay network with intelligent relay placement.

When comparing equation (2.11) and (2.12) one can see that for $h_{\mathrm{SR}}^2 E_{\mathrm{SR}} >> h_{\mathrm{RD}}^2 E_{\mathrm{RD}}$ and for the asynchronous case $\beta = 0$ the second term will determine both the capacity in equation (2.11) and R_1 in equation (2.12). Hence, the achievable rate and the upper bound for the capacity coincide and decode and forward is the optimal strategy when the relay is very close to the source.

The one dimensional relay topology illustrated in Figure 2.3 is an interesting way to present the capacity results. The capacity gain/loss for different relay placements give a good indication about the range of relay placements where relaying can be beneficial. In a practical system only a limited set of relays will be available and the mobile terminals will be distributed over the coverage area of a cell. Thus, if the performance gains are very sensitive to the relay placement, the practical gains from relaying might be limited.

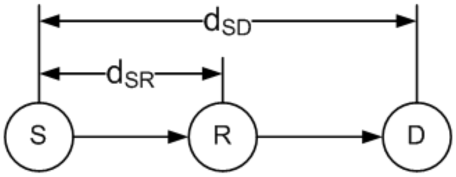
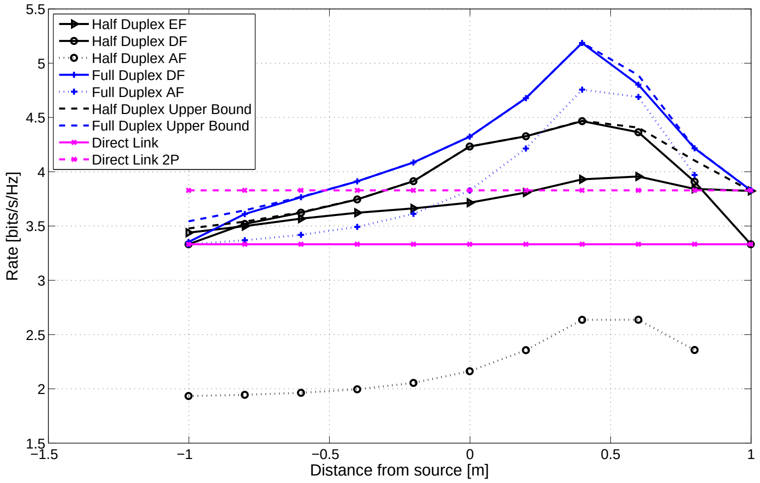


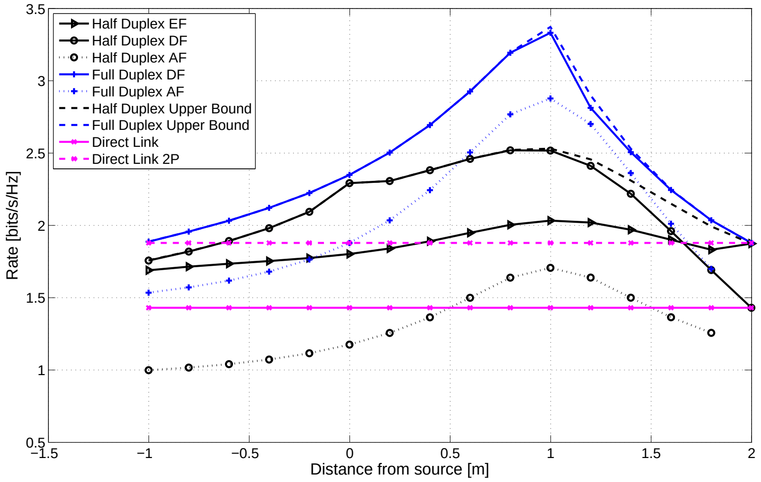
Figure 2.3: Line topology with Source (S), Relay (R) and Destination (D) on a line.

Figure 2.4 and 2.5 illustrate the achievable rates and the upper bounds on the capacity for different relay placements and source destination distances in the line topology. The results have been obtained for an AWGN channel with a noise power $\sigma^2_{n_\mathrm{R}} = \sigma^2_{n_\mathrm{D}} = 1$ and using a transmit power which is 20dB higher than the noise power for both the source and the relay. The received power at the relay and the destination can be found as $E_\mathrm{SD} = \frac{P_\mathrm{S}}{d^\alpha_{SD}}$, $E_\mathrm{RD} = \frac{P_\mathrm{R}}{d^\alpha_{RD}}$ and $E_\mathrm{SD} = \frac{P_\mathrm{S}}{d^\alpha_{SR}}$ where $\alpha = 4$ denotes the pathloss exponent and d the distance between the different nodes.

Looking at the results one can immediately see that the benefits of relaying are more prominent for a larger S-D distance. For a S-D distance of 4, all relaying protocols outperform the direct communication for all relay placements and for most relay placements even when doubling the S transmit power for the direct link. This shows the great potential of using relays in coverage limited networks. The best placement of the relay is in the middle between S and D which almost doubles the achievable rate for a S-D distance of 1 and achieves a six-fold increase of the rate for a S-D distance of 4. Another interesting observation is that DF outperforms AF over the whole range. Nevertheless, full duplex AF outperforms half duplex DF relaying over a wide range of relay placements. Both half duplex DF and full duplex AF do not require block Markov encoding to achieve the rate and therefore impose lower requirements on the MT. Thus, full duplex AF relaying may be an option for a cellular system where the antenna isolation is sufficiently large to support full duplex operation. Furthermore it is also interesting to note that EF outperforms DF for relay placements close to the destination. This corresponds to the uplink of a cellular system with an intelligent placement, i.e. a good S-R link.



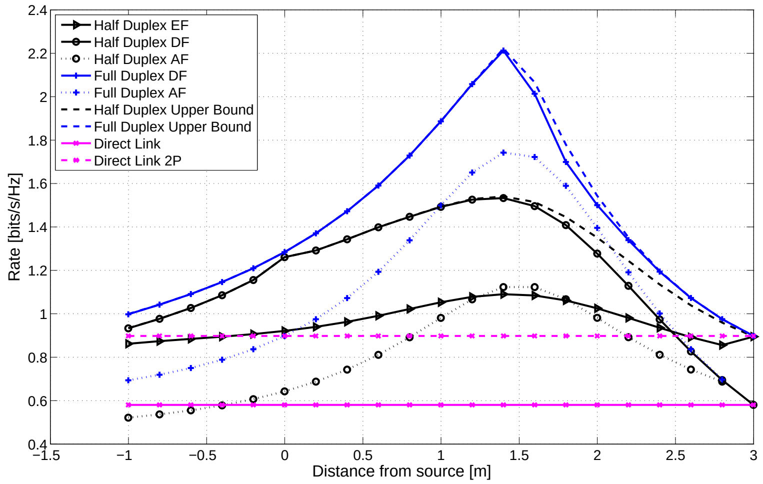
(a) S-D distance 1



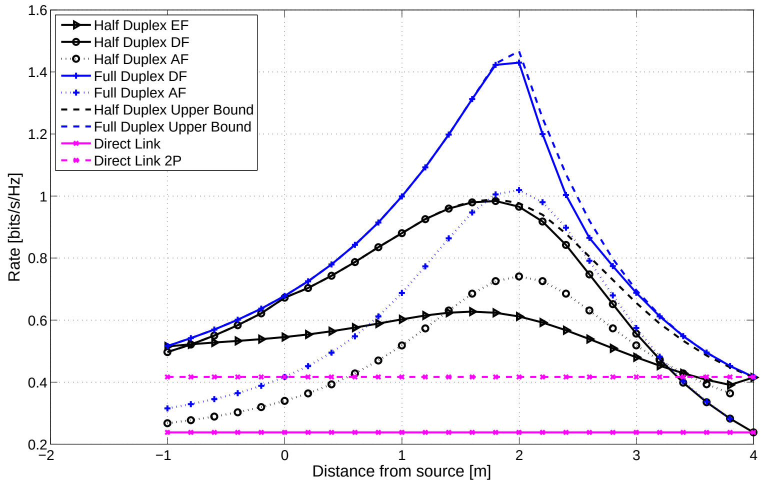
(b) S-D distance 2

Figure 2.4: Upper bounds and achievable rates for different relaying protocols and relay placements in the line topology. The direct S-D capacity is plotted with the same and double transmit power (2P) of the source (S) compared to the relaying cases.

The information theoretic studies have for example been extended to fading relay



(a) S-D distance 3



(b) S-D distance 4

Figure 2.5: Upper bounds and achievable rates for different relaying protocols and relay placements in the line topology. The direct S-D capacity is plotted with the same and double transmit power (2P) of the source (S) compared to the relaying cases.

channels in [49] and MIMO relay channels in [50]. Power allocation strategies for the relay channel have been investigated in [45] for decode and forward on a fading relay channel. An alternative estimation and forward strategy is presented in [51] which combines scalar quantization and source coding with a relay protocol where only the relay transmits during the multiple access phase and interference cancelation at the destination is avoided.

Next to the relay channel as described in Figure 2.1 the information theoretic analysis has been extended to the Gaussian relay networks with two parallel relays and without cooperation between source and relay in [52]. The analysis in [53] introduces a multi-user perspective with two sources cooperating in uplink to a destination. An analysis of multi-hop networks can for example be found in [54].

2.3 Cooperative Relaying Protocols

The information theoretic results in the previous Section suggest a cooperation between source and relay. Unfortunately, the proposed Block Markov encoding and full-duplex operation as well as interference cancelation at the destination requires high complexity receivers. In the simplest form of relaying the destination receives only from a half-duplex relay where the receiver at the destination is only active during the relay transmission phase and no signal processing related to combining different signals is required. Nevertheless, the potential gains from cooperation have inspired a lot of research on practical cooperative relaying protocols with low complexity that outperform relaying without cooperation.

In this section we will focus on cooperative relaying protocols that have been proposed for fading relay channels. The performance for the fading relay channel can be described by the ergodic capacity and the probability of outage. The ergodic capacity can be used if the coherence time is much shorter than the code length and the codeword experiences all the fading states. However, in most cellular communication systems the codewords are short in time to enable short round trip delays (e.g. 1ms in 3GPP LTE) and thus the ergodic capacity is not a good measure. In this case the probability of outage is commonly used as figure of merit and will be also used for the discussion in this section. The probability of outage describes the probability that the achievable rate is higher than a given target rate. The outage capacity describes the capacity that is available for example for 95% of the channel realizations.

In a Rayleigh fading channel and for large SNR the probability of outage is proportional to

$$p^{out} \propto \frac{1}{\rho^d}, \quad \rho >> 1 \tag{2.19}$$

where d denotes the order of diversity and ρ the SNR. In general the free dimensions available for a radio link due to for example multiple antennas can be used either for diversity, to increase the reliability of a link or for multiplexing to increase the rate. Not surprisingly most cooperative relaying protocols proposed in literature benefit from a combination of the transmissions in two phases, first from the source and then from the relay. Thereby, diversity gains can be achieved compared to single-path relaying and direct transmission.

Cooperative relaying protocols have been proposed for both amplify-and-forward and decode-and-forward protocols. Further, the relay may transmit in all cases, only when the S-R channel exceeds a certain quality or when it receives feedback from the destination. Cooperative relaying is also referred to as cooperative diversity, cooperation diversity and coded cooperation. An overview of different protocols can be found in [55], [56] and [57]. The protocols have been designed for single and multiple relays and the antennas of multiple relays can be combined to a virtual antenna array [58].

In the following we will discuss only two of the many cooperative relaying protocols proposed in literature. Both protocols, non-orthogonal Amplify and Forward (NAF) and Dynamic Decode and Forward (DDF), have been proposed in [59]. They have been developed based on an analysis of the diversity-multiplexing trade-off in relay networks using similar ideas than [60] which studies the optimal diversity-multiplexing trade-off in multi-antenna systems.

In the NAF protocol the relays retransmit only half of the symbols transmitted by the source and the source continues to transmit while the relays transmit. Thereby higher multiplexing rates than 0.5 can be achieved which is different from the LTW-AF protocol proposed in [46]. Nevertheless, both protocols achieve a diversity order determined by the number of transmitters and have a lower outage probability than non cooperative transmission. The comparison of the outage probability in [59] shows that for a probability of outage of 2 bits/s/Hz both protocols perform very similar. For a more stringent outage probability of 6 bits/s/Hz the NAF protocol clearly outperforms the LTW-AF protocol.

For the case of a more stringent outage probability of 6 bits/s/Hz direct transmission has a lower probability of outage up to an SNR of 40dB. In practical cellular systems an S(I)NR of 40dB is rarely available and therefore the difference between the NAF and the LTW-AF will be minor. The results have been obtained with the assumption of a 3dB better S-R link compared to the S-D and R-D link. Similar to non-cooperative relaying, a more favorable placement of the R between S and D, as discussed in the line topology in Section 2.2, will result in higher gains from cooperative relaying compared to the direct link.

Besides the NAF protocol the Dynamic Decode and Forward (DDF) protocol is proposed in [59]. The relays observe the transmissions by the source until they can decode the message. Then they re-encode the message using another codebook and start transmitting. Thus, the protocol adapts automatically to the S-R channel quality. The DDF protocol achieves a better diversity-multiplexing rate over the whole range. The results in [59] show that this protocol outperforms direct transmission over the whole SNR range and that it has a gain of 2.5dB compared to the NAF protocol when considering the outage probability for a rate of 2bits/s/Hz.

Another interesting aspect is the range of channel gain difference for which cooperative relaying protocols are beneficial. The results in [42] show that the lowest outage probability is achieved for two cooperating nodes with the same channel quality. The outage probability for a distributed Alamouti scheme doubles for an average channel gain ratio of 9 and triples for a ratio of 10. Thus, the highest gains from cooperative relaying will be achieved if the channel gains are similar. For a difference of 10dB in the channel gains direct transmission or single-path relaying will achieve a similar performance as cooperative relaying. Hence, in a practical system a proper relay selection algorithm is needed that selects cooperative relaying only when the channel gains are for example within 5dB. Otherwise without power control the transmitter with the lower channel quality will mainly generate unnecessary interference in the network.

All cooperative relaying protocols in literature achieve lower outage probabilities than direct transmissions. However, it should be noted that typically in a communication system additional sources of diversity are available. An OFDMA system offers for example frequency diversity by coding over multiple OFDMA resource units, spatial diversity from multiple antennas and an Hybrid-Automated-Repeat-Request (H-ARQ) protocol for failed transmissions. Thus, the diversity gains from cooperative relaying on top of the other sources of diversity might be limited.

2.4 Relays in OFDM systems

In this section we will discuss the integration of relays in an Orthogonal Frequency Division Multiplexing (OFDM) system. We will focus on amplify and forward (AF) the simplest operational mode for relays. First we will present the signal model and after that we present link simulation results for an AF relay in half-duplex and in full-duplex mode. The full-duplex mode is used for example by gap-fillers in DVB-T [61], [62] and makes use of the cyclic prefic (CP) contained in an OFDM symbol. The signal received by the relay is amplified and forwarded and arrives within the cyclic prefix (CP) of the OFDM symbol at the destination. Thus, inter-symbol interference is avoided and the relay is transparent to the mobile terminal. The receiver of the mobile terminal sees the relayed signal simply as an additional multi-path component. This allows an easy system integration of relays and no additional transmission resources, such as time or frequency, are required.

However, as the relay operates in full-duplex mode, a high enough isolation between the transmit and receive parts of the relay is required to avoid a feedback loop. Typically, the signal transmitted by the relay can for example be 120dB higher than the received signal.

Installations of receive/transmit antenna that can possibly provide high enough isolation are for example antenna on rooftop/antenna at street level or antenna outdoor/antenna indoor. In the later presented link simulations we study the first example and both the half-duplex, as well as the full-duplex operation mode.

2.4.1 System model

Let $\mathbf{F}$ denote a $P \times P$ discrete Fourier transform (DFT) matrix, where $[\mathbf{F}]_{p,q} = 1/P \exp(-j2\pi(p-1)(q-1)/P)$. The inverse DFT matrix, applied at the OFDM transmitter is given by $\mathbf{F}^H$, the transpose conjugate of $\mathbf{F}$. We assume that the signal is transmitted through a finite impulse response channel of length L and that a cyclic prefix of length $L_c > L$ is used at the transmitter.

After removing the cyclic prefix, the effective received signal model for a single-antenna OFDM signal is

$$\mathbf{y} = \mathbf{F}\mathbf{H}\mathbf{F}^H\mathbf{x} + \mathbf{n}, \tag{2.20}$$

where $\mathbf{H}$ denotes a circulant convolution matrix with entries $[h]_{p,q} = h((p-q) \bmod P)$, where $h(l)$ designates the lth channel tap. $\mathbf{x}$ represents the transmitted symbol vector and $\mathbf{n}$ additive complex Gaussian noise. Since the DFT diagonalizes a circulant matrix, the model can be written as

$$\mathbf{y} = \mathbf{D}\mathbf{x} + \mathbf{n}, \tag{2.21}$$

where $\mathbf{D} = \mathrm{diag}(h[0], ..., h[P-1])$, with $h[p] = \sum_{l=0}^{L} h(l) \exp(-\mathrm{j}2\pi lp/P)$. The concise model given above is well-known, and the reader is directed e.g. to [63, 64] for additional details.

The signal model for relays in the OFDM case is very similar to the model presented in Section 2.1. The received signal at the relay for subcarrier p for the network in Figure 2.1 can be found as

$$y_{\mathrm{R}}[p] = \sqrt{E_{\mathrm{SR}}} h_{\mathrm{SR}}[p] x[p] + n_{\mathrm{R}}[p], \;\; 0 \leq p \leq P-1 \tag{2.22}$$

where E_{SR} denotes the average signal energy per subcarrier received from the source and h_{SR} the bin of the channel frequency response for subcarrier p. The transmitted signal x is normalized to have unit average energy. E_{SR} is the same for all subcarriers and captures slow fading and shadowing effects as well as the source transmit power. h_{SR} captures the frequency selectivity of the radio channel and is normalized to have unit average energy. n_{R} is the additive white Gaussian noise at the relay with zero mean and variance $\sigma^2_{n_{\mathrm{R}}}$. The relay amplifies the received signal and forwards it in a second time slot. Without cooperation from the source, i.e. *pure AF* the destination receives

$$y_{\mathrm{D}}[p] = \sqrt{\frac{E_{\mathrm{SR}} E_{\mathrm{RD}}}{E_{\mathrm{SR}} + N_0}} h_{\mathrm{RD}}[p] h_{\mathrm{SR}}[p] x[p] + \tilde{n}_D[p], \;\; 0 \leq p \leq P-1 \tag{2.23}$$

where E_{RD} denotes the average of the signal energy per subcarrier received from the relay and $\sqrt{\frac{1}{E_{\mathrm{SR}}+N_0}}$ is a power normalization term used at the relay. $h_{\mathrm{RD}}[p]$ denotes a bin of the channel frequency response, has unit average energy and captures the frequency selectivity of the radio channel. $\tilde{n}_D[p]$ denotes the effective noise contained in the received signal, which consists of the noise at the relay, amplified by $\sqrt{\frac{E_{\mathrm{RD}}}{E_{\mathrm{SR}}+N_0}}$ and filtered by $h_{\mathrm{RD}}[p]$, as well as the additive white Gaussian noise $n_{\mathrm{D}}[p]$ with zero mean and variance $\sigma^2_{n_{\mathrm{D}}}$ at the destination:

$$\tilde{n}_D[p] = \sqrt{\frac{E_{\mathrm{RD}}}{E_{\mathrm{SR}} + N_0}} h_{\mathrm{RD}}[p] n_{\mathrm{R}}[p] + n_{\mathrm{D}}[p], \;\; 0 \leq p \leq P-1 \tag{2.24}$$

For the pure AF protocol we assumed that the destination does not receive the direct signal from the source in the first time slot and the source does not transmit in the second time slot. This changes for the AF within the cyclic prefix (CP) protocol. The relay receives the signal from the source, amplifies and forwards the signal immediately, which then arrives with a delay shorter than the cyclic prefix of the OFDM symbol at the destination and the destination receives

$$y_{\mathrm{D}}[p] = \sqrt{E_{\mathrm{SD}}} h_{\mathrm{SD}}[p]x[p] + \sqrt{\frac{E_{\mathrm{SR}}E_{\mathrm{RD}}}{E_{\mathrm{SR}} + N_0}} h_{\mathrm{RD}}[p]h_{\mathrm{SR}}[p]x[p] + \tilde{n}_D[p], \;\; 0 \leq p \leq P-1 \quad (2.25)$$

Without loosing generality we assume that both signals arrive at the same time at the destination. To get a more compact expression we introduce $\tilde{h}[p] = \sqrt{E_{\mathrm{SR}}} h_{\mathrm{SD}}[p] + \sqrt{\frac{E_{\mathrm{SR}}E_{\mathrm{RD}}}{E_{\mathrm{SR}}+N_0}} h_{\mathrm{RD}}[p]h_{\mathrm{SR}}[p]$. Thus, for subcarrier p the received signal at the destination is

$$y_{\mathrm{D}}[p] = \tilde{h}[p]x[p] + \tilde{n}_D[p],, \;\; 0 \leq p \leq P-1 \quad (2.26)$$

In our model we assume perfect channel knowledge at the receivers (R and D). In the case of AF and AF within the CP the destination knows the effective channel. When taking into account practical constraints of pilot aided channel estimation it can be beneficial to estimate the S-R and R-D channel separately instead of the effective S-R-D channel. It has been shown in [65] that it would be beneficial in the case of half duplex amplify and forward to estimate the S-R channel at the relay, then insert new pilot signals at the relay and forward the channel estimate to the destination. In [66] it has been shown that decomposing the S-R-D channel into S-R and R-D channel and performing independent transmit and receive beamforming at the S and D outperforms transmit beamforming applied to the effective S-R-D channel when considering pilot aided channel estimation.

2.5 MIMO-OFDM Relay Network

Figure 2.6 illustrates the MIMO relay network studied in this section. It consists of 3 nodes, the source S, the relay R and the destination D.

The different links are denoted by subscripts as illustrated in Figure 2.6, where E_{xy} denotes the average received signal energy per subcarrier of the link between x and y, $\mathbf{H}_{\mathrm{xy}}$ the $(N_{\mathrm{rx}} \times N_{\mathrm{tx}})$ channel frequency response matrix of the link for subcarrier p. E_{xy} is the same for all subcarriers and captures the slow fading, the shadowing, the antenna gains and the transmit power for the link. $\mathbf{H}_{\mathrm{xy}}$ captures the frequency selectivity of the radio channel and is normalized to have unit average energy elements. $\mathbf{n}_x$ is the additive white Gaussian noise vector at the relay or destination with zero mean and variance N_0 elements.

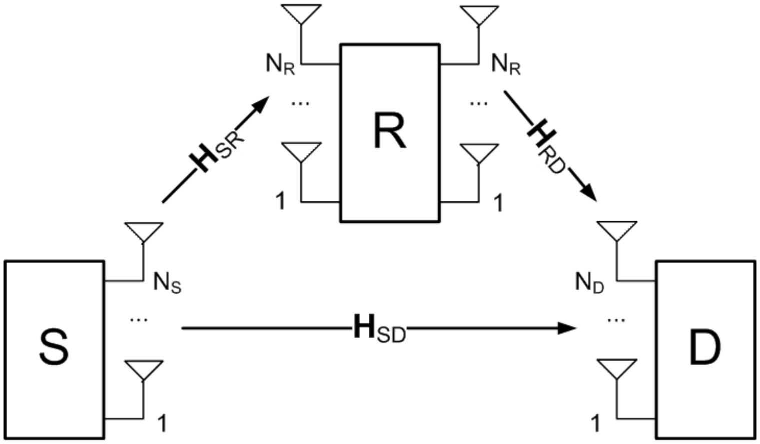


Figure 2.6: MIMO Relay Network.

The source transmits the signal vector $\mathbf{x}$, normalized to have unit average energy, in the first time slot to the relay and the relay receives the baseband signal vector $\mathbf{y}_{\mathrm{R}}[p]$ at subcarrier p

$$\mathbf{y}_{\mathrm{R}}[p] = \sqrt{E_{\mathrm{SR}}}\mathbf{H}_{\mathrm{SR}}[p]\mathbf{x}[p] + \mathbf{n}_R[p],\ \ 0 \le p \le P-1 \tag{2.27}$$

In the remainder of this section we will drop the index of the subcarrier to get more compact formulas. The relay amplifies the received signal, and forwards it in the second time slot. The destination receives for the pure AF protocol

$$\mathbf{y}_{\mathrm{D}} = \sqrt{\frac{E_{\mathrm{SR}}E_{\mathrm{RD}}}{N_{\mathrm{R}}(E_{\mathrm{SR}}+N_0)}}\mathbf{H}_{\mathrm{RD}}\mathbf{H}_{\mathrm{SR}}\mathbf{x} + \tilde{\mathbf{n}}_D, \tag{2.28}$$

where N_{R} denotes the number of antennas at the relay node. $\tilde{\mathbf{n}}_D$ denotes the effective noise vector contained in the received signal, which consists of the noise at the relay, amplified by $\sqrt{\frac{E_{\mathrm{RD}}}{N_{\mathrm{R}}(E_{\mathrm{SR}}+N_0)}}$ and filtered by $\mathbf{H}_{\mathrm{RD}}$, as well as the additive white Gaussian noise vector $\mathbf{n}_D$ with zero mean and variance N_0 elements at the destination.

In case of the Amplify and Forward within the Cyclic Prefix protocol also the direct signal is received at the destination:

$$\mathbf{y}_{\mathrm{D}} = \sqrt{E_{\mathrm{SD}}}\mathbf{H}_{\mathrm{SD}}\mathbf{x} + \sqrt{\frac{E_{\mathrm{SR}}E_{\mathrm{RD}}}{N_{\mathrm{R}}(E_{\mathrm{SR}}+N_0)}}\mathbf{H}_{\mathrm{RD}}\mathbf{H}_{\mathrm{SR}}\mathbf{x} + \tilde{\mathbf{n}}_D. \tag{2.29}$$

Table 2.1: Path-loss models.

Link	Path-Loss (dB)
BS-RN	$\mathrm{PL}(d) = 43 + 23.5\log_{10}(d)$
RN-MT (LOS)	$\mathrm{PL}_1(d) = 40.3 + 23.4\log_{10}(d)$
RN-MT (NLOS)	$\mathrm{PL}(d) = \mathrm{PL}_1(d) + 23.3\log_{10}(d - W/2 + 1)$
BS-MT	$\mathrm{PL}(d) = 42.5 + 35\log_{10}(d)$

2.5.1 Test case: Downlink of a Metropolitan Area Network

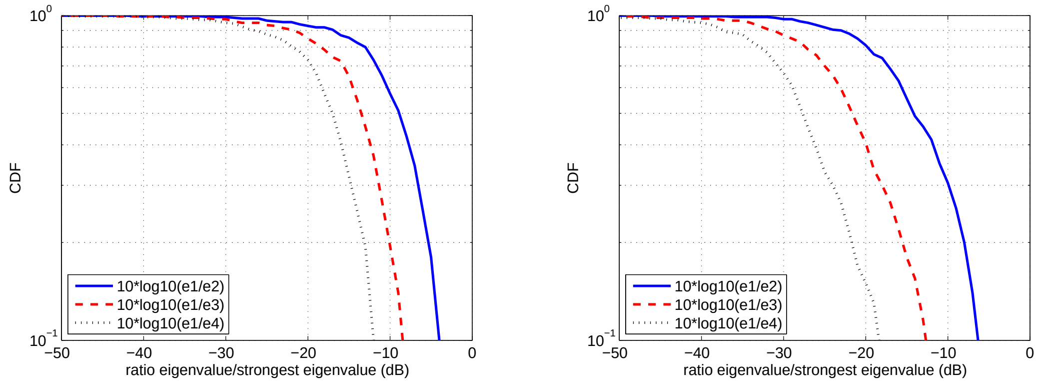
In this section we illustrate the potential benefits from relays in the downlink of a metropolitan area network. We describe the deployment scenario and the corresponding channel and path-loss model in Section 2.5.2. For this scenario we investigate the potential gains from amplify and forward relaying in section 2.5.3. In Section 2.5.4 we compare the throughput of the AF and DF relaying protocols to the throughput of the direct link for multi-stream MIMO communication, using eigenbeamforming.

2.5.2 Path-Loss and Channel Model

The achievable gain by relaying depends heavily on the underlying scenario. In this section we assume relays in a metropolitan area network in downlink at a center frequency of 5.3GHz. The BS is mounted on a mast or on the highest building in the cell. Within the cell are several relays that receive the signal from the BS via antennas, mounted on rooftops. The relays have a second antenna towards the mobile terminals which is below the rooftop level. A mobile terminal (MT) can be in the same street as the relay, the line-of-sight (LOS) street, or in a perpendicular street, the non-line-of-sight (NLOS) street. Because of a relatively high amount of relays compared to the amount of BS the probability of LOS between the relay and the MT is much higher than between the BS and the MT. In both cases the MT has NLOS connection to the BS. In our simulations, presented in Section 2.5.3, we compare the performance of the direct link between the BS and the MT to the performance of one such relay link.

The channel and path-loss models used in the simulations are based on the channel models developed in the WINNER project [67]. Based on the aforementioned assumptions we chose the Scenario B5a (rooftop-rooftop relaying), LOS for the first hop, Scenario B1 (Urban Micro), LOS and NLOS for the second hop and Scenario C2 (Urban Macro), NLOS for the direct link. For each multi-antenna node we assumed an antenna spacing of 10λ.

First we compare the spatial multiplexing properties of MIMO relaying for the AF and the DF relaying protocol. The eigenvalue spread of the channel matrix is an important measure of the multi-stream transmission capability of a MIMO system.



(a) Single hop

(b) AF relay link

Figure 2.7: Eigenvalue ratio CDF comparison for a 4×4×4 relay network and i.i.d Rayleigh fading channels.

The eigenvalue ratio is calculated for each subcarrier as

$$R_n = 10log_{10}\frac{e_n}{e_1}. \tag{2.30}$$

where, e_1 is the strongest eigenvalue and e_n is the n-th strongest eigenvalue of $\mathbf{H}^H\mathbf{H}$ for the subcarrier. The greater the eigenvalue ratio, the more power is needed to use multiple eigenvectors for spatial multiplexing. Figure 2.7 compares the eigenvalue ratios of a single hop MIMO channel matrix with i.i.d. Rayleigh fading elements to the eigenvalue ratio of the effective MIMO channel matrix for the AF relaying protocol with two i.i.d. Rayleigh fading hops for a 4×4 MIMO configuration. It clearly shows that the eigenvalue ratios of the AF relay link are much higher than the eigenvalue ratios of the single hop. For example in 50% of the cases all four eigenvalues are within 18dB for the single hop compared to 28.5dB for the AF relay link. The spatial multiplexing possibilities for the DF protocol are determined by combining two single hops and therefore DF will support more parallel streams than AF.

To get a feeling for the spatial multiplexing properties of the relay link, using the WINNER channel model with the main parameters listed in Table 2.2. We created 200 channel instances and calculated the eigenvalue ratios for each subcarrier. Figure 2.8 illustrates the eigenvalue ratio cumulative distribution function (CDF) of the AF relay

Table 2.2: Main channel model parameters.

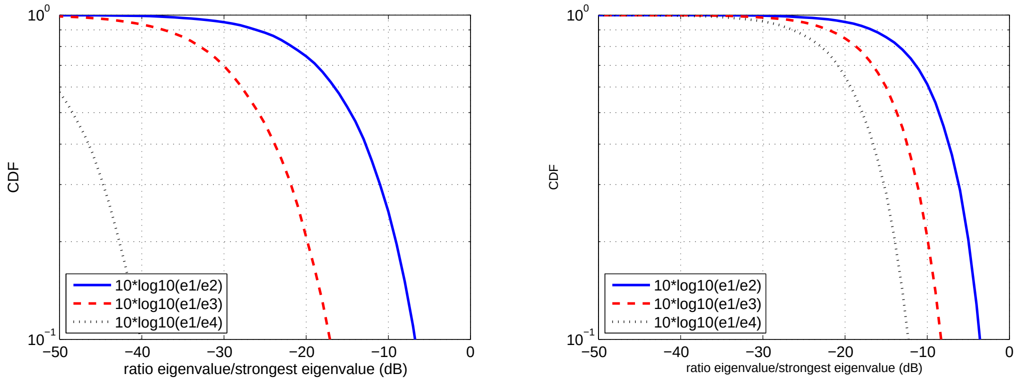
Link	delay spread (ns)	Ricean K (1)
BS-RN	40	10
RN-MT (LOS)	100	10(d≤200m), 2(d>200m)
RN-MT (NLOS)	100	1
BS-MT	200	0

link and the direct link for the pure AF relaying protocol. To give more insight the eigenvalue ratio CDF of the first hop and the second hop are plotted as well. The direct link eigenvalue ratio distribution is close to the case of the i.i.d. Rayleigh fading channel matrix, illustrated in Figure 2.7. At the 50% level 4 eigenvalues are within 20dB, 3 eigenvalues within 15dB and 2 eigenvalues are within 10dB. This changes for the relay link, where in 50% of the cases only 2 eigenvalues are within 15dB, 3 eigenvalues within 25dB and 4 eigenvalue only within 50dB. Thus, the direct link offers much better spatial multiplexing possibilities than the relay link. In case of the AF within the CP protocol the direct signal is received as well and will improve the spatial multiplexing possibilities compared to the pure AF relaying protocol.

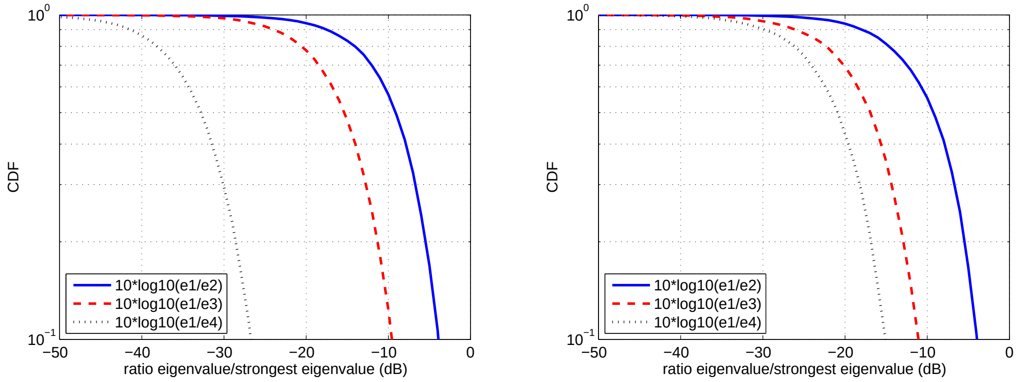
2.5.3 Numerical evaluation of Amplify and Forward Relays in OFDM systems

Using the path-loss and signal model described in Section 2.5.2 we tested the performance of Amplify and Forward relaying compared to direct communication between a BS and a mobile terminal in an OFDM network.

As a test case we used the OFDM parameters of the IEEE 802.11a standard, summarized in Table 2.3. All nodes in the network are equipped with a single antenna. At the BS we assume a 120° sector antenna with a gain of 17dBi. At the relay we assume a more directive antenna towards the BS with 10° half-power beamwidth (HPBW) and a gain of 17dBi and a less directive antenna with a HPBW of 180° and a gain of 10dBi towards the MT. The remaining parameters necessary to calculate the signal-to-noise ratio (SNR) for a given link distance are also summarized in Table 2.3. Note that the relay uses a 13dB lower transmit power than the BS. For the Amplify and Forward within the cyclic prefix case we assume that the signal from the relay arrives within the cyclic prefix of the signal from the BS at the MT. In our simulations we assumed a block fading channel and the simulation results contain 10000 simulated packets.



(a) AF relay link (b) Direct link



(c) 1st hop (d) 2nd hop

Figure 2.8: Eigenvalue ratio CDF comparison for the simulated 4 × 4 × 4 relay network.

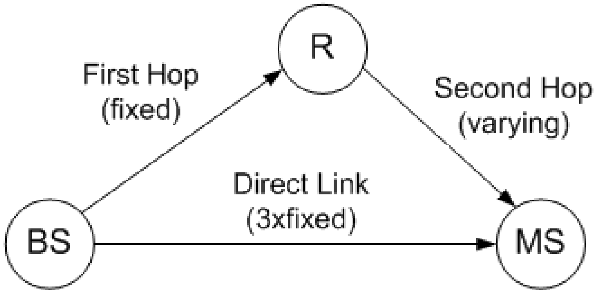


Figure 2.9: Network geometry used for the relay link simulation results in Figures 2.11 and 2.14.

Using these parameters we first compare the Packet Error Rate (PER) performance of the direct link between the BS and the MT to the performance of the AF relay link for a LOS and a NLOS second hop. Figure 2.10 illustrates the results for a first link distance of 1524m, or an SNR of 30dB. Because of the high first hop SNR the performance of the relay

Table 2.3: OFDM parameters and general assumptions.

Bandwidth	20MHz
Nr. Subcarriers	64
Nr. Data Subcarriers	48
Coding scheme	Convolutional Code 64 states
Coding Rate	1/2
Interleaving	Bit interleaving
Modulation	16QAM
Packet Length	91Bytes
Frequency Error	No
Channel Estimation	Ideal
Analog Imperfections	No
Tx power of BS	10.8dBm/subcarrier
Tx power of Relay	-2.2dBm/subcarrier
Noise power	-127dBm/subcarrier
Receiver implementation loss	7dB

link is determined by the second hop. The direct link can provide coverage up to 500m, where the PER reaches 20%. By using the AF relay the coverage can be extended in the LOS street up to 2000m and more. However, when the MT is located in a perpendicular NLOS street the relay can only provide coverage for the first 40 to 50m. As a consequence, to provide coverage the relays should be located in every street.

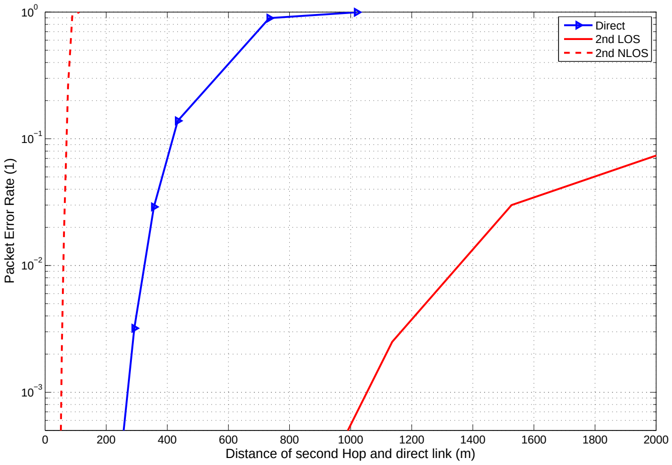


Figure 2.10: PER performance of AF vs. direct communication.

Next we will present the results for the AF within the CP protocol and a line-of-sight second hop. The network geometry is presented in Figure 2.9.

The results for this protocol are illustrated in Figure 2.11. Again we compare the PER for the direct link between BS and MT, the pure AF link and AF within the CP against

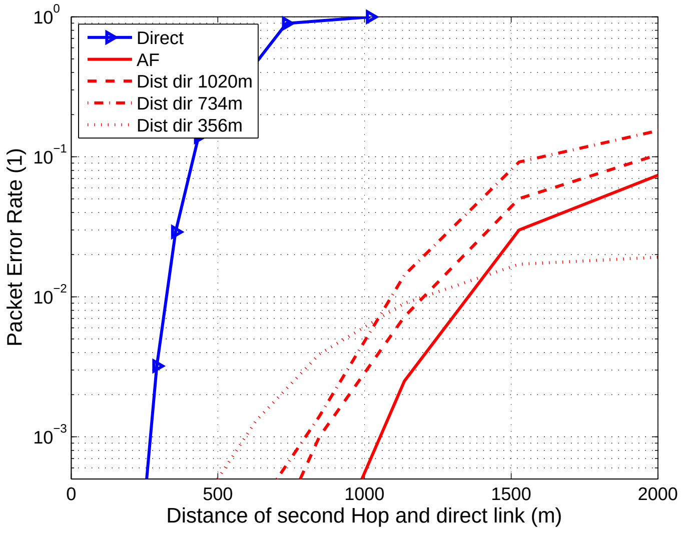


Figure 2.11: PER performance of AF vs. AF within the CP.

the second hop distance. The first hop distance has again been fixed to 1524m. The 3 AF within CP curves illustrate the PER performance for 3 fixed direct link and varying second hop distances. For all 3 cases AF within the CP has a higher PER in the low PER area than pure AF. Especially for a relatively strong direct signal at a direct distance of 356m a PER of 0.5% is exceeded already at a second hop distance of 500m compared to 1000m for the pure AF link.

The reason for this performance degradation lies in the effective channel frequency response for the AF within the CP link. Figure 2.12 illustrates a sample channel frequency response comparison between the pure AF link and the AF within the CP link.

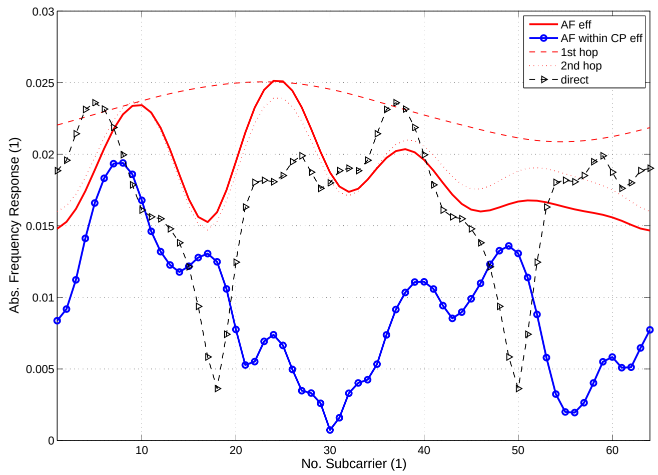
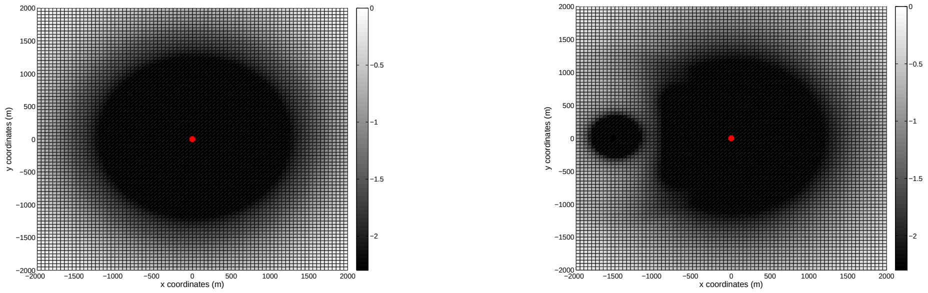


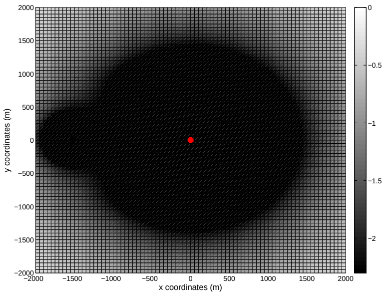
Figure 2.12: Sample of Channel Frequency Response

Especially the first but also the second hop has a strong LOS component. Therefore the effective channel frequency response has a Ricean component and is not strongly fading. On the contrary the direct signal has a much higher frequency selectivity and is strongly fading. The direct signal can add up constructively or destructively to the relay signal. As a consequence, even though the average received energy at the destination increases, the PER in the low PER area increases.



(a) $\log_{10}$(PER) map AF

(b) $\log_{10}$(PER) map AF within the CP



(c) $\log_{10}$(PER) map AF within the CP+subcarrier allocation

Figure 2.13: PER map comparison for different AF protocols.

The AF within the CP PER curves in Figure 2.11 illustrates the PER for fixed first hop, fixed direct link and varying second hop distances. These curves were plotted to be able to compare the PER performance with pure AF and do not reflect real network geometries. To illustrate that the effects are relevant, we simulated a larger set of PER curves and mapped the results to positions of the MT on a map. The first hop distance was again fixed to 1524m, which corresponds to an SNR of 30dB, the second hop and the direct link distances were varied. Figure 2.13(a) illustrates the PER for the pure AF relay link. Figure 2.13(b) illustrates the PER for the AF within the CP relay link, which includes also the direct signal. The relay is placed in the center of the map and the BS at (-1524m/0m) in both plots. For the AF within the CP protocol the dark area served by the relay, indicating a PER lower than 0.5%, clearly decreases towards the BS. For example at the point (-1000m/0m) the PER of the pure AF relay link is still lower than 0.5% but already 2% for the AF within the CP relay link. Note that the colors correspond to $\log_{10}(\text{PER})$.

A simple method to exploit the additional frequency selectivity is subcarrier allocation. The results in Figure 2.14 illustrate in addition to the curves in Figure 2.11 the performance of the AF within the CP protocol, when allocating the 12 subcarriers with the highest power of the effective channel frequency response $\tilde{H}$ in (2.26). For all three direct distances AF within the CP utilizing subcarrier allocation has a lower PER than pure AF.

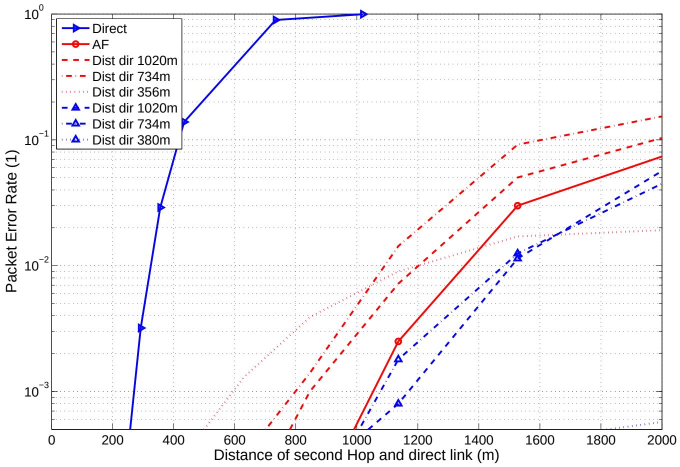


Figure 2.14: Performance of AF, AF within CP with (dashed and dotted with markers)/without (dashed and dotted without markers) subcarrier allocation

The PER map for AF within the CP utilizing subcarrier allocation, plotted in Figure 2.13(c), shows even better performance than the pure AF relay link. These results illustrate that subcarrier allocation is a viable option to overcome the negative effect of the direct signal in the AF within the CP protocol. However, please keep in mind that these results correspond to the ideal case and that the gain will be reduced if practical constraints of a communication system are incorporated in the subcarrier allocation scheme.

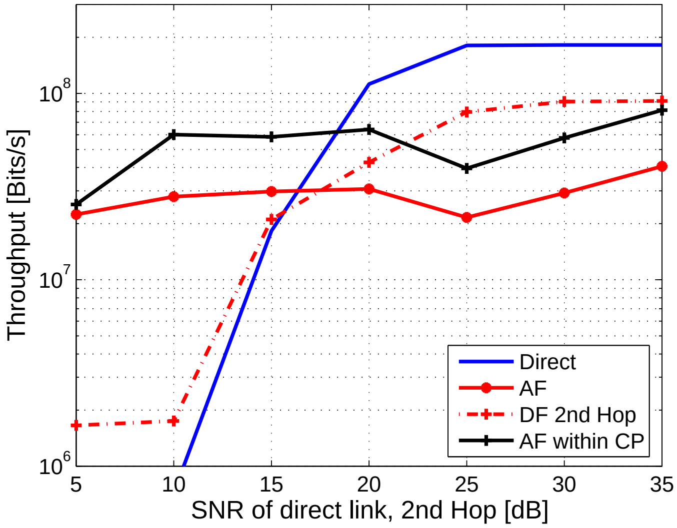
2.5.4 Numerical evaluation of a MIMO-OFDM relay network

After the single antenna case, we study a scenario where the BS, the RN and the mobile terminal are equipped with four antennas. For the pure AF and DF protocol we assume that the relays operate in half-duplex, i.e. using 50% of the resources for the first and 50% for the second hop. For the AF within the CP protocol the SNR of the direct signal has been fixed to 0dB and the first hop SNR has been fixed to 40dB for all relaying protocols. Thus, the second hop will determine the performance for the relays. All the protocols use the same link adaptation and eigenbeamforming scheme, whereas perfect channel knowledge at each transmitter is assumed.

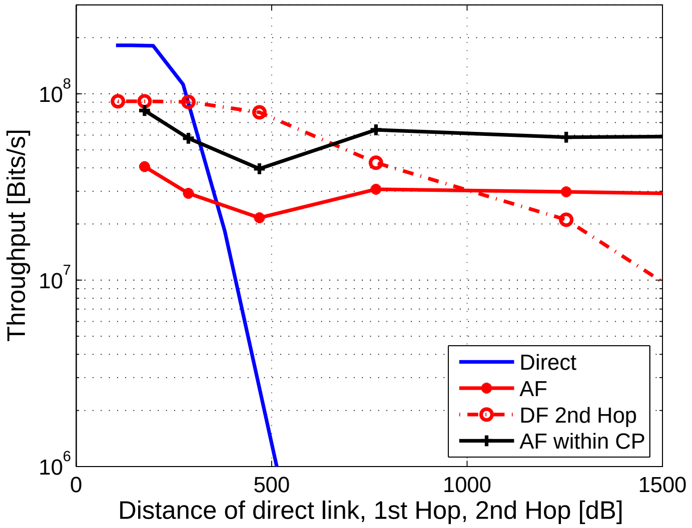
We used the OFDM parameters of the IEEE 802.11n standard (training symbols, synchronization, nr. of sub-carriers, etc.). All nodes in the network are equipped with four antennas. At the BS we assume 120° sector antennas with a gain of 17dBi. At the relay we assume more directive antennas towards the BS with 10° half-power beamwidth (HPBW) and a gain of 17dBi and a less directive antenna with a HPBW of 180° and a gain of 10dBi towards the MT. The relay uses a 13dB lower transmit power than the BS. In our simulations we assumed a block fading channel and the simulation results contain 10000 simulated packets.

Figure 2.15 illustrates a throughput comparison of the AF, the AF within the CP and the DF relay link, as well as the direct link. Figure 2.15(a) shows the throughput against the SNR of the direct link and against the SNR of the second hop for the relay links. Note that the SNR of the direct link signal for the AF within the CP protocol has been fixed to 0dB and is the same for the whole curve, only the second hop SNR is varied. The SNR of the 1st hop has been fixed to 40dB for the relay links. The throughput of the direct link is much higher in the high SNR regime than the throughput of the relay links due to the better spatial multiplexing possibilities. However, in the low SNR regime the throughput of the relay links is higher. Please note that the drop in throughput at 25dB for the AF relaying protocols is caused by the simulator implementation. We used a non-ideal link adaptation scheme which uses in some simulation runs for SNR higher than 25dB more streams than the effective channel matrix can support.

The AF within the CP protocol does not suffer from the half-duplex constraint and achieves higher throughput at SNR up to 20dB compared to the other relaying protocols. Only at higher SNR the DF protocol can outperform the AF within the CP protocol due to its better spatial multiplexing properties.



(a) Throughput vs. SNR



(b) Throughput vs. distance

Figure 2.15: Eigenbeamforming: dynamic number of streams. Throughput comparison of direct link and AF, DF, AF within CP for $4 \times 4 \times 4$ relay network.

Figure 2.15(b) illustrates the throughput against the corresponding distances. Even though the direct link offers better spatial multiplexing possibilities, the throughput drops fast with the distance and is outperformed by the relay links already at a distance of 300m. Because of the LOS assumption and the resulting lower pathloss exponent the throughput of the relay links drop only slowly with the distance. Thus, relays that support the BS can significantly improve the high bit rate coverage of a cell.

2.6 Information Theoretic Aspects of Large Relay Networks

As illustrated in the previous sections, already the simple relay channel gives a lot of degrees of freedom, which are analyzed and studied in numerous articles found in literature.

2.6.1 Gaussian Relay Networks

Next to the relay channel, the Gaussian relay network as illustrated in Figure 2.16 has been studied in literature. Upper and lower bounds for the capacity of a two relay network have been presented in [52]. Upper and lower bounds for the capacity of relay networks with N_r relays have been derived in [68]. The upper bound on the capacity can be found again by utilizing the maximum cut minimum flow theorem as suggested already in [6]. The cut around the source for the broadcast relay channel gives a similar capacity than a Single-Input-Multiple-Output (SIMO) system with N_r receive antennas. Correspondingly, the cut around the destination for the multiple access relay channel gives a similar capacity than a Multiple-Input-Single-Output MISO system with N_r transmit antennas. The lower bound can be found by assuming amplify and forward relay operation. Requiring a decoding at the relay would require the source to code the signal for the weakest source-relay link. By simply amplifying and forwarding the received signal each relay can contribute to the signal received at the destination. The transmit power of the relays is chosen according to the channel quality and the phase of the relay transmissions are adjusted to combine coherently at the destination.

In [68] it is shown that for large N_r the upper and the lower bounds meet and that the total network capacity scales with $\log N_\mathrm{r}$ as for a MISO or SIMO system. In all these results the relays increase the total power in the network. To meet the upper bound from the broadcast channel cut the total relay transmit power has to increase with the number of relays. Even though the analysis presented so far assumes full-duplex operation of the relay nodes, the network model in Figure 2.16 does not consider interference from other relays and self-interference of the relay. Another interesting result in [68] is that even when considering the interference of relays to each other, the capacity will still be at least half of the capacity from the broadcast channel cut. However, this only applies if a “dead zone” around each relay is applied. The dead zone ensures that the relays are sufficiently far apart. The presented bounds meet only for a very large number of relay nodes which have similar channels to both source and destination. In real networks this implies that they are close to each other. Nevertheless, the capacity scaling with $\log N_r$ can be observed also for a lower number of relays.

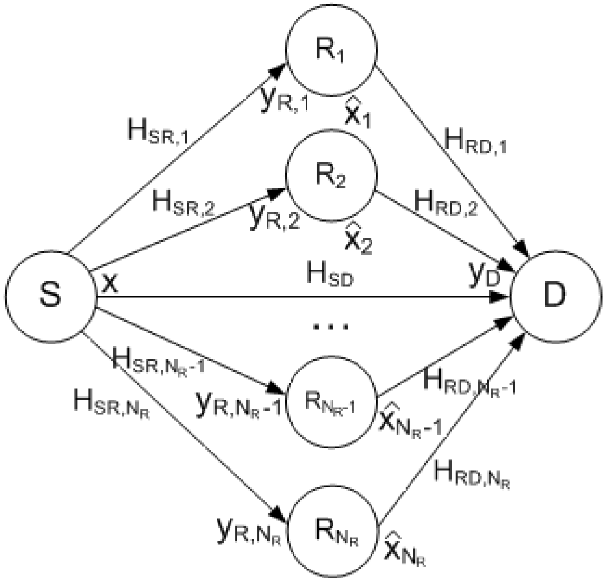


Figure 2.16: The Gaussian relay network

For the Gaussian relay network only one source and destination is assumed. In reality, many S-D pairs will communicate at the same time and more general structures of wireless networks should be studied. However, the capacity of a wireless network is much harder to determine but it has been tried in [69] for a unit disc area with randomly located nodes. The main results state that even under optimal conditions the throughput per randomly selected node pair approaches zero for dense networks. The throughput is non-zero only, when restricting communication to neighboring nodes. If the nodes considered in this scenario are moving and the application can tolerate significant delays, the throughput per node in such a network can be constant even if the node density increases [70]. Every source and destination also acts as relay for other source destination pairs. The mobility of the nodes together with the use of relays ensures that every destination will be sufficiently close to a relay or its source so that the throughput per node does not approach zero. However, both results do not exploit the broadcast nature of the wireless channel and only point-to-point connections are considered.

2.6.2 Interference Relay Networks

Another interesting concept has been proposed in [71], the interference relay network. It considers multiple source-destination pairs and exploits the broadcast nature of the wireless channel. Instead of avoiding interfering sources, the impact of interfering signals is mitigated by active scatterers [72] using amplify-and-forward relaying and matched filtering and thereby effectively orthogonalizing the channels of distinct communicating pairs in a distributed manner. The matched filtering operation requires channel knowledge for both the S-R and R-D channel to perform the matched filtering. For the relay protocol in [73] the relays assist one S-D pair and thus only channel knowledge to one source and destination is required. For the protocol presented in [74] each relay assists every S-D pair with equal weight when calculating the matched filtering amplify-and-forward gain factor. We have presented in [30] and [39] a generalization of these protocols where the relays can weight the amount of assistance to each S-D pair. We have suggested in [40] to apply this concept to a multi-cell scenario where active scatterers at the cell border orthogonalize signals of multiple cells to provide relay division multiple access and to balance the load between the cells.

The capacity scaling analysis [75] of large interference relay networks shows that for a large number of source-destination pairs N_s, $N_{\mathrm{r}} \propto N_{\mathrm{s}}^{\alpha+3}$ (α is a real valued constant) relays are required to achieve an end-to-end link capacity scaling of at least $\log(N_{\mathrm{s}}^{\alpha})$. However, for practical cases it is beneficial to investigate the performance for small number of communicating pairs and we studied in [30] an interference relay network with $N_{\mathrm{s}} = 4$ S-D pairs. For $\alpha = 1$ or N_s^4 (256) relays and a binary phase shift keying (BPSK) modulated signal the bit error rate (BER) is about 1% and communication is already possible. The distributed orthogonalization works very well for $\alpha = 2$ or N_s^5 relays but it requires already 1024 relays for 4 communicating pairs. Similar to the information theoretic analysis presented in literature these results assume the same average channel gains to all sources and destinations. This is clearly not the case in real network topologies and we have presented in [30] simulation results for spatially separated interference relay networks which includes a single cell like scenario. It corresponds to a situation where four distant terminals want to communicate to a BS and they are assisted by a ring of relays between them and the BS. In such a scenario $\alpha = 1$ achieves a BER of 0.07% but it still requires 256 relays which is not practical in a cellular network. Hence, even though the concept of interference relay networks is very interesting it is probably not applicable to cellular systems.

2.7 Summary and discussion

In this chapter we have reviewed some of the work on the relay channel that is available in literature. The discussion of the information theoretic studies in Section 2.2 shows the great potential of relaying to improve the performance of a wireless link. Further in Section 2.3, we introduced and discussed some cooperative relaying protocols proposed in literature. These protocols are designed for fading relay channels to effectively reduce the outage probability of the wireless link.

Secondly, we have presented the signal model for relays in an Orthogonal Frequency Division Multiplexing (OFDM) network. For such relays we presented selected results which we have presented in [28]. These results show that significant throughput gains can be expected from relays when they transform a non-line-of-sight link into two line-of-sight links. This gain can already be achieved by amplify and forward relays. A particular interesting option for OFDM systems is the use of amplify and forward (AF) within the cyclic prefix (CP) relays. Both the signal transmitted by the source and the relay arrive within the cyclic prefix at the destination and the receiver simply treats the signal from the relay as an additional multi-path component. Thereby, it avoids the rate loss from half-duplex operation but requires full-duplex operation of the relays. Our results show that AF within the CP has a similar packet error rate performance than pure AF.

Further, we presented the idea to use multi-antenna AF within the cyclic prefix (CP) relays in an OFDM system as we have proposed in [29]. We compared the performance of different relaying protocols in combination with multi-stream communication based on eigenbeamforming. The eigenvalue spread of the effective channel matrix is much higher for the Amplify and Forward relaying protocols compared to the Decode and Forward protocol and thus Amplify and Forward offers less spatial multiplexing possibilities. Nevertheless, the AF within the CP protocol performs significantly better at SNR up to 20dB than DF because it does not suffer from the half-duplex constraint. Only at higher SNR it is outperformed by the DF protocol because of its better spatial multiplexing possibilities.

Even though these results are very promising there are challenges related to the use of AF within the CP relays in a next generation communication systems such as 3GPP Long Term Evolution, Worldwide Interoperability for Microwave Access (WiMAX) or 3GPP2

Ultra Mobile Broadband (UMB) which are all based on Orthogonal Frequency Division Multiple Access (OFDMA). An OFDMA system can divide the available system bandwidth (subcarriers) between multiple users. Thereby it adapts to different traffic demands and the BS can utilize feedback to allocate the available subcarriers in an optimal way to its associated mobile terminals (MT). AF within the CP relays cannot selectively forward a signal, i.e. each RN that serves a MT which receives data in a particular OFDMA symbol has to be activated. Other relaying protocols allow the RN to selectively forward only data to users in their coverage area which lowers the amount of interference in the cellular network. Nevertheless AF within the CP is well suited for OFDM systems and it is utilized for example by gap fillers in Digital Video Broadcasting systems (DVB). Similarly, it could be utilized to enhance a Multimedia Broadcast Multicast Service (MBMS) of a cellular network.

Secondly, the full-duplex operation requires the RN to receive and transmit on the same resources. This requires separate transmit and receive antennas as well as a sufficient isolation between these antennas due to differences of up to 120dB in the received and the transmitted signal levels. In DVB-T and DVB-H systems the isolation is provided by a careful placement of the antennas and AF relays (repeaters) are already used in 3rd generation communication systems to cover isolated spaces such as tunnels and underground car parks.

The previous discussion focused on link performance and we extended the discussion to relay networks. In particular we reviewed some information theoretical work on Gaussian relay networks and interference relay networks. Even though there are some information theoretic results available, they cannot be applied to cellular communication systems. The assumed topologies do not reflect "real world" cellular networks and signal propagation aspects are not taken into account. Thus, the system performance of a cellular system with relays can only be studied in system simulations. Nevertheless, the information theoretic results on the relay channel generate some intuition about promising relaying protocols and can be used to narrow down the options to be studied in system simulations. Link results do not capture "real world" network topology either but can be used to provide a mapping from link level results to system throughput depending on the signal-to-interference and noise ratio calculated for each link in the system.

Chapter 3

Relays in Cellular Systems

3.1 Introduction

In the previous chapter we have introduced information theoretic and link level aspects of relaying. Further, we have shown some studies on generic relay networks. These studies give some intuition about the potential gains of relays in a cellular system but they do not take the practical aspects of cellular networks into account.

In this chapter we extend the discussion to relays in cellular networks. Many practical limitations have to be taken into account when integrating relays into a cellular network. Some examples that we have considered in the relaying task of the WINNER project [8] are: the mobile terminals (MT) should have the same interface when served by a relay as when served by a base station (BS), relaying should not cause any overhead when it is not present in the system, relaying should only slightly increase the minimum delay and most importantly relays have to enable cost effective deployments.

In our research we have found radio resource management (RRM) in relay enhanced cells to be the most important function to exploit the potential benefits of relay networks. The RRM should adapt to changing user and traffic densities and it should be flexible enough to be applicable to deployment scenarios ranging from wide area to local area office deployments. We present an RRM framework based on flexible and dynamic resource assignment for relay enhanced cells in a cellular OFDMA system that we have introduced in [25] and [16]. We present in more detail a dynamic resource assignment scheme based on soft frequency reuse that we have introduced in [76] and [15]. Further, we present the interference aware scheduling scheme which we introduced in [18]. The scheduling scheme exploits the signal-to-interference plus noise ratio (SINR) variations introduced by soft frequency reuse. In addition to dynamic resource assignment we found cooperative relaying as a promising technique to further increase the performance of relay based deployments. We present our MIMO cooperative relaying concept that we have partly introduced in [20] and [16] and presented in [25].

The frequency bands allocated to cellular communication systems are fragmented and the propagation conditions in these bands can be very different. It is foreseen that future communication systems will operate in multiple bands and relays are an effective way to balance the coverage of the different bands. We present our view on relay operation in such a multiband environment together with the concept of a multiband scheduler that we have introduced in [27] and [23].

The remainder of this chapter is organized as follows. In Section 3.2 we introduce related work on relays in cellular networks. In Section 3.3 we introduce relays in the WINNER system architecture. In Section 3.4 we show how the data forwarding is implemented by WINNER relays. The main focus however is on our work on RRM in relay enhanced cells and on the integration of cooperative relaying into the WINNER relaying concept. In particular we will present the concept of dynamic resource assignment in relay enhanced cells in Section 3.5; the resource allocation and control signaling for cooperative relaying in Section 3.6. Moreover we will present an end-to-end ARQ scheme for reliable data transmission over multiple hops and for cooperative transmissions in Section 3.7. Next we discuss relays in multiband operation in Section 3.8 and resource assignment in relay networks with more than two hops in Section 3.9. We conclude the chapter with a short summary and a discussion in Section 3.11.

3.2 Cellular Systems with Relays

Early work on relays to improve the performance of cellular communication systems includes for example the iCAR system [77]. The iCAR concept is illustrated in Figure 3.1. It uses ad-hoc relay nodes to balance the load of the cells. If no BS is available the calls between close by MT can be routed directly through the RNs. In [77] it is proposed that the relay use for example the license exempt band at 2.4GHz, to offload the cellular network which operates in the licensed band at 1900MHz. The relay interface is not the same as the cellular interface and is based on the IEEE 802.11 standard. A disadvantage of this approach is, that it requires the RN and the MT to have both a cellular and a relay interface, i.e. requiring two transceivers. Even though there are many high-end devices with both a WLAN and a cellular radio on the market, it is still a non-negligible cost component for low-range and mid-range devices. Second, requiring two radio interfaces to be active will increase the energy consumption of the terminal. Further, the iCAR concept relies on transmissions on the license exempt band for which no quality of service levels can be guaranteed.

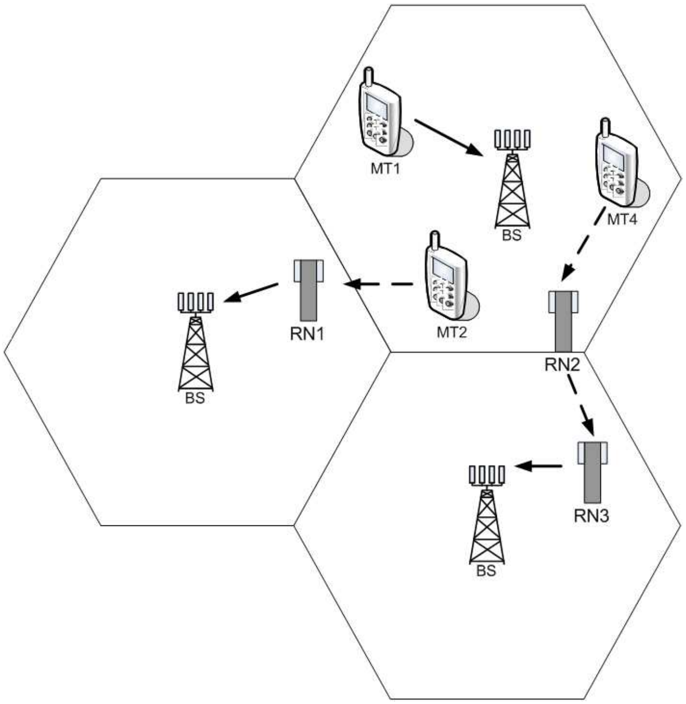


Figure 3.1: iCAR uses ad-hoc relay nodes (RN) to balance the load between the cells. Solid lines indicate cellular communication with the BS and dashed lines indicate a relay interface.

The multihop cellular network in [7] uses mobile terminals within a cell as relays as illustrated in Figure 3.2. The mobile relays can be used to either decrease the transmit power in the cell (decrease the transmission range, MCN-p) or to reduce the base station density (MCN-b). Each of the transmitters within the multihop cellular network forms a small sub-cell. Multiple sub-cells can be active at the same time, allowing for example more than one multihop connection in parallel within the cell.

The results in [7] show that for 100% of the traffic within a cell (local traffic) the end-to-end throughput could be increased by more than 40%. However, in practical applications the MT density within the network is limited and they are not located at ideal locations for multihop connections. Second, the MTs move and routing protocols are required to determine the multihop routes in the cell. Especially, when a short response time for the

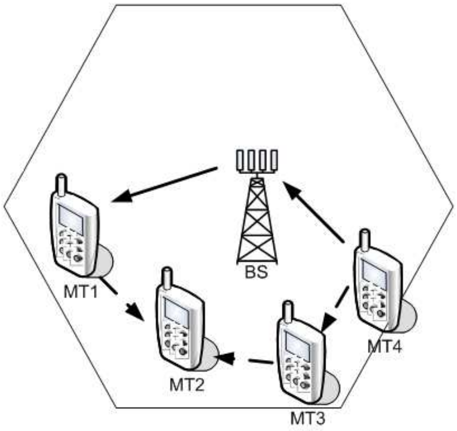


Figure 3.2: The multi-hop cellular network (MCN) allows multihop connections through multiple mobile terminals.

session setup is required, the overhead from these routing protocols can reduce the gain to zero. Further, in a cellular network the bulk of the traffic does not stay within a single cell and there is no gain from this concept if the share of local traffic is zero. Thus the multihop cellular network concept does not seem promising for IMT-Advanced cellular networks.

More recent work considers relays with a centralized scheduler at the base station (BS) in an 1xEVDO network [78]. However, a centralized scheduler requires that the relay forwards the current achievable rate or channel state information and the queue size information of each mobile terminal to the base station. The additional overhead can be prohibitive especially for the feedback of the channel state information since most next generation systems will be based on Orthogonal Frequency Division Multiple Access (OFDMA) with bandwidths of up to 100MHz and support for multiple antennas.

The main part of this chapter discusses various aspects of the integration of relays into a cellular system. In the WINNER project the radio resource management for relay enhanced cells has been identified as the most important function to exploit the potential benefits of relay networks.

Only some work on resource allocation in ODFMA relay systems can be found in literature. In [79] the resource allocation from multiple sources via multiple relays to one destination is formulated as an optimization problem. The resulting algorithm may be applicable to the uplink of a cellular system; however it requires channel state information feedback for all possible paths between BS and mobile terminals (MT) as well as relay nodes (RN) and MT within a cell.

In [80] a combined power control and resource allocation scheme for the uplink of a cellular OFDMA system is proposed. The uplink and the downlink of a cellular network can be imbalanced caused by a difference between the BS and the MT transmit power of more than 20dB. The BS aims to keep the received power spectral density from the MTs in the cell within a limited dynamic range. Thus, the received power from the MT having the weakest link will determine the transmit power and the S(I)NR of all MTs in the cell. Since RNs shorten the link distance to the MT, RNs will help to increase the achievable rates in uplink. Further in [80] it is proposed to allocate less OFDMA resource units (chunks) to MT with a weak link to increase the power spectral density used in the system.

In our work we have focused mainly on the downlink of a multi-cell OFDMA system. To our best knowledge there is only few related work on radio resource management for the downlink of an OFDMA system. In [81] the OFDMA resource allocation for a single cell with multiple users is analyzed. The downlink performance of a multi-cell OFDMA network is studied in [82]. Similar to our work it is also based on the WINNER relaying concept.

The second main aspect of this chapter is on the protocol integration of relays in a cellular system. Relays have already been standardized by the task group j (TGj) of IEEE802.16. The IEEE802.16j standard [5] is an amendment to the IEEE802.16 standard which enables the operation of RNs without changes to the legacy MT specification. In non-transparent mode the RN acts like a BS sector and transmits its own preamble, Frame Control Header and signals UL and DL resource allocation.

In transparent mode the RN does not transmit a preamble and control information. The RN is only active for data transmissions. For RN in transparent mode the 802.16j standard also specifies the possibility for cooperative BS-RN transmissions. It mentions two basic possibilities: “cooperative source diversity” (repetition coding) and “cooperative transmit diversity” established through distributed Space-Time Block Coding (STBC) and a combination of both.

3.3 Relays in the WINNER System Architecture

We have presented an overview on the WINNER system concept with relay nodes (RN) as an integral part of the radio access network in [11] and [24]. One of our main goals when developing the WINNER relaying concept has been to avoid increasing the complexity of mobile terminals (MT). In particular we have decided that the MT should have the same interface (IWU) towards the BS and the RN. The BS forms together with the RNs a relay enhanced cell (REC). Figure 3.3 shows the basic elements of a multi-hop connection. The MT is always connected via an access link to a radio access point (BS or RN). The link between two radio access points is called relay link. The multi-hop link is comprised of at least one relay link and an access link. The RN acts like a MT to the BS and RNs closer to the BS and like a BS to MT and RN further away from the BS.

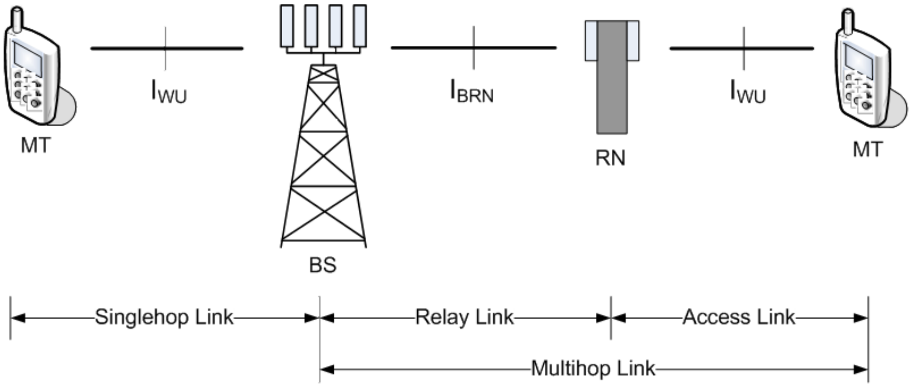


Figure 3.3: Relays in the WINNER system architecture.

The BS controls the RNs, e.g. determines routes (i.e. handovers), and forwards packets to the respective relay. The BS and the RN form a tree topology to avoid complex routing schemes. The integration of the RN to the control plane of the WINNER system is depicted in Figure 3.4. A detailed description of the WINNER system architecture and the protocol layers can be found in [10].

The WINNER protocol architecture encompasses the three lowest layers of the OSI stack, supporting both single hop and multi-hop communication. The two lowest layers, represented by the physical (PHY), Medium Access Control (MAC) and Radio Link Control (RLC) sub-layers are present in all BS, MT and RN logical nodes. This enables an efficient co-design of these layers which are controlled by the scheduler, for example the fast Hybrid Automatic Repeat Request (HARQ) with low signaling overhead takes place at the MAC layer and a more robust RLC-ARQ facilitates the recovery from occasional NACK to ACK errors.

In the control plane the Radio Resource Control (RRC) layer terminated in the BS is located above the RLC. The control and configuration of the RN, is performed by the sub-layer RRC2. The RN receives on the RRC2 sub-layer for example broadcast information,

information about the establishment, maintenance, reconfiguration and release of flows to MT served by the RN, resource assignments and paging information. Further, it sends information to support the flow control between BS and RN, e.g. a stop signal if the buffer at the RN is exceeding a threshold. Towards the MT the RN controls measurements and reporting as well as broadcasts system information. In addition it forwards information received from the BS, e.g. related to handovers, QoS management or paging,

In the following we will focus on the radio resource management, Automated Repeat Requests (ARQ) with relays and the integration of cooperative relaying where we have put most of our efforts. Other important functions such as the forwarding of user data, broadcast signalling of relays, handovers, load balancing, admission control will be addressed only briefly.

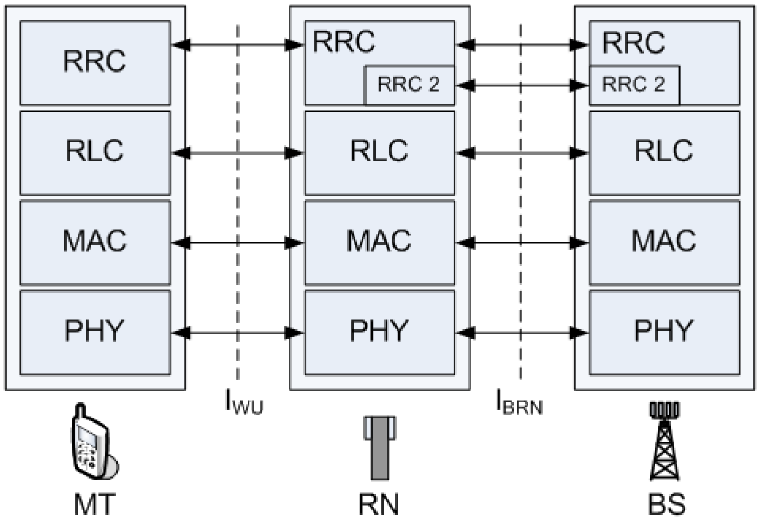


Figure 3.4: Control plane of the WINNER architecture enhanced by RN.

3.4 Forwarding of user data within the WINNER MAC Protocol

The main function of the RN is to forward user data, i.e., user data received either from the MT (UL) or the BS (DL) or a preceding RN (UL or DL). In the WINNER relaying concept we assume that the BS and the RN form a tree topology and the forwarding takes place along the branches of the tree. Thus, complex routing protocols are avoided. In the rare case of node failures the tree topology is reorganized and can be considered as self-healing. We define DL traffic as all the traffic from the BS to a MT and UL traffic as all the traffic from a MT to the BS. All DL communication takes place during the DL phases and all UL data is transmitted during the UL phases in order to avoid harmful interference to adjacent relay enhanced cells.

In the WINNER TDD mode we assume half-duplex operation for the RNs because a sufficient isolation between transmit and receive antenna cannot be guaranteed. The WINNER relaying concept supports half-duplex RNs in FDD mode as well to avoid duplex filters and allow a cost efficient implementation. The half duplex approach forces the RN to switch between MT and BS operation modes. These two alternating modes of operation are highlighted in Figure 3.5. The RN can either serve its MT in the BS mode or communicate with the BS in the MT mode. In other words the RN is not able to serve its MTs while communicating with the BS. On the other hand, the BS or RN may serve its associated MTs while serving a RN.

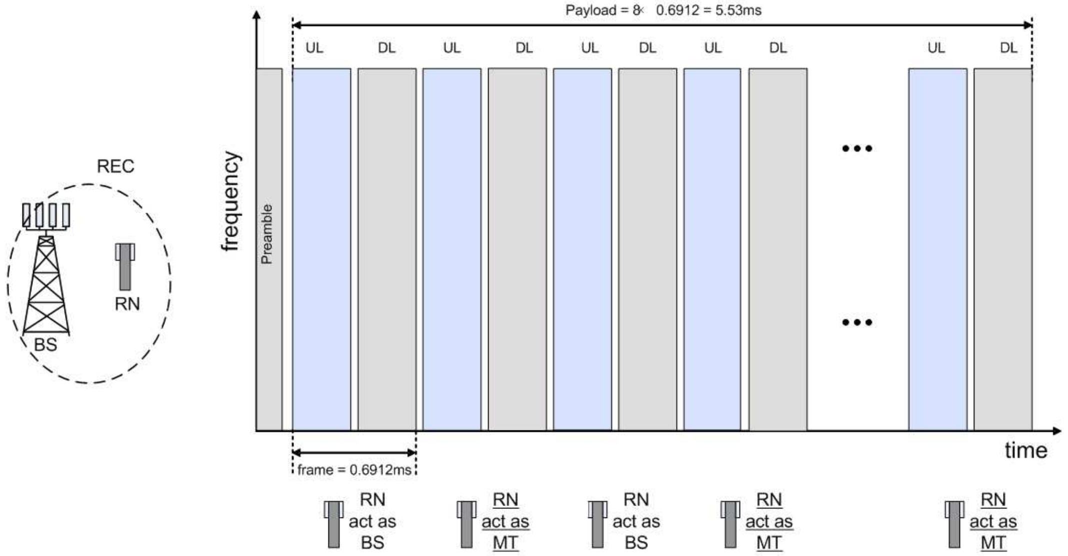


Figure 3.5: WINNER Superframe for TDD mode consisting of 8 MAC frames. The role of the half-duplex relay node is indicated below.

Figure 3.5 depicts a WINNER superframe in TDD mode consisting of 8 Medium Access Control (MAC) frames with example roles of the RN in each frame. Due to the short MAC frame duration of 0.69ms, the delay and the round trip time (RTT) of the system are kept short also in the presence of RNs. In this example the RN switches with every MAC frame between its role as BS and MT. In this configuration the RN can forward user data already in the next frame and the minimum delay increases only to 1.4ms in a two hop network. In UL direction the RN and MT have to first signal a resource request and the minimum delay for two hops increases from 1.4ms to 2.1ms.

Dedicated parts of the resources within the superframe are reserved for both BS and RN to transmit the broadcast channel (BCH) and to transmit synchronization symbols on the DL. Some UL resources are reserved for the Random Access Channel which appear periodically according to the MAC SF period. Besides the BCH, the MTs have to receive control information such as scheduling information in the common control channel (CCCH) of each MAC frame. The BCH and the CCCH are usually transmitted using a low modulation and coding scheme and therefore they are well protected against transmission errors. We assume that the WINNER RNs act like a BS, i.e. the RN transmits broadcast information and resource allocation addressed to its sub-cell (as part of the REC), using its own dedicated resources.

3.5 Dynamic Resource Assignment in Relay Enhanced Cell

Without a proper radio resource management (RRM) strategy the potential benefits of relay networks are lost as our results in Chapter 4 illustrate. In this section we present the dynamic resource assignment framework for relay enhanced cells, which we have developed in the WINNER relaying task. In particular we will illustrate in detail the application of the dynamic resource assignment to a metropolitan area network which is the main focus of this thesis.

Our proposal assumes a distributed MAC, i. e. the BS only assigns resources to itself and the RNs in the relay enhanced cells but it does not centrally schedule the transmissions to the mobile terminals (MT). The RNs can then independently allocate these resources to its associated MTs. Thus, frequency adaptive transmissions and multi-antenna transmission schemes can be supported without forwarding channel state information, pre-coding weight feedback, etc. to the BS. This decision can also be justified by the results in [81] indicating that the performance loss of the distributed MAC is only about 10% compared to a centralized scheduler even without considering the signaling overhead for a centralized scheduler.

Scenarios where relays will be deployed can have very different properties as illustrated by the test scenarios in Chapter 4. Moreover, real world deployments are not as regular as these test scenarios and relays may generally be deployed to increase the coverage, to increase the capacity or to cover shadowed areas. Further, due to the small size of the sub-cells formed by BS and its RNs the traffic density can vary significantly in these sub-cells.

Thus, a fixed and static resource assignment will not allow to exploit the full potential of relay based deployments. Therefore, we propose that the BS flexibly assigns parts or all of the available system resources to itself and to each RN in the relay enhanced cell (REC). In particular the BS assigns the frames in which the RN communicates with the BS (act as a MT) or serve its MT (act as a BS). Further, it assigns the OFDMA resource units (chunks) that the RN can use when acting as a BS. The assigned resources are then available for autonomous scheduling at each individual radio access point (RAP), i.e. BS or RN.

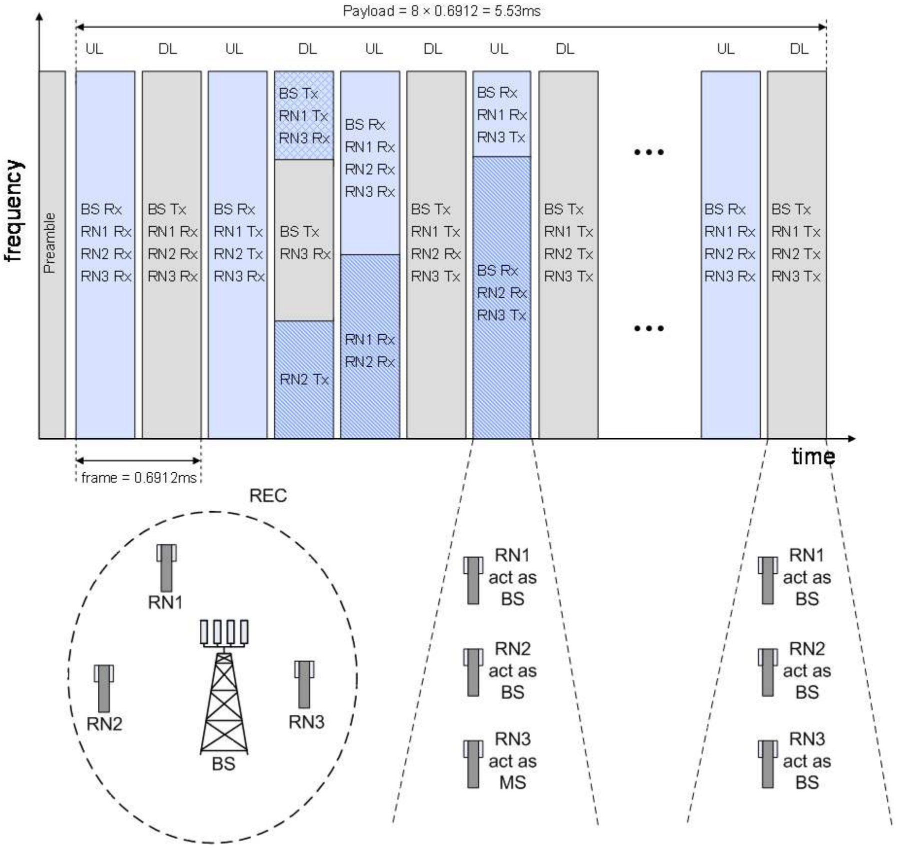


Figure 3.6: Example allocation of a super-frame using the Flexible Resource Assignment scheme in a relay enhanced cell with three relays (RN). The super-frame consists of a preamble and an 8 frames payload following the WINNER system specifications [10]. The Base Station (BS) allocates (a part of) the resources to the RNs, the RNs independently schedule their associated MT within their allocations when acting as BS.

The actual resource assignment will also depend on the utilized interference coordination and multi-antenna techniques. Consider, for instance, a scenario where multi-antenna macro-BSs, mounted on a mast, provide wide area coverage. In such a scenario beamforming has been shown to be an effective way to improve the cell capacity [83]. The interference from the sub-cells formed by the BS to the sub-cell of a RN can be coordinated by using beams with low interference to a RN sub-cell for resources that have been assigned to the RN. The amount of resources for the RN is dynamically adjusted depending on the traffic and interference situation. This scheme has been introduced as Dynamic Resource Sharing (DRS) [84] and extended in [85]. Our work has mainly focused on the metropolitan area for which we present an interference coordination scheme based on soft frequency reuse in Section 3.5.1.

Table 3.1 summarizes the essential elements of the resource assignment. The MT does not need to perform additional measurements to support the resource assignment. It takes the received signal strength from neighboring radio access points (BS or RN) reported by the MT as an input, which are anyway required for handover purposes. Please note that the logical beams are a dynamic version of sectors and therefore also measurements for the logical beams will be available.

Table 3.1: Example of essential elements of resource assignment scheme with a grid of beams used at the BS and for single antenna RNs.

Resources to be assigned	Frames in superframe where RN serves MT/communicates to BS, chunks assigned to RN
Granularity of resources	Group of four OFDMA resource units (chunks) in the frequency domain, TDMA frame in the time domain (0.7ms)
Measurements/Information related	
Measurements required	Received signal strength of beams formed by serving BS
Who performs measurements	MT
Additional information	Estimate of required chunks to serve MT
How often	New measurement and message every 100ms
Who collects it	Serving radio access point
Who uses it	BS in REC
Information push or poll	Push
Resource assignment message	
Content	frames assigned to serve MT in super-frame, chunks assigned within the UL/DL frames to the RN
What timing constraints	New assignment at most every super-frame

3.5.1 Soft-Frequency Reuse for Metropolitan Area Networks

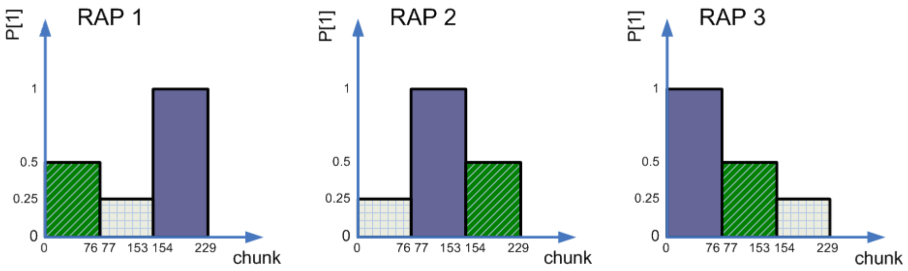
Beamforming is not as effective in coordinating interference in the metropolitan area, because the radio signal propagates very well in the street canyons and the separation of the different beams disappears. On the other hand buildings provide strong shadowing from perpendicular streets. Thus, interference coordination is mainly needed at street crossings and in the border area between radio access points, whereas the border area is smaller than in a wide area deployment.

In this scenario we propose a resource assignment based on soft frequency reuse (SFR) that assigns power masks (in the frequency domain) to neighboring radio access points to coordinate the mutual interference. Thereby, soft frequency reuse enables frequency reuse one and at the same time each radio access point has high power resources with reduced interference available to schedule MT located at the border area. The concept of SFR, also known as soft-resource partitioning, and power planning was first introduced in [86] in the context of capture division packet access.

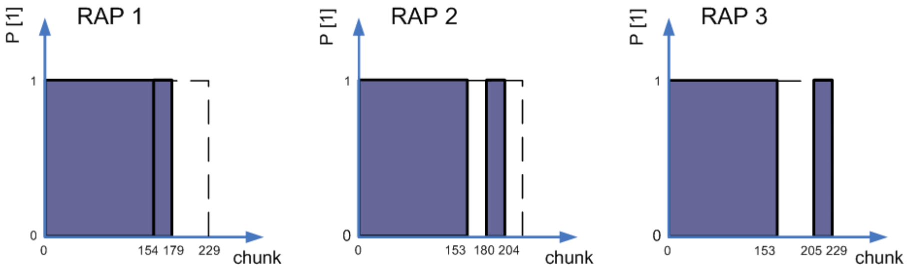
In addition to SFR, fractional frequency reuse (FFR) is seen as an interesting interference coordination scheme in OFDMA systems to improve data rates experienced by cell edge users [87]. It can be implemented for example in WiMAX by combining Full Usage of SubCarriers (FUSC) for users close to the base station (BS) and Partial Usage of SubCarriers (PUSC) for cell edge users. Please note that this is transparent to the MT since it receives and transmits on the resource blocks (subchannels in WiMAX terminology) indicated in the downlink MAP and uplink map, respectively. Similarly the power mask assignment can be transparent to the MT. It will simply experience increased SINR variations caused by the power masks.

Figure 3.7 illustrates the concept of SFR, FFR and reuse one. SFR assigns different power masks to neighboring radio access points. Thus, SFR enables frequency reuse one and at the same time each RAP has high power resources with reduced interference available to schedule mobile terminals (MT) in the border area between RAPs. In this example, the OFDMA resource blocks (chunks) have been subdivided in the frequency domain into equal sized groups and a power level is assigned to each of the groups as illustrated in Figure 3.7(a).

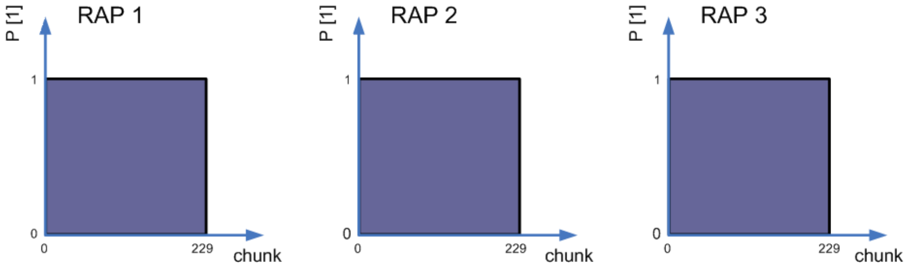
In the case of FFR, reuse one is used for part of the chunks and reuse three for the rest as illustrated in Figure 3.7(b). Thus, users scheduled in chunks with reuse three will not experience any interference from neighboring radio access points. No interference



(a) Soft frequency reuse.



(b) Fractional frequency reuse.



(c) Reuse one.

Figure 3.7: Power mask levels for different interference coordination schemes and groups of radio access points (RAP).

coordination between neighboring radio access points is utilized for reuse one as shown in Figure 3.7(c). We will compare the performance of SFR, FFR and reuse one for a metropolitan area network in Chapter 4.

Table 3.2 summarizes the essential elements of the dynamic resource assignment based on soft frequency reuse.

Table 3.2: Essential elements of resource assignment scheme for SFR.

Resources to be assigned	Frames in superframe where RN serves MT/communicates to BS, power mask to be used
Granularity of resources	Group of four OFDMA resource units (chunks) in the frequency domain, TDMA frame in the time domain (0.7ms)
Measurements/Information related	
Measurements required	Received signal strength of neighboring radio access point
Who performs measurements	MT
Additional information	Status of buffer at RN
How often	New resource partitioning every 100ms
Who collects it	Serving radio access point
Who uses it	BS in REC
Information push or poll	Push or poll
Resource assignment message	
Content	Power mask, frames assigned to serve MT in super-frame

3.5.1.1 Interference Aware Scheduling for Soft Frequency Reuse

In order to exploit the potential benefits of Soft frequency reuse (SFR) the cross-layer interactions have to be considered. In particular the scheduler should be designed to exploit the SINR variations introduced by SFR. In this section we present a novel interference aware phased scheduling scheme for SFR and fractional frequency reuse (FFR) that we have introduced in [18]. The phased scheduler aims to increase the throughput of low throughput users while keeping an at least similar cell throughput as a proportional fair scheduling algorithm.

The proposed phased scheduler algorithm for SFR is depicted in Figure 3.8. Similar to [88] we introduce a two phase scheduling process. In a first phase a time domain scheduler groups the users into users with low and high signal-to-interference and noise ratio (SINR). It then selects users of each group for frequency domain scheduling. A frequency domain scheduling algorithm then allocates the physical resources utilizing the

SINR variations introduced by SFR.

The time domain packet scheduler selects a specified maximum number of L out of N active mobile terminals (MT) ($L < N$) for frequency domain scheduling based on either a round robin (RR) or an equal throughput (ETP) time domain (TD) fairness criteria, i.e. selecting the MTs that have not been scheduled for the longest time or the MTs with the lowest average throughput in for example the last 200ms, respectively.

Additionally we propose that the time domain packet scheduler (TDPS) splits the N active MTs with data to send in a group of K MTs with low and a group of $N - K$ MTs with high SINR. The SINR is calculated as average SINR of the chunks with low power levels in the case of SFR and over the whole bandwidth for FFR. M MTs are then selected from the low and $L-M$ MT from the high SINR group in every scheduling round. The split ensures that high and low SINR users are available for each frequency domain scheduling round to exploit the SINR variations introduced by SFR or FFR. Please note that the sorting into groups does not depend on the absolute SINR, i.e. the proposed strategy adapts well to varying user distributions.

The ratio of MTs from the low SINR group corresponds to the ratio of chunks with reduced interference to the overall available chunks. Here we assume that a similar amount of chunks is allocated to every MT by the frequency domain packet scheduler (FDPS). Using the example of Figure 3.7 in the case of FFR one sixth of the users are selected from the low SINR group and the rest from the high SINR group and for SFR one third is selected from the low SINR group. Please note that FFR offers the possibility to adjust the amount of chunks with reduced interference. Selecting two third of the chunks for reuse one and having only one ninth with reduced interference for each AP works well in a metropolitan area, where relatively few MTs at street crossings experience the most challenging interference conditions. This selection will likely be different for macro-cellular scenarios. If one of the groups does not have enough MTs, then additional MTs from the other group are selected until the sum is L MTs. When applying the time domain packet scheduler split the strategy is referred to as split in Chapter 4.

Secondly, the split can be used to reduce the amount of feedback that is required from the MTs, which is especially important for MTs with low SINR. To reduce feedback, we propose that the frequency domain packet scheduler (FDPS) allocates chunks with high power mask levels to MTs from the low SINR group and chunks with low power mask levels to MTs from the high SINR group. For the resource partitioning illustrated in Figure 3.7

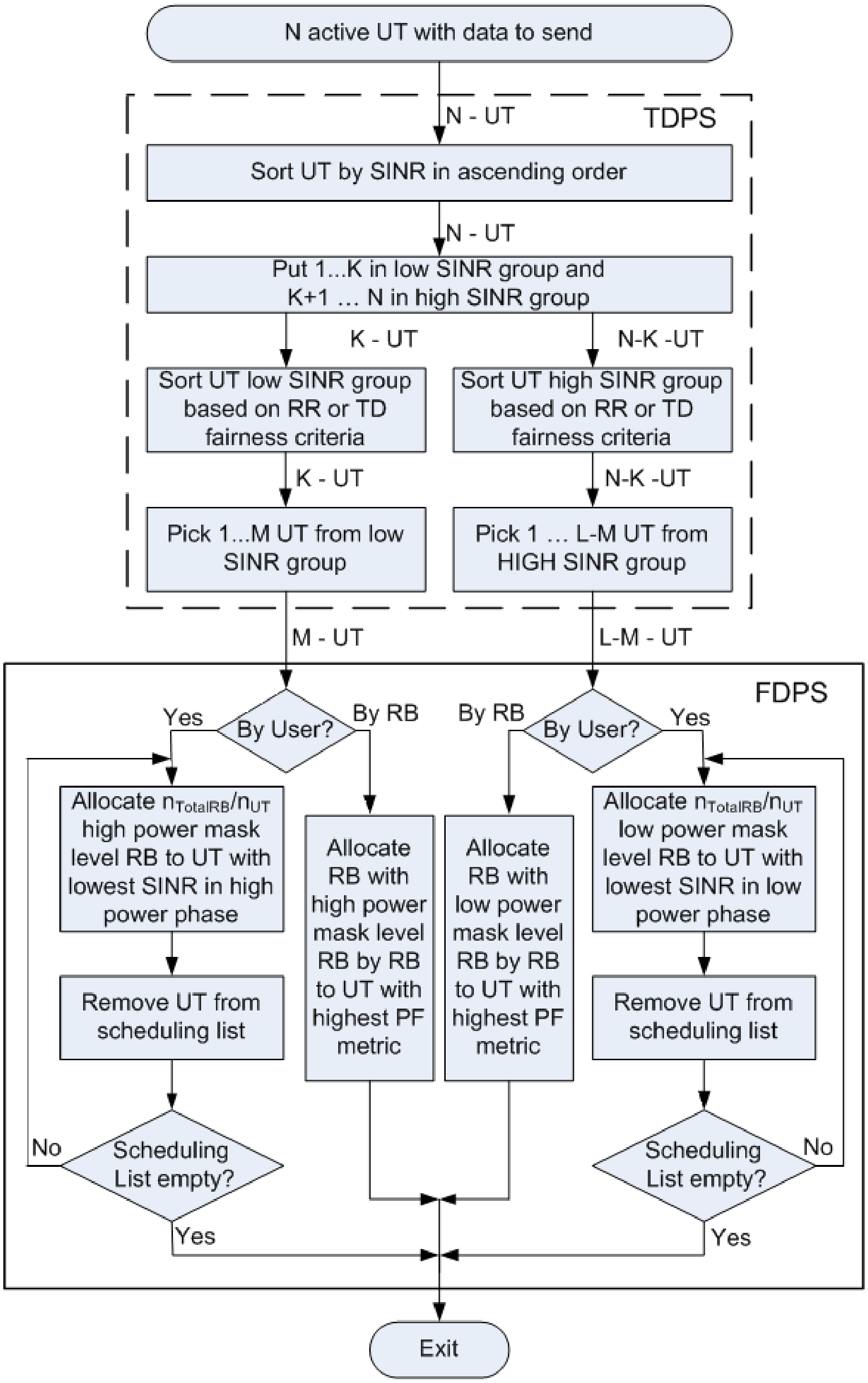


Figure 3.8: Phased scheduler for both by User and by chunk (RB) frequency domain scheduling strategy.

the low SINR group only needs to send feedback values for 25 out of 230 chunks in the FFR case and 76 in the case of SFR. Additionally the MTs have to provide one feedback value to support the sorting into groups. The amount of feedback can be further reduced by reporting one feedback value for each power mask level or by reporting feedback values for the best M chunks in each power mask level as we have proposed in [33]. However, this option has not been evaluated in our results in Chapter 4.

The frequency domain packet scheduler then allocates the physical chunks to the MT selected by the time domain packet scheduler. When using the reduced feedback option, the frequency domain packet scheduler allocates chunks with high power mask levels only to MTs from the low SINR group and chunks with low power mask levels only to MTs from the high SINR group. The reduced feedback option will be denoted as redFB in Chapter 4. The frequency domain allocation of chunks to MTs can follow a byUser strategy, assigning resources user by user, or a byRB strategy, assigning resources chunk by chunk.

3.5.1.2 Frequency Domain Packet Scheduler with byRB strategy

For the byRB strategy a proportional fair (PF) metric is calculated for each chunk and each user. The proportional fair metric $d_{p,k}$ for chunk p and user k is given by

$$d_{p,k} = \frac{R_{p,k}}{\bar{R_k}} \tag{3.1}$$

where $R_{p,k}$ denotes the predicted rate for chunk p and $\bar{R_k}$ the average rate over all chunks for user k.

Then each chunk is allocated to the user that has the highest proportional fair metric.

3.5.1.3 Frequency Domain Packet Scheduler with byUser strategy

The strategy in [89] without split and reduced feedback option will be used as a reference case in Chapter 4. It calculates n_{chunks}, the number of chunks that a MT has available for scheduling as

$$n_{chunks} = \frac{n_{Totalchunks}}{n_{MT}} \tag{3.2}$$

where $n_{Totalchunks}$ denotes the total number of chunks to be allocated and n_{MT} the number of MTs to be scheduled. The MT with the worst SINR picks first its share of chunks, then the MT with the second worst SINR and so on.

The byUser version utilizing the reduced feedback option, denoted as redFB in Chapter 4, is implemented as follows. The algorithm starts with the low power phase of the power mask and continues with the high power phase. First it calculates for each MT the average SINR for the current power mask phase based on feedback received from MTs. Then n_{chunks} are allocated to the MT with the lowest average SINR in that phase. Starting with the MT that has the lowest SINR ensures that this MT can pick the best chunks from this power mask phase.

3.5.1.4 Adaptive Soft Frequency Reuse

A relay enhanced cell (REC) can have multiple RNs, each providing different traffic load to the network due to its cell size and user density variations. Moreover, the traffic load is expected to change depending on the time of the day and the day of the week. Therefore a fixed power mask assignment to each radio access point (BS or RN) does not result in an efficient use of the available radio resources. A local power mask adaptation would be desirable and we proposed in [19] and [31] a mechanism for adapting the power mask based on the traffic load within the relay enhanced cell.

We also consider scenarios where RNs add significant coverage area to the cell. Therefore any resource partitioning between relay enhanced cells, that is divided between the base station (BS) and the RNs will not be the optimal solution. We propose to treat sub-cells formed by RNs similar to cells formed by BS, e.g. a soft-frequency reuse pattern does not assign a single power mask for the whole cell, where the high power resources are then split between the RNs. Instead a power mask pattern will be assigned to each sub-cell formed by BSs and RNs.

Figure 3.9 depicts an example relay network consisting of Relay node (RN) 1 and its neighbors. RN 3 belongs to the same relay enhanced cell (REC) and RN 4, RN 5 and RN 6 belong to neighboring RECs. The RN can find its neighbors for example by gathering information from MTs making interference and signal level measurements for handover purposes. The relays are not only used to cover shadowed area, but they can have similar power and coverage area as the BS.

We will describe the scheme illustrated in Figure 3.10 from the view point of RN 1 and starting from the power masks assignment as presented in Figure 3.9. We assume that such an initial power mask exists. It can be set by a network planning tool or it can be found by other means, e.g. the network learns its topology and sets the power masks

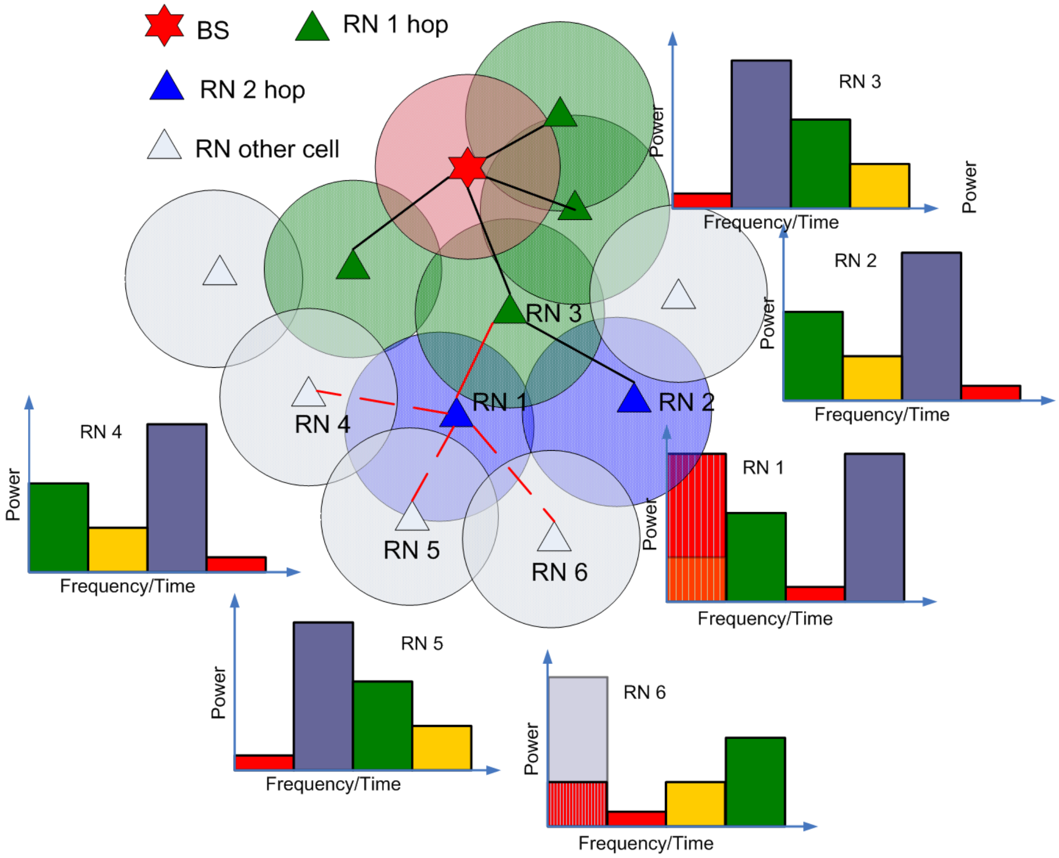


Figure 3.9: Relay scenario using power masks.

accordingly. The operation is starting from this initial power mask and the radio access points (BS or RN) will try to operate within this power mask.

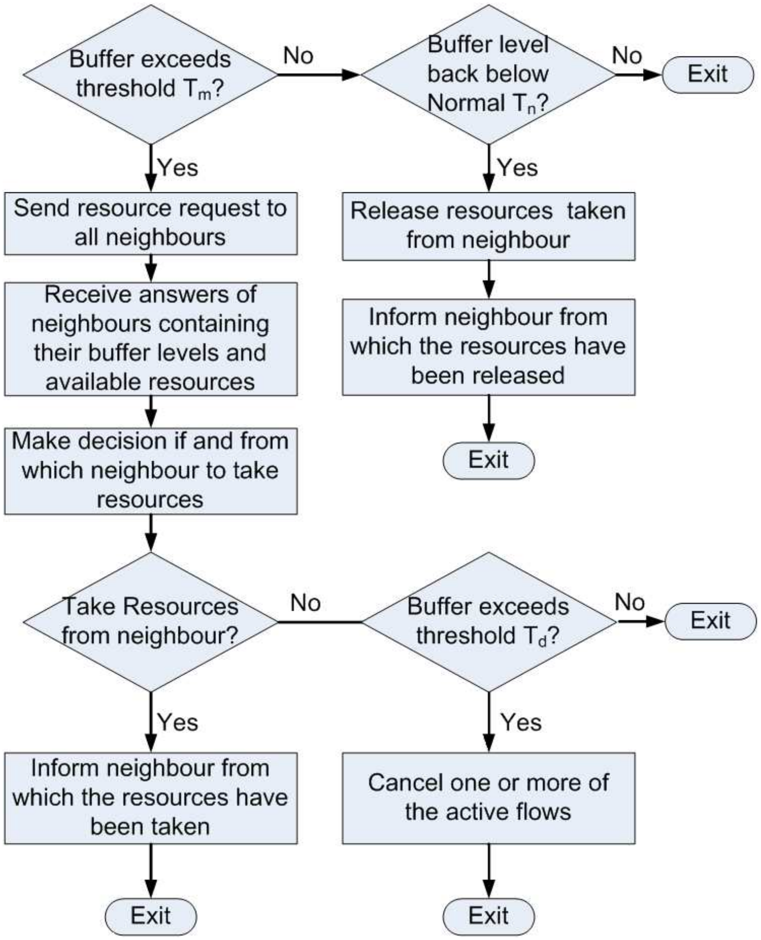


Figure 3.10: Flow chart of power mask adaptation.

RN 1 monitors its buffer level. There are three pre-defined thresholds, a maximum threshold (T_m) that if exceeded triggers a resource request and a normal threshold (T_n) below which the operation is normal. Additionally a drop threshold (T_d) is defined, that if exceeded causes the drop of one or more data flows to MTs. The difference between the thresholds is large enough so that the resource requests happen only at a relatively slow time scale, e.g. every 200ms-500ms. Thereby the amount of signalling between the nodes involved in the resource request is kept low.

RN 1 will check its current state of operation. If the buffer level exceeds the max threshold, then RN 1 sends a “resource request” message to its neighbors RN 3, 4, 5 and 6. RN 3, 4, 5 and 6 will answer to this message with a ”resource status” message containing their buffer level and the available resources, i.e. their current power mask. RN 1 will check the buffer levels from the other RNs and decide if it takes high power resources from one of the other RNs. It will base the decision on the following two criteria. First, take resources only from nodes where the buffer level is below the normal threshold. Second, take the resources from the neighbor that has the lowest buffer level and for which the highest power gain (difference of new high power level and currently used power level) can be achieved. The resources are taken from the neighbor with the highest utility function u given by

$$u = \max\left(a(T_n - v) + b\triangle p_{chunk}\right) \tag{3.3}$$

where T_n denotes the normal threshold, v the current buffer level, $\triangle p_{chunk}$ the power difference for a chunk. The weighting coefficients a and b allow to give more priority to neighbors with an empty buffer or to neighbors from which the highest power gain could be obtained. We have used $a = 0.5$ and $b = 0.5$ as a default value in [19].

RN 1 will then signal to the node from which it takes the resources that it should use the power level that RN 1 was using before. Figure 3.9 illustrates an example where RN 1 requests resources from RN 6 and the striped areas of the first resource block indicate the updated power mask. After signalling the updated power mask to RN 6, RN 1 is using the highest power level and RN 6 is using the power level that RN 1 was using in the first resource block. If no resource can be taken from the neighboring nodes and the drop threshold T_d is exceeded, then RN 1 will drop one of the active data flows it is serving. RN 1 drops for example the flow, which has the lowest average throughput d (e.g. in the last 5 seconds).

$$d = \min\left(\bar{d}\right) \tag{3.4}$$

where $\bar{d}$ denotes the average throughput.

If the buffer level drops below the normal operation threshold RN 1 returns power resources taken from its neighbors. It will signal the released resources and the neighbors increase the power mask by the same level that RN 1 decreases its power level.

The mechanism how to exchange messages with the neighbors will depend on the possibility of having a direct communication between the neighbors. The solid lines in Figure 3.9 indicate the connections of RN 1 with other RNs in the same cell over which regular data communication is taking place. The dashed lines indicate possible direct connections to RNs of neighboring cells over which no regular data communication happens but that can be used for exchanging messages.

If direct communication is not possible, the RNs communicate indirectly through the BS of the involved relay enhanced cell(s) or use the shortest route between the RNs for the communication. In any case, direct communication is preferred as it offers the fastest means of communication and requires the least resources.

Even though it is illustrated for RNs, the same method can also be used for interference coordination when BSs are involved. We have evaluated it in system simulations for an OFDM network and we have presented the results in [19]. The results show an increase in the lower parts of the user throughput cumulative distribution function. The user throughput drops in overloaded cells and adding additional power resources while reducing interference from one neighboring cell helps to increase the user throughput in these cells.

However, we have identified some issues that should be resolved before the scheme is taken into practical use. First, we have not included a mechanism that guarantees fairness between the cells. If one of the radio access points (RAP) takes resources from another and as a consequence the buffer level at the other RAP increases, there is no mechanism for the other RAP to get the resources back. Second, each RAP might need some high power resources to serve users with low Signal-to-Interference plus Noise ratio. Therefore a part of the high power resources should be guaranteed. Third, when requesting resource from one of the other RAP, not only the buffer level and the power gain but also the share of MT that are interfered by each of the neighboring RAP could be taken into account. Fourth, instead of swapping the power levels the RAPs could also increase and decrease the power for certain parts of the power mask by a pre-defined or negotiated value.

Instead of considering a decentralized scheme, we have outlined a power mask adaptation scheme where the BS adapts the power mask of the RNs in its relay enhanced cells based on interference reports by MT in [34]. The BS takes the local interference situation of the MTs in the cell and their resource usage into account when assigning the power masks to the RNs. It is for further studies if such a scheme could outperform the proposed decentralized scheme.

3.5.2 Signalling of the Resource Allocation

The signalling of the new resource assignment is routed through an own radio link control (RLC) instance to ensure a reliable data transfer. All resource assignment messages have to be forwarded to the RNs in the REC before the new resource assignment is active. In WINNER the maximum update frequency has been restricted to once every 8 frames (one super-frame of 8ms in the WINNER system [10]). However, it is uncertain if there are benefits from such a high update frequency and it might be sufficient to adjust the resource assignment for example every 100ms. The adaptation of the resource assignment is an interesting research topic that could be studied in the context of self-optimizing networks.

3.5.3 Application to IEEE802.16j

Figure 3.11 depicts the frame structure for a RN in non-transparent mode. In non-transparent mode the RN acts like a BS sector and transmits its own Uplink (UL) and Downlink (DL) MAP to signal resource allocation to the MT. The RN receives control information and user data during the DL access zone from the BS and forwards it to MTs in the Relay Access zone. The IEEE802.16j standard [5] allows already a dynamic resource assignment in the time domain by varying the length of the relay zone. Further, the BS or multiple RN can share the same resource (slots in 802.16 terminology).

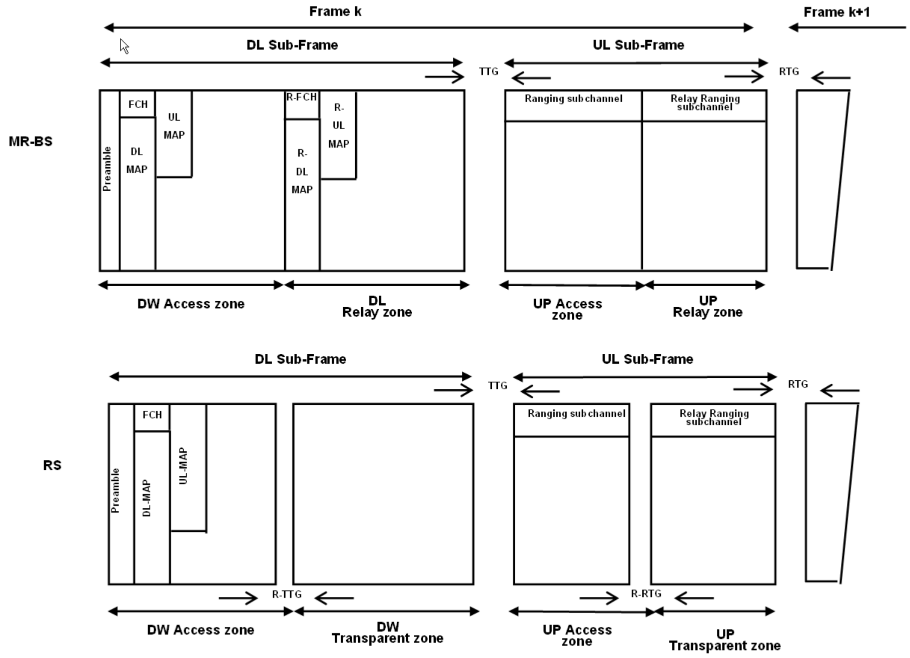


Figure 3.11: WiMAX frame structure in non transparent operation mode (RN is denoted as RS in WiMAX terminology).

However, no mechanism has been standardized for dynamic resource assignment in the frequency domain. For the case of dynamic resource sharing the resource assignment in frequency domain can simply be done by signaling chunks (subchannels in WiMAX terminology) that should not be used by a RN. For soft-frequency reuse, in addition the power mask to be applied for chunks has to be signaled. Thus, with small additional signaling the 802.16j standard can support the flexible resource assignment proposed in this article.

3.6 Cooperative Relaying as an Add-On

Next to the flexible resource assignment, cooperative relaying is a crucial technology to enhance the capacity of a relay enhanced cell (REC). In the DL of conventional relaying, the data is first transmitted from the BS to the RNs and then in a second phase the RN forwards this data to the MT. Cooperatively served MTs receive the signal from multiple cooperating radio access points (BS-RN or RN-RN cooperation). Cooperative relaying should only be applied for MT that can benefit from the cooperation, i.e. if the link from the cooperating radio access points is of similar quality.

Most cooperative relaying schemes in literature combine the transmission of these two phases. However, in a multiple-antenna based system this implies that dedicated multi-antenna techniques cannot or only partially be applied, e.g., beamforming and other space division multiple access (SDMA) algorithms, since one stream is only optimized to one destination. Furthermore, as we assume an “intelligent” deployment, the achievable data rate on the BS-RN link is likely to exceed the data rate on the RN-MT links. However, to enable cooperation on the physical layer the same modulation and coding scheme or only a limited set of very specialized and sophisticated modulation and coding schemes can be used.

Thus, in WINNER, we have not only considered cooperative relaying that exploits large scale spatial diversity but we have mainly investigated cooperative relaying, where multiple radio access points (RAP) form a Virtual Antenna Array (VAA) [90]. Any multi-antenna transmission technique, including spatial multiplexing, that is used in the system can then be applied for example to the BS antennas augmented by the antennas of a RN. The results in [91] illustrate that MIMO cooperative relaying based on distributed LQ pre-coding as described in [92] increases the fifth percentile of the user throughput cumulative distribution function by 90% compared to single path relaying.

3.6.1 Resource Allocation for Cooperative Transmissions

In our cooperative relaying proposal, presented in [20] and [25], the first common node in the tree topology schedules the cooperative transmission. Thus, in a network that is limited to two hops, the BS allocates resources to all cooperative transmissions. The resource allocation is done in a similar way as for MT served by the BS. Similar feedback information, e.g. Channel State Information of the cooperative channel, is used to optimize the resource allocation.

The BS then sends the resource allocation and the selected transmission mode (MIMO transmission scheme, pre-coding weights, modulation and coding scheme for different streams, etc.) together with the data to the RN(s). Both BS-RN cooperation and RN-RN cooperation are supported. Figure 3.12 illustrates the resulting restrictions at the RN from cooperatively served MT. The RN has to take these restrictions into account when allocating resources to the MT served solely by the RN within the resources assigned by the dynamic resource assignment procedure described in Section 3.5.

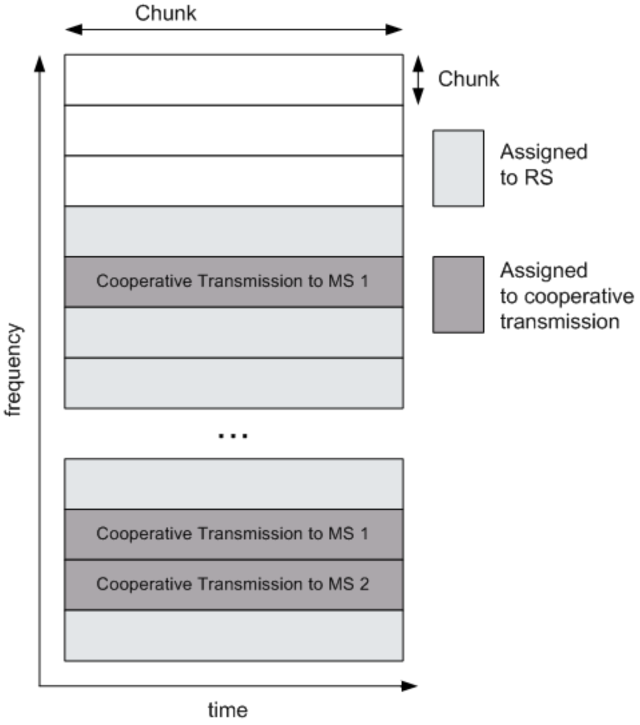


Figure 3.12: Scheduling restrictions at the RN. The RN receives resource allocation for cooperative transmissions from the BS. Together with the flexible resource assignment they put restrictions on the resources the RN can use to schedule non-cooperatively served MT.

Next to data transmissions the MT have to receive control information. In our cooperative relaying proposal the control information is not transmitted cooperatively but each MT has a serving radio access point which can be the BS or a RN. In either case, the serving radio access point performs retransmissions, transmits the broadcast channel, receives feedback from the MT and signals the resource allocation to the MT.

One of the big challenges in the design of an OFDMA system with frequency adaptive scheduling is to keep the signaling load low, while still capturing most of the potential frequency domain scheduling gain. In the case of cooperative relaying this is even more challenging when a RN is the serving radio access point. All the feedback signaling has to be forwarded by the RN to the BS and the resource allocation has to be sent to the RN before it can signal it to the MT. The resulting additional delay will restrict the applicability of frequency adaptive scheduling to lower speeds, e.g. to stationary MT and MT at walking speed.

Please note that this scheme can easily be extended to multi-hop networks with more than two hops. In this case the role of the base station is taken by the first common node in the tree topology. However, in practice to limit the delays for cooperative transmissions this node should be reached by one hop.

3.6.2 Cooperative RN selection

Cooperative relaying gives the most benefits if the signals from the cooperating radio access points have similar strength. Therefore, in WINNER it has been proposed that the BS uses handover measurements of the MTs and a static version of the REACT algorithm [93] to identify potential cooperative radio access points. If no candidates are found, then the MT is served directly by a RN or the BS.

3.6.3 Application to IEEE802.16j

The 802.16j standard [5] also specifies the possibility for cooperative BS-RN transmissions. It mentions two basic possibilities: *cooperative source diversity* (repetition coding) and *cooperative transmit diversity* established through distributed space–time block coding (STBC) and a combination of both. We propose a much more flexible scheme that supports also RN-RN cooperation and any MIMO scheme that is used in a system. Thus, major additions would be required to the standard in order to support our concept.

3.7 Relay ARQ

Transmissions over multiple hops should result in the same reliability as over one hop to guarantee a required maximum residual packet error rate. In order to achieve the required maximum residual packet error rate over multiple hops with a separate retransmission protocol on every hop, the residual packet error rate on each hop has to be even lower than in the single hop case. This could only be achieved with higher overhead than in the single hop case.

In order to increase the reliability of a link with low overhead it has been proposed to introduce and inner and outer Layered Automated Repeat Request (ARQ) process for single hop transmissions. The inner ARQ is based on hybrid ARQ (HARQ) with fast feedback and lower code protection to save overhead. The outer ARQ feedback uses a higher code protection and is mostly used to recover from HARQ errors, e.g. a Not Acknowledged (NACK) interpreted as Acknowledged (ACK). Moreover, the outer ARQ in relay networks can be enhanced by incorporating an end-to-end ARQ process that terminates in the BS and MT. Thus, the BS is aware of the packets that have been acknowledged by the MT and this information can be utilized to support resource efficient (and lossless) handovers. The resulting ARQ processes are depicted in 3.13.

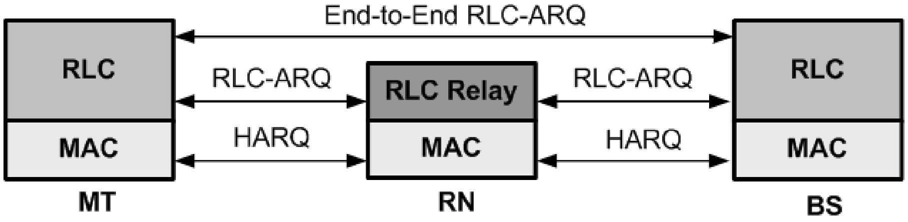


Figure 3.13: ARQ processes in relay network to ensure reliable data transmissions.

In WINNER we have decided to utilize an outer-layer RLC-ARQ not only between BS and MT but also at the RN. The benefit of this approach is that the ARQ process may be used for local error recovery over multiple hops which leads to faster recovery (HARQ errors on the second link will only lead to retransmissions on the second link).

Moreover, to support handovers the BS will only need to poll the RN for the MT status (if needed the RN may poll the MT for its status). Secondly, the BS can poll the RN for its buffer status to see the differences between packets acknowledged by the RN and the MT. This information can be used for flow control, i.e. if the difference is high, the BS will reduce the data rate for the flow to the RN. Depending on the frequency of polling, we have identified two options for RLC-ARQ at the RN in WINNER:

- Case 1: We have proposed in [32] to poll the RN or MT packet buffer status separately, using one bit in the request to distinguish between them. Similarly, in the status report one bit in the RLC-ARQ message indicates whether the RLC-ARQ feedback is sent on behalf of the MT or the RN.

- Case 2: Two bits per entry are used to indicate the packet buffer status for both, the RN and the BS/MT. That is, outer-ARQ is enhanced with Relay-ARQ at the RN (i.e. the RN may respond to the transmitter with either NACK (not received by peer), RACK (received by peer but not by the final receiver), or ACK (received by final receiver). See [94] for more details.

Our proposal has been included in the IEEE802.16j standard [5]. It reduces the overhead compared to case 2 when the hop outer ARQ at the RN is mainly used to recover from errors of the inner HARQ between BS and RN, e.g. NACK to ACK errors. Instead of using the RLC-ARQ feedback for flow control a simple stop and go signalling can be used, i.e. the RN sends a stop signal to the BS if the buffer for a flow to a MT exceeds a threshold.

Combining the acknowledgements of the RN and the MT reduces the overhead if frequent polling is implemented, since only one message has to be sent. Thus none of the options has been selected as preferred option, but one of them should be implemented in a relay based deployment.

In WINNER we have mainly considered relay networks with two hops. In cases where packets are transmitted over more than two hops the additional delay from retransmissions on each hop can be significant. Therefore we proposed in [35] to use retransmissions preferably for the access link between RN and MT which experiences typically the most challenging interference situation and has the lowest link quality. This can be achieved by setting a lower target packet error rate for links between the BS and the RN than for the access link.

3.7.1 ARQ for Cooperative Transmissions

In general it is not so straightforward to find an efficient ARQ protocol for cooperative relaying that ensures reliable communication. If the BS waits for all the first hop acknowledgements and performs first hop retransmissions before scheduling the cooperative transmission, the delays and the signalling overhead will be increased. Therefore we have proposed an ARQ protocol in [16], where a RN only sends a NACK for a first hop transmission if it is the serving radio access point and if it does not receive an ACK from the MT.

Figure 3.14 illustrates the ARQ protocol for the challenging case of a RN-RN cooperation in downlink. When allocating transmission resources to cooperative transmissions the BS assumes that the first hop transmissions have been successful and it can schedule them accordingly. Thus, no additional delays are introduced. The RNs that successfully decoded the first hop transmission participate in the cooperative second hop transmission. Please note that this procedure will only work well for a low error probability on the first hop. For the case of fixed RNs the channel quality will be stable and it should be possible to keep the error probability low.

The acknowledgments of the MT are forwarded by the serving radio access point to the BS. If necessary the BS retransmits the first hop transmission and the serving radio access point uses its allocated resources for non-cooperative transmissions to perform retransmissions.

3.8 Relays in Multi-Band Environment

The additional demand for spectrum, to provide the total capacity needed for delivering the predicted services and traffic in 2020, has been estimated to be 1280-1720MHz for a low and high user demand scenario in the ITU-R studies [95] [96].

The newly identified spectrum for IMT-systems at the World Radiocommunications Conference (WRC'07) in 2007 comprises the following spectrum bands: 450-470 MHz was identified globally, 698-802 MHz was identified in the Americas and some Asian countries, 790-862 MHz was identified in Europe, Africa and most Asian countries, 2300 - 2400 MHz has been identified globally, and 3400 - 3600 MHz was identified in most countries in Europe and Africa, and in several countries in Asia. In addition IMT-Advanced systems can also operate on bands that are currently allocated to 2nd and 3rd generation communication systems.

Consequently, it would be advantageous for IMT-Advanced systems to be able to operate in multiple bands. They can use these multiple bands for balancing the load of the networks or for providing required quality of service levels. It is also predicted that

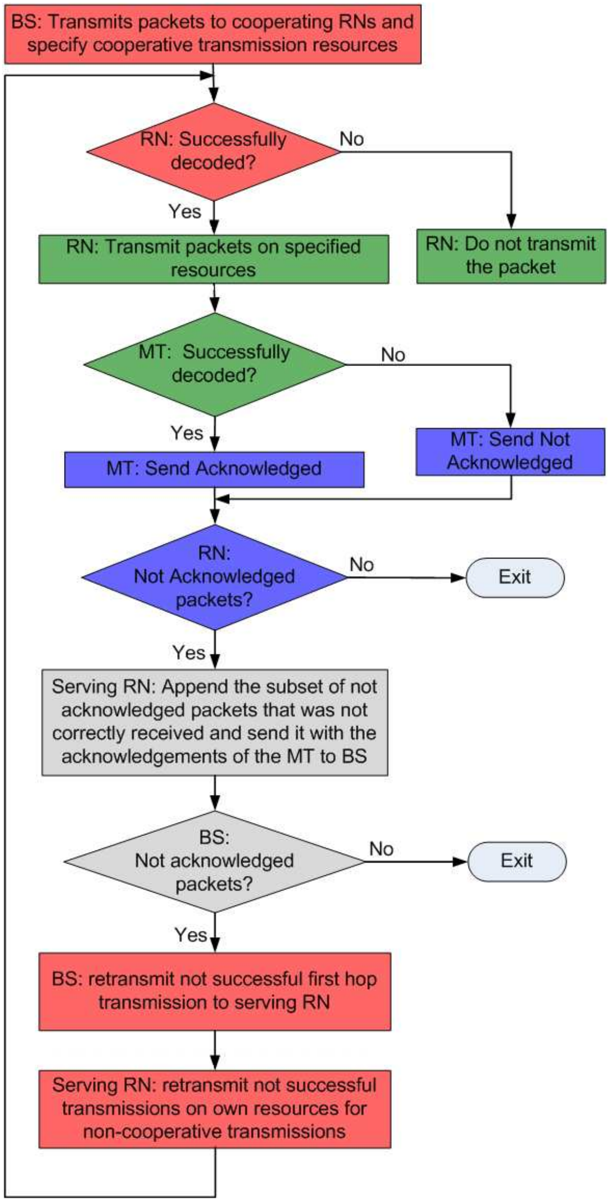


Figure 3.14: Proposed ARQ procedure for cooperatively served MT in the case of RN-RN cooperation. Only the serving RN will perform retransmissions.

some of these bands, here referred to as basic (B) bands, might be dedicated to specific services or operators, and that other bands, the extension (E) bands, might be shared between different operators and/or different services (e.g. mobile communications and fixed satellite services (FSS)).

Sharing the spectrum with other radio technologies is seen as a promising technique for increasing the spectrum utilization [97]. However, flexible and fast mechanisms for band transfers are required when the extension bands are (temporarily) unavailable. In [23], [27] and [36] we have introduced a Multiband Scheduler (MBS) which enables fast switching between bands. The MBS is located in the medium access control (MAC) system layer, which controls the physical layer, including the radio resource allocation, the spatial processing and the packet scheduling [98]. The functional blocks of the MBS are depicted in Figure 3.15. It schedules protocol data units (PDU) to the correct band, enables fast switching to other bands, the transfer of HARQ buffers and provides functions for load balancing between the bands.

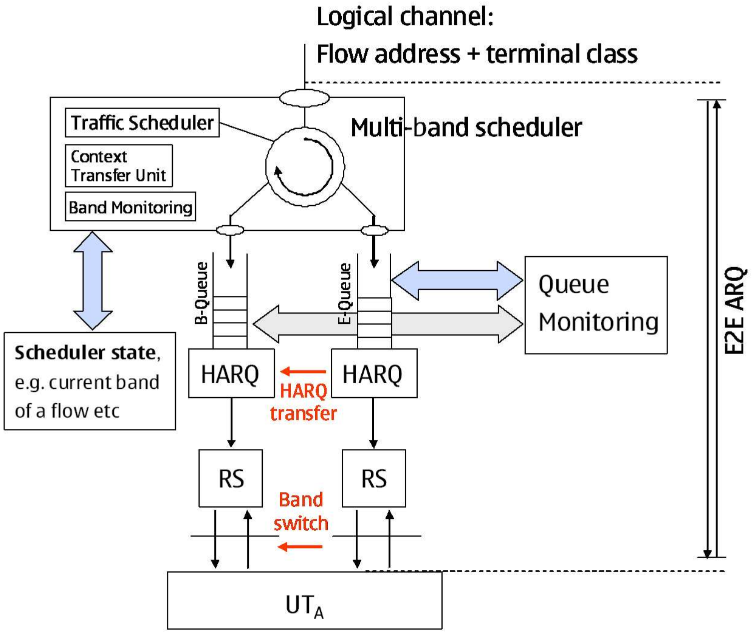


Figure 3.15: Multiband scheduler.

In [23] and [27] we have also discussed how to utilize RNs in multiband operation to balance the coverage area of different frequency bands. Bands with lower center frequency have better propagation properties (larger ranges) than higher frequency bands, and RNs are a cost efficient way to extend the coverage area of the higher bands.

For an example spectrum allocation in Figure 3.16 a BS is able to provide wide area coverage on the basic (B) band at 860MHz. However it cannot cover the same area with the shared extension (E) band at 3.4GHz because of the differences in the propagation loss due to the different carrier frequencies.

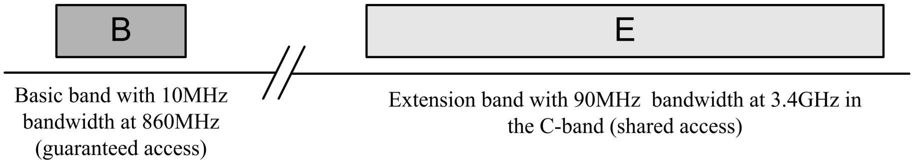


Figure 3.16: Possible spectrum allocation for IMT-Advanced in a multi band deployment.

A RN may operate in only one or in several spectrum bands. In the first case an MBS is needed only at the base station (BS). In the latter case an MBS can also be beneficial at the RN. A RN with an MBS can receive PDUs from the BS on the higher-capacity band and forward them to the mobile terminal (MT) using any band. For the example spectrum allocation in Figure 3.16 a RN equipped with a B-band interface can provide for instance the outdoor-to-indoor coverage for a sparse BS deployment.

Figure 3.17 illustrates the case where the RN closest to the BS is equipped with an MBS and therefore packets that should be transmitted on the B band to the MT by the RN can be received on the E band. Typically the E band offers higher capacity than the B band. Thus, it is beneficial to use the E band on the BS-RN link, even if the RN serves the MT on the B band. Here the MBS allows balancing the load of the two bands on the link between the BS and the RN.

When combining an MBS with relays the experienced delays in the network should still meet the set requirements. The end-to-end delay between two peer IP entities should not be higher than 20ms (this is the maximum delay for highly interactive services [99]). To achieve this, for example a delay of maximum 10ms is required over the air interface itself (as in 3GPP-LTE [100]). Thus, there is not much delay budget available for the combination of multiband operation and relaying. As we have shown before, relays add an additional delay of at least one MAC frame to the network.

Allowing one retransmission over two hops and assuming an air interface transmission delay of 1 ms, the delay budget can then be determined as follows: one transmission on each link, plus one feedback message and a retransmission adds up to 4 ms plus additional processing delay, leaving a margin of only 6 ms for multiband operation at both the BS and the RN, if both operate on multiple bands. Therefore, the efficient multiband operation enabled by the multiband Scheduler will be crucial to exploit the benefits of multiple bands

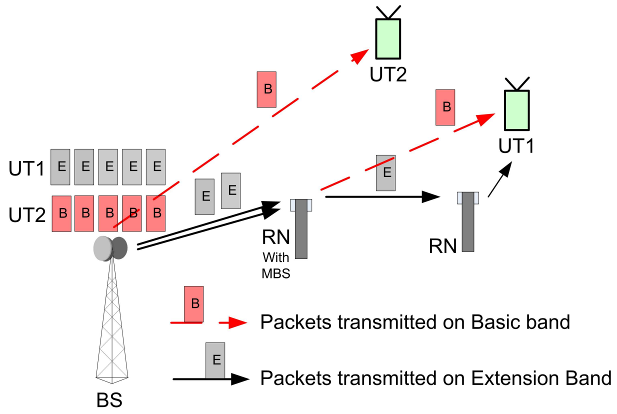


Figure 3.17: Packet delivery in a network with MBS at the RN. The RN receives on the high capacity E band and forwards delay sensitive traffic on the B band to the MT. Non-delay sensitive traffic can be forwarded to another RN and then to the MT on the E band.

in relay networks.

Next to single path relaying, cooperative relaying can be integrated as an add-on to single path relaying as proposed in Section 3.6. Thus, it is important to show, that the MBS concept fits well with cooperative relaying.

Multi-hop diversity is one example, in which a receiving node combines the signals received from previous nodes in the path. In a 2-hop DL path, the MT combines the signal from a RN with the signal from the BS that can be received on different resources. MIMO cooperative relaying is another example, where the BS first transmits the data to be forwarded in a cooperative transmission to the RN. Then the BS and the RN antennas form a virtual antenna array and perform a joint MIMO transmission on the same resources.

In both cases the BS allocates the resources for all the cooperative transmissions, i.e. even in a case where the RN is equipped with an MBS, the BS also decides on which band and resources the cooperative transmissions will take place. For the multi-hop diversity case, cooperative transmissions could in principle be scheduled on two different bands requiring the MT to be associated with two bands at the same time which increases the MT complexity and power consumption.

Thus, cooperative transmissions on different bands should be avoided and the BS has to balance the gain from utilizing cooperative relaying and from using different bands on the first and second hop. However, as described above, by using the HARQ context transfer, retransmissions can be performed on another band and additional diversity gain can be obtained without requiring the MT to operate simultaneously on two bands. This is not an issue in the MIMO cooperative relaying case, where the BS can send for example data on the E band and then perform a joint MIMO transmission on the B band, whereas the MT only receives on the B band.

3.9 Resource assignment for more than two hops

In WINNER the main focus has been on two hop relaying. In recent years there has also been a lot of interest in high performance wireless multi-hop networks with more than two hops to cover metropolitan areas. However, most of the research effort was concentrated on sensor and ad-hoc networks with the main goal of energy efficient multi-hop communication [101], [102] and [103].

Wireless mesh networks based on WiFi technology have already been deployed in cities such as San Francisco, Minneapolis, Oklahoma city or Philadelphia and mesh networks are standardized in IEEE802.11s [104]. Even though most of these deployments failed to be a commercial success there is still interest in these networks. For example, some municipalities have acted as anchor clients for the network ensuring revenues for the provider. Others have focused on the use of the WiFi network as utility for police, fire brigade and other public needs, e.g. automated meter reading [105]. Further, a start-up company called Meraki tries to grow municipal WiFi networks organically with the help of the users who deploy wireless routers themselves [106]. Typically these networks utilize a standard IEEE 802.11 air interface for the access link while the relay links can use a proprietary protocol.

In [37] we have proposed to organize the infrastructure network in a hierarchical tree structure which operates in time division duplex. The traffic is divided into downlink traffic from the BS to the MT and the uplink traffic from the MT to the BS. The tree structure reflects the physical topology of the infrastructure nodes that forward the traffic to the MTs. In TDD mode, a single node cannot simultaneously transmit in downlink and receive in uplink. Therefore we divide the operation of the mesh network into four phases. The phases are arranged in such a way, that in each phase the nodes of one group are transmitting and the nodes of the other group are receiving.

Figure 3.18 illustrates the four phases of the mesh network operation. The BS and the second tier RNs form one group and the first tier of RNs form the second group. A third tier of RNs would belong to the second group and a fourth tier of relays to the first group

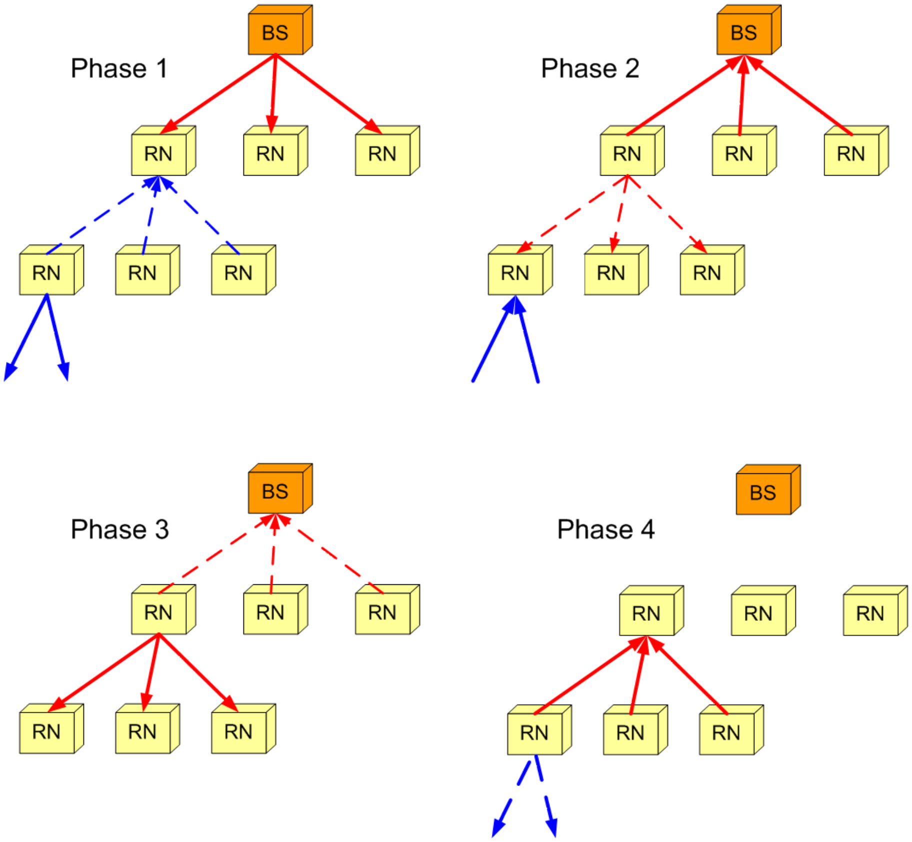


Figure 3.18: 4 phase operation with fast ARQ using OFDMA control sub-channels for acknowledgements (dashed lines).

and so on. In phase one the first group (solid arrows) is transmitting in downlink and in phase two the second group is transmitting in uplink. In phase three the second group is transmitting in downlink and finally in phase four the first group is transmitting in uplink. Typically in wireless communication systems there is an imbalance between uplink and downlink traffic. Therefore we propose to adjust the amount of MAC frames assigned to uplink and downlink phases depending on the needs in the network.

The operation mode has been especially designed to enable efficient mesh network operation. Every receiving RN has one phase time to decode the received data, before its next possibility to forward the data. For example the first tier RNs receive the downlink data in phase one and forward the downlink data in phase three. They receive the uplink data in phase four and forward the uplink data in phase two. Our proposed four phase network operation as such is not optimal for fast ARQ mechanism. For example, the first tier RNs receive the downlink data in phase one and during phase two they decode the data. Especially for cases where the UL phase uses only one MAC frame (0.7ms in WINNER), the RNs might not be able to decode the data and send acknowledgements before the end of phase two. The next possibility to send the acknowledgements is then only in the next phase two. Therefore, we propose to make use of OFDMA to reduce the ARQ delays. The dashed lines in Figure 3.18 illustrate our proposal. For example the first tier RNs receive the downlink data in phase one and will transmit in downlink in phase three. While transmitting the downlink data they will use dedicated control sub-channels to transmit the acknowledgements for the downlink data received in phase one to the BS. The same mechanism is used by all nodes in the mesh network and the acknowledgements can be sent up to three phases earlier than without the possibility for fast acknowledgements.

The hierarchical operation mode offers several advantages. Clear defined transmission and reception phases allow RNs from one layer to transmit/receive to/from every node in the next layer where a route is established. Thus, the transmitting/receiving node can utilize sophisticated multi-antenna techniques, i.e. multi-user precoding in downlink and spatial division multiple access (SDMA) in uplink to maximize the throughput. Especially close to the BS the traffic will accumulate and very high throughput is needed. In contrast to a distributed control approach based on the 802.11 MAC [107] the delays in the network will be predictable and will remain fairly constant up to a certain network load. As the phases are an integral part of the system, it does not have to be signalled (only changes in the UL/DL split have to be signalled) and the signalling load can be reduced. The phased operation supports very well the scheduling of “regular” traffic (e.g. VoIP).

Assuming for example that a single WINNER MAC frame with a duration of 0.69ms includes both a downlink and an uplink phase, a successfully received packet can already be forwarded in the next frame. Thus, each hop adds only about 1ms delay. To further reduce the delays it is possible to combine the last two hop transmissions by using amplify and forward relaying to immediately forward the last hop transmission as we have proposed in [38]. However, this requires that the second last hop transmission uses the same transmission format as the last hop.

3.10 Relay Handover

Some additional signaling is required if a RN is involved in a handover process. A typical flow chart of a handover between RNs of the same cell is depicted in Figure 3.19. The handover candidates have to be forwarded by the source RN to its serving BS. The BS then decides on the target radio access point (RAP). If the target RAP is a RN of another cell, the handover request has to be sent to the BS of the other cell and the BS of the other cell then forwards it to the target RN. The target RN confirms the handover request and the BS sends the confirmation to the source RN which forwards it to the MT. Some of this signaling is over the air and will add additional delay to the handover process. In order to save time the handover confirmation can be sent by the BS, because it is aware of the operational state of the RNs in its cell. In addition to the signaling delay, some additional delay will be caused by the forwarding of the data packets from the BS to the target RN. More details on the handover process can be found in [15].

The common sequence numbers for RLC PDUs at the BS and the RN and the end-to-end ARQ process between the BS and the MT ease the handover process. The same end-to-end ARQ process can be continued in case of an intra-REC handover and a PDU context transfer can be performed by the BS without requiring a data transfer from the source RN to the BS. Further, the BS can poll the source RN for its buffer status and can delay the handover in order to empty first the buffer of the source RN.

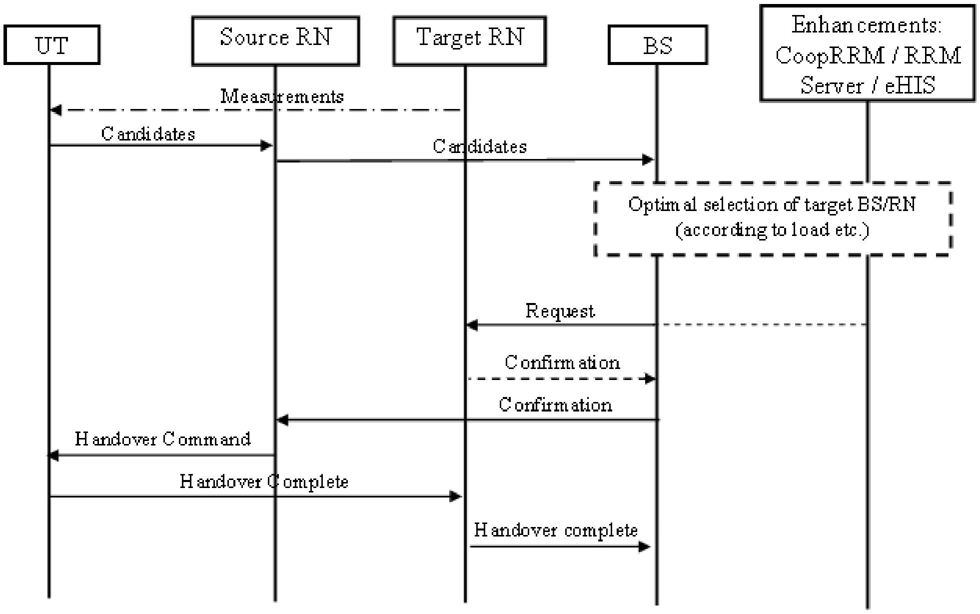


Figure 3.19: Radio handover flow chart for a handover between two RN in the same cell.

3.11 Summary and discussion

In this Chapter we have introduced some selected functions which are crucial for the performance of cellular relay networks. In particular we have presented our work on dynamic resource assignment in relay enhanced cells, on the integration of cooperative relaying into the WINNER relaying concept, on ARQ in relay networks and on multiband operation of relay networks.

The radio resource management (RRM) in a relay network should be flexible enough to adapt to different modes of operation. The relays can be used to increase the coverage area, increase the capacity in the cell or to cover otherwise shadowed areas. In WINNER we have investigated several scenarios including a wide area, a metropolitan area and a local area deployment. We developed a dynamic resource assignment framework that is flexible enough to accommodate all of these different scenarios. The framework allows a coordination between different radio access points in the frequency, spatial and time domain. For the metropolitan area we have proposed to utilize soft frequency reuse to coordinate the interference between neighboring radio access points in the frequency domain. In addition we have presented an interference aware scheduling scheme that aims to exploit the SINR variations introduced by soft frequency reuse. We have also presented the necessary additions to apply the framework to the IEEE 802.16j standard specifying relays for WiMAX. Thus, the schemes presented in this Chapter can be applied to WiMAX relay networks as well.

In the WINNER relaying task we have identified cooperative relaying as a promising technology option to enhance the performance of a relay network. However, the system integration of cooperative relaying into a cellular network has not received much attention so far. As an example, in the 802.16j standard cooperative relaying is specified only for transparent relays, i.e. relays that do not transmit control information. We propose to give the control of the cooperative transmissions to the first common node in the tree topology. Using the first common node ensures short delays and gives flexibility in the nodes that can cooperate. As a consequence, cooperative relaying is not restricted to BS-RN cooperation. Further, we assigned the role of the serving radio access point to one of the cooperating nodes. The serving radio access point signals control information, such as the resource allocation to the cooperatively served MT and performs retransmissions which are not done cooperatively. This enables fast retransmissions since there is no coordination between the cooperating radio access points needed.

The integration of relays into a cellular network requires a careful cross-layer design and many functions have to be designed with relays in mind. In particular we have presented an end-to-end relay ARQ scheme that ensures reliable data communications without excessive overhead which has been included in the IEEE802.16j standard [5]. In addition to a reliable end-to-end connection, it allows the relay to send outer-layer acknowledgements. The relay can for example use one bit to indicate that the feedback message did not originate from a MT but from the RN. The additional bit is only needed in the network and it does not increase the amount of data transmitted by the MT.

We have introduced a new concept called Multi-Band Scheduler (MBS) for future communication systems. The MBS allows for operation on multiple bands in a delay constrained environment. The proposed tight integration between multiple bands enables a fast and seamless switch between different bands. The operation of the MBS was discussed in detail for a relaying scenario with different propagation properties and thus different coverage area of the used bands. In this scenario RNs are used to extend the coverage of the high capacity extension band that has a higher propagation loss than the basic band.

To sum up, we have presented a selection of enabling technologies for an efficient and reliable operation of relay networks. In Chapter 4 we will present a large set of performance assessment results for the proposed technologies.

Chapter 4

System Simulations

4.1 Introduction

In this Chapter we will present system simulation results on the performance of relay networks. We will focus on the techniques introduced in Chapter 3, in particular dynamic resource assignment, soft frequency reuse and multiband operation. Further, we will present a cost comparison of relay networks to BS only deployments in a metropolitan area network.

In Section 4.2 we will give a short introduction to the tools commonly used to evaluate the performance of cellular networks. We will motivate our choice of using a dynamic system simulator for assessing the performance of relay networks and we will briefly introduce the simulation tool.

To be able to compare results of different research groups without implementing each and every alternative it is beneficial to have a standardized evaluation scenario. For base station based deployments such evaluation scenarios exist. However, no such widely accepted scenarios exist for relay deployments and the results of different research groups are not comparable. Therefore in WINNER three relay deployment scenarios have been developed that can serve as a reference, a wide area, a metropolitan area and a local area scenario. In Section 4.3 we will present the metropolitan area scenario where the main focus of our work has been.

In Section 4.4 we present the performance assessment results. The main focus has been on the downlink performance of relay deployments in the metropolitan area test scenario. We compare the performance of relay networks to BS only deployments with dynamic resource assignment and find the BS to RN cost ratio for which a relay based deployment is more cost efficient. Further, we present the performance gain achievable from multiband operation with RNs. All results have been obtained with parameters from the WINNER system. Nevertheless, these assessment results give also insights on the potential benefits from relays for Orthogonal Frequency Division Multiple Access (OFDMA) based cellular systems like WiMAX, 3GPP LTE and 3GPP2 UMB.

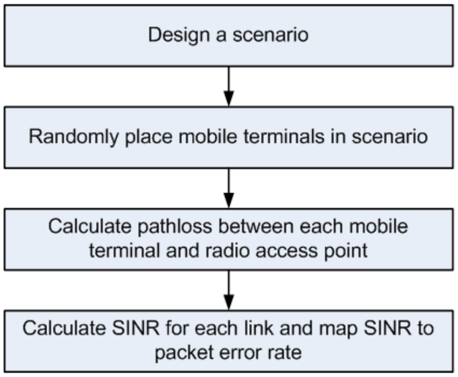
In Section 4.5 we will give a brief review of system performance results for cellular relay networks available in literature. Moreover, we will compare our results and assumptions to these results.

4.2 System Simulation Tool overview

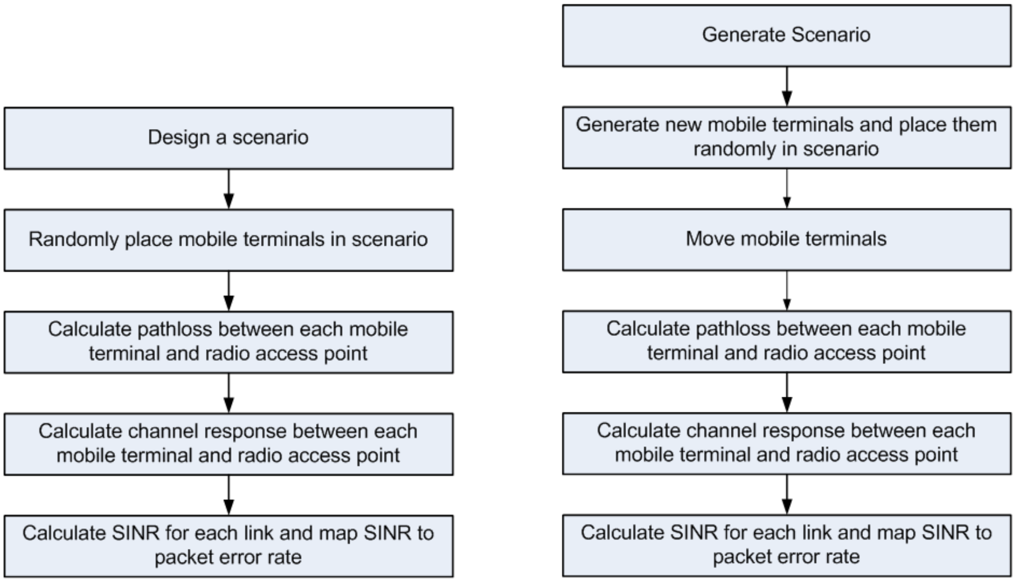
System simulation tools try to capture the main effects that affect the performance of wireless networks. When the network size grows, it is not feasible to model all aspects of every link explicitly, i.e. the transmitter chain, the wireless channel and the receiver chain. Especially the decoding of the signal requires high computational resources and it is typically modeled by a link to system level mapping as proposed in [108].

The most complex task of a system simulator is to calculate the Signal-to-Interference plus noise ratio (SINR) for each receiver in the wireless network. For example in a network with 144 access points and 2000 mobile terminals (MT), each time instant requires the calculation of 288 000 signal levels and the calculation of the resulting SINR values even when assuming FDD or synchronized TDD operation with the same uplink/downling switching point in the whole network. The signal levels are calculated from the transmit power level, the current shadow fading and fast fading values. The shadow fading (also called large scale or slow fading) and fast fading values (also called small scale fading) are calculated from models such as the WINNER model [109]. Typically a system simulator spends up to 90% of the computational power on the calculation of the Signal-to-Interference ratio of each receiver in the network.

Since the SINR calculation requires most of the processing power, system simulators try to simplify this task. We can distinguish three different classes of system simulators depending on the assumed MT mobility. Figure 4.1(a) depicts the main steps of the SINR calculation for a static, Figure 4.1(b) a semi-static and Figure 4.1(c) a dynamic system simulator. All simulators start first with the generation of the scenario, i.e. the location of the BS and RN following for example the test scenario presented in Section 4.3.1. Then the MTs are randomly placed in this scenario.



(a) Static Simulator.



(b) Quasi-static simulator.

(c) Dynamic simulator.

Figure 4.1: Flowchart of SINR calculation for different classes of system simulators.

Static simulators assume stationary MTs. The slow fading and fast fading values are calculated at the beginning of the simulation and kept constant during the whole simulation run. The MTs do not change their position during a simulation run and multiple simulation runs ensure that a sufficient amount of statistics is obtained. Static simulations have the shortest simulation time and the results converge faster than for semi-static or dynamic simulators. Static system simulators are commonly used to obtain for example cell throughput or coverage results for different deployment options or transmit power levels to quickly compare different BS and relay placements.

Semi-static system simulators assume stationary MTs with constant shadow fading calculated at the beginning of the simulation run. The fast fading is fully modeled but handovers between different radio access points are not modeled. The MT speed affects the speed with which the fast fading values are changed. Again the MTs do not change their position during a single simulation run and a sufficient amount of simulation runs ensures that the obtained statistics are meaningful. Semi-static system simulators are commonly used for example in 3GPP standardization to study radio resource management strategies or multi-antenna techniques.

Dynamic system simulators model the full user mobility. For example outdoor users move along streets with some probability of turning at street crossings in a metropolitan area scenario, modeled by the Manhattan grid. Thus, a dynamic simulator should model the time evolution of both shadow fading and fast fading. The results can be obtained in one or multiple simulation runs. A single simulation run should be sufficiently long to cover the effects of time correlation in the network. If only one simulation run is used, a sufficient amount of user mobility is required. Alternatively, calls can be ended and new calls are created whereas a short call duration ensures that a high amount of calls is generated during a simulation run. However, the call duration cannot be chosen arbitrarily and should follow a model derived from user observations.

It can be easily seen that dynamic system simulators are the most complex class of system simulators. In the following we will argue why it is still the preferred class of simulators when studying relay networks. A dynamic system simulator is the only simulator within these classes that captures the effect of handovers in the network. Typically in a cellular network with only BSs it can be assumed that the user context is transferred between the BSs and the handover is lossless, i.e. no user data is lost. Thus, the impact of handovers to the cell throughput and user experience is quite small. However, in a relay network the user data has to be forwarded to a relay node (RN) when the MT is served by a RN. If too much data is forwarded to the RN and the MT performs a handover to another RN or BS, this data is typically lost. The excessive data has used resources from the BS and the other RNs in the transmission path. Thus, it will be visible as reduced cell throughput. Secondly, the sub-cells formed by relays in the network decrease the cell size and handovers will be more common than in deployments based on BSs only.

In addition to the effects from user mobility, the assumed traffic models have a great impact on the performance of the wireless network. For static and semi-static simulators typically a full buffer traffic model is assumed, i.e. the MT buffer is always full and it is not limited in size. In real world situations the traffic generated by a user will depend on the application. Commonly used models include the transfer of a file with fixed size using a file transfer protocol (FTP), streaming, Voice over Internet Protocol (VoIP) and web browsing. A set of such traffic models can be found for example in the draft cdma2000 evaluation methodology document [110] or in the traffic models document for IEEE802.16 MAC/PHY simulations [111].

In combination with the traffic models also the effects of higher layer transport protocols should be modeled. For example the slow start feature of TCP/IP will cause a drastic rate decrease after a handover in the wireless network. It interprets the short disruption in the connection due to the handover as network congestion and it will slowly start to increase the data rate from a low level. While this works well for wired networks, it causes a significant degradation to a wireless network with frequent handovers.

It is difficult to separate the effects of the traffic models from other effects in the network. Since we have been mostly interested in comparative studies of different resource allocation and interference coordination strategies for OFDMA based systems, we have used only full buffer traffic models. Together with a maximum throughput scheduler the full buffer traffic model will generate the highest possible cell throughput in the network. To introduce some fairness among the different users we follow the proportional fair principle. The proportional fair scheduler has been introduced in [112] and extended to multicarrier systems in [113].

When comparing the performance of BS only deployments with relay based deployments the effects of handovers are visible in the simulation results even though the interaction with higher layer protocols such as TCP/IP are not considered. Nevertheless this interaction should be carefully studied and the results should be used when designing handover procedures for relay networks.

In the following we will describe the operation principle of the dynamic system simulation tool together with details on some selected functions relevant for our work.

4.2.1 Simulator description

We utilized a dynamic system simulator to evaluate the performance of relay networks with different resource assignment schemes. A flowchart of the steps performed by the system simulator can be found in Figure 4.2.

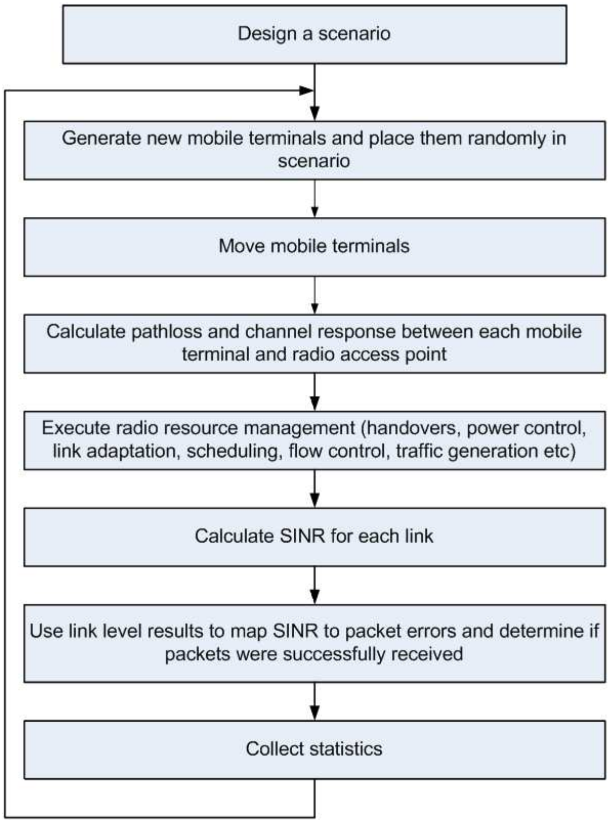


Figure 4.2: Flowchart of the dynamic system simulator operation.

We have already classified the different classes of simulators based on the mobility models and the resulting SINR calculation steps. Now we will focus on some important aspects of the simulator and how it was implemented. In particular we will present some details on the implementation of the scheduling, link adaptation, relay operation and statistics collection.

4.2.1.1 Scheduling

Similar to [88] we introduce a two stage scheduling process as depicted in Figure 4.3. The time domain (TD) packet scheduler selects a specified maximum number of L out of N active mobile terminals (MT) for frequency domain scheduling based on either a round robin or an equal throughput time domain fairness criteria, i.e. selecting the MTs that have not been scheduled for the longest time or the MTs with the lowest average throughput in the last 50ms, respectively.

The second stage frequency domain (FD) scheduler tries to increase the spectral efficiency for the selected MTs using a proportional fair metric as in (3.1).

For the byUser strategy each MT gets an equal share of chunks. First the MT with the

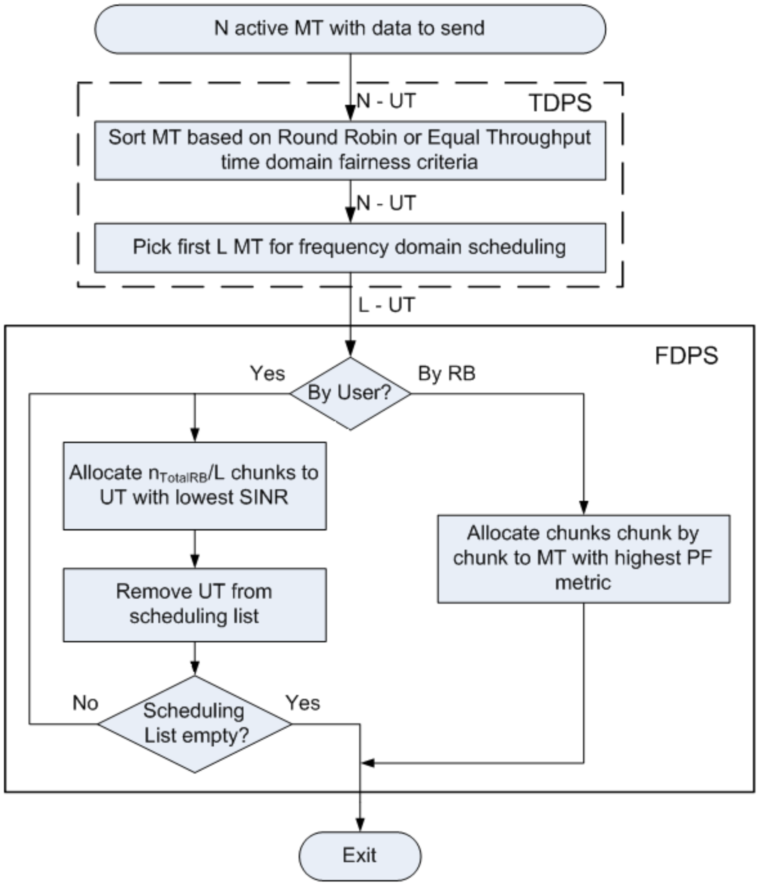


Figure 4.3: Two stage scheduling process. M mobile terminals are selected by the time domain packet scheduler (TDPS) for frequency domain scheduling (FDPS).

lowest overall SINR is allocated its share of chunks, followed by the MT with the second lowest overall SINR and so on until all MT have been scheduled. For the byRB strategy each chunk is allocated to the MT which has the highest proportional fair metric.

These scheduling algorithms have been used as default algorithm. In addition we have proposed and implemented an interference aware scheduler for soft-frequency reuse and fractional frequency reuse which is described in Chapter 3.

The flowchart in Figure 4.3 does not show the treatment of retransmissions. In our simulation we have prioritized HARQ retransmissions. For example in a case where two MTs have pending retransmissions, they will be selected first by the time domain scheduler and for the byUser frequency domain strategy they will be allocated first.

4.2.1.2 Link adaptation

The link adaptation is based on channel state information (CSI) feedback from the user terminal. We assume that the frequency domain scheduler has channel state information (SINR) for each OFDMA resource block (chunk). Based on the channel state information for the chunks allocated by the scheduler a mutual information effective SINR mapping as described in [108] is used to calculate the expected throughput. The modulation and coding scheme maximizing the expected throughput is chosen.

An outer loop link adaptation is used to stabilize the packet error rate (PER) performance [114]. It corrects systematic errors in the link adaptation, e.g. due to fractional load in the network or the used mapping of CSI to the modulation and coding scheme. The outer loop link adaptation generates an offset that is added to the feedback values (CSI) reported by the MT for each resource block. It decreases the offset value by $\Delta down$ for every acknowledged packet and it increases the offset value by Δup for every not acknowledged packet. The relation between $\Delta down$ and Δup depends on the target packet error rate (PER) as suggested in [115]:

$$\Delta down = \Delta up \frac{\mathrm{PER}}{1 - \mathrm{PER}} \tag{4.1}$$

4.2.1.3 Relay operation

Here we present some general aspects of the RN implementation in the simulator. More details, e.g. about the multiband or soft frequency reuse implementation are given together with the results.

The relay inherits both BS and MT functionalities depending on its role assigned by the BS. When it is receiving from or transmitting to the BS it acts like a MT, e.g. the same receiver and transmitter structure is used. When the RN acts like a BS, it performs the same tasks as a BS towards the MTs it serves, e.g. scheduling and link adaptation.

In addition to these functions additional functionalities are needed to control the RN operation. The BS assigns frames to the RN where the RN acts as a BS. In the other frames the RN acts as a MT. This assignment can be done dynamically but in our simulations we use the same assignment throughout a simulation run spanning about 65s of network operation.

The handover procedure is different from the handover between BS. The MT context cannot be forwarded directly to the target BS or RN if the serving radio access point is a RN. Instead the BS forwards the MT context to the target BS or the BS that serves the target RN. The end-to-end ARQ process allows the BS to know which packets have been acknowledged by the MT. After a successful handover the BS tells the RN to empty the buffer for the MT. The handovers are triggered by measurements of the MT. When the MT measures a radio access point (BS or RN) with higher received signal strength it will report it to the serving radio access point. The network will then decide if the handover takes place. Optionally, a penalty value ν can be assigned to RNs so that a handover from a BS to a RN only takes place if the received signal strength is ν dB higher than the received signal strength of the BS. Please note that ν is used in addition to hysteresis values applied in the system to avoid too frequent handovers.

In many cases the BS-RN link will have a higher SINR than the RN-MT link. In order to balance the rate on these links we implemented a simple stop-and-go flow control that depends on the rate of the RN-MT link. The RN sends a stop signal to the BS when the queue size for a MT exceeds ι. The threshold ι depends on the current channel quality of the RN-MT link and is calculated as

$$\iota = nR_{fullBw} \tag{4.2}$$

where R_{fullBW} denotes the predicted rate when the MT is assigned the full bandwidth and n is a parameter, e.g. 2. The threshold ensures that the RN has enough data in the buffer for at least two sub-frames even if there is no second users to be served. The parameter n could also depend on the number of users served by the RN or the maximum time until the RN is able to send a go signal to the BS.

Typically the RN properties are different from the BS and also from the MT properties. For example, the RNs can be deployed below rooftop whereas the BSs are deployed on a mast. The different heights will affect the applicable pathloss equations and different pathloss and channel models have to be used for the BS-RN, RN-MT and BS-MT links. In addition, the RN may have two antennas with different antenna patterns, one antenna to communicate with the BS and the other one to serve its MT. When the RN is powered on, it will associate with its serving BS which is the one having the highest received signal strength. In cases where the RN is exactly in the mid-point between two BSs a directive antenna pattern decides which BS the RN will associate with.

4.2.1.4 Statistics Collection

The simulator collects statistics for all packets, MTs and all radio access points. For each packet it collects the calculated SINR, the chosen modulation and coding scheme, the success of the transmission and whether it was sent to/received from a RN or a BS. Further, the delay until a packet is successfully transmitted is collected. In addition, the average SINR of the received packets depending on the location of the MT in the scenario can be plotted.

For each MT the simulator logs the average throughput over periods of 200ms which are collected in a cumulative distribution function. Next to the period throughput also the overall session throughput is obtained. The statistics can be separated for MTs that are served by a BS and MTs that are served by a RN.

Besides the statistics collected for each packet and each MT, the simulator also collects the overall cell throughput and the cell throughput separated for MTs served by BSs and MT served by RNs.

In simulations without wrap-around, edge effects can distort the results. Therefore, by default all the statistics are only collected for center cells. The period throughput and the session throughput of a MT will only be considered if the MT spends at least 75% of the period or session in a center cell.

4.2.1.5 Default simulation parameters

A selection of the most important default simulation parameters that have been used for most of the simulation results presented in Section 4.4 can be found in Table 4.1.

The test scenarios used in our simulations are described in Section 4.3 and the OFDMA parameters of the WINNER system in Section 4.4. All simulations have been performed utilizing a 6 channel stop-and-wait Hybrid Automated Repeat Request (HARQ) process using Chase combining [116]. The retransmissions have been prioritized over the first transmissions and the target error rate for the outer loop link adaptation was set to 10%. The time division duplex (TDD) network has been fully synchronized, i.e. there is no interference from UL transmissions in one cell to DL transmissions in other cells and vice versa. Around 9000 calls have been generated in each simulation run, simulating 65s of network operation. The MTs move at a speed of 3km/h.

For the first stage of the two stage scheduling process, described above, a round robin time domain scheduler and for the second stage a proportional fair frequency domain scheduler has been the default setting.

Table 4.1: Default simulation parameters

Scenario	Metropolitan area (Wide Area)
Wrap around	No
HARQ	Chase Combining
Prioritized HARQ	Yes
Link Adaptation	Yes
MCS set for user data	BPSK 1/2, QPSK 1/2, 16 QAM $\frac{1}{2}$, 2/3, 3/4, 64 QAM $\frac{1}{2}$, 2/3, 3/4
Target PER	10%
Initial RAP Selection	RAP with highest RSSI
Network synchronization	Fully Synchronized
Traffic Model	Full buffer
Simulation Time	65s of network operation
Call arrival process	Poisson arrivals
Max. number of MT	1500 (9000 calls)
MT speed	3km/h
TD scheduler	Round Robin (ETP)
Number of scheduled MT	$L = 12$
FD scheduler	Proportional Fair

4.3 Test Scenario

Agreed test scenarios among research groups are important to be able to compare each others results without for example implementing each and every proposed algorithm. For base station based deployments the hexagonal grid cell layout with variable inter site distance and the Manhattan grid following the UMTS 30.03 recommendations [117] have been accepted as standard evaluation scenarios in standardization and research. However, no such standard scenarios exist for relay deployments and the results of different research groups are not comparable. Therefore we have developed in WINNER deployment scenarios that can serve as a reference.

The main motivation to deploy relays is to save costs while reaching a similar performance as less dense BS only deployments or to increase the performance of a BS deployment cost efficiently by adding relays. Hence, most of the following design choices are motivated by cost considerations.

In our test scenarios we mainly assume an intelligent deployment with favorable propagation conditions between the BS and the RN, e.g. line-of-sight (LOS) to the base station (BS). This assumption is based on cost comparison studies of relay based and BS only deployments. For intelligent relay deployments studied in [118] and [119] RNs are already cost efficient if the costs are 88% of the costs of a micro BS. Without intelligent deployment the RN cost should be only 6.5% of the BS costs [120].

The number of RNs per BS is an important design parameter that affects both the costs and the performance of the relay network. We have limited the number of RNs to three per BS sector based on the result curves in [118] which do not suggest more than 4 RNs per BS.

To keep the size of RNs small we assume in all scenarios a limited transmit power for RNs and a maximum of two antennas. Small RNs that do not require shelter, cooling and backhaul connection increase the deployment flexibility and allow for example a deployment on lamp posts. Thereby, the site acquisition and site rental costs can be significantly reduced even compared to a micro or pico BS. According to cost studies in [121] site rental and the cost of the transmission line account for more than 60% of the overall costs of a micro BS over 10 years.

Our test scenarios are primarily designed and optimized for two hops (BS-RN-MT) in order to achieve a high performance in terms of throughput and delay. Further, we assume a tree topology to avoid the overhead from complex routing protocols. In the rare case of node failure the RNs can autonomously connect itself to another radio access point in its range.

In the following we present the relay test scenario for a metropolitan area scenario based on micro-cells deployed in a Manhattan grid following the recommendation in [117]. It covers the important case of an operator that wants to upgrade an existing UMTS network and to reuse the existing BS locations.

The test scenario uses path-loss and channel models developed in Phase II of the WINNER project. The properties of the channel model and a comparison to other models can be found in [122]. The path-loss equations and the corresponding channel models can also be found in [109]. Since [109] offers several possible path-loss models for BS-RN and RN-MT links, we have decided to state the path-loss equations for the convenience of the reader. The path-loss models can be applied to carrier frequencies in the range from 2-6GHz.

4.3.1 Metropolitan Area Test Scenario

The metropolitan area test scenario is an urban micro-cellular scenario modeled by a two-dimensional Manhattan grid consisting of 12x12 streets (width 30m) and 11x11 buildings (200m x 200m block size). The BS deployment follows the UMTS 30.03 recommendation [117] with 73 BS deployed below rooftop level (10m height) and placed in the midpoint between two crossroads. Two sectors are formed with bore-sight along the street direction and one antenna per sector (antenna gain 8dBi). The added relays extend the coverage area of these BSs and distribute the cell capacity more evenly.

A single RN is added to each BS site in the midpoint between two BSs (5m height), as depicted in Figure 4.4. Thereby the amount of radio access points is doubled. Our results in Section 4.4 show that adding a second relay per BS site does not increase the cell throughput and hence does not justify the additional costs. The RNs are equipped with two antennas, a directional antenna (antenna gain 14dBi) to communicate with the serving BS and an omni-directional (antenna gain 7dBi) antenna to serve its MTs. Soft-frequency reuse is utilized for interference coordination between the radio access points as described in Chapter 3. The transmit power is limited to 37dBm for each BS sector and to 30dBm for the RNs.

A LOS link is assumed for nodes in the same street and a NLOS link for nodes in different streets and MTs are located inside of a building or in a street. The corresponding channel and path-loss models for all links are specified in [109]: urban micro-cell (B1) LOS for nodes in the same street as in equation (4.3), urban micro-cell (B1) NLOS for nodes in different streets as in equation (4.4) and the outdoor to indoor urban micro-cell model (B4).

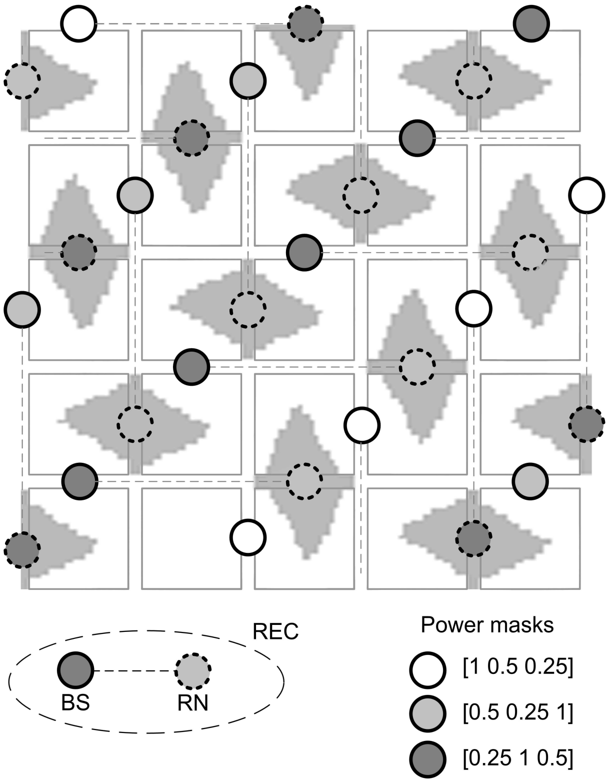


Figure 4.4: Sketch of metropolitan area cell layout with relay stations and assigned soft-frequency reuse power masks. The relay coverage area is marked in gray.

The path-loss in the same street can be found as:

$$\begin{aligned}
\mathrm{PL}_{\mathrm{LOS}}[\mathrm{dB}] =& \max\{22.7\log_{10}(d_1) + 41.0 + 20\log_{10}(f/5.0) \\
& + \sigma, \mathrm{PL}_{\mathrm{Free}}\}, \quad 30\mathrm{m} < d_1 < d_{\mathrm{BP}} \\
\mathrm{PL}_{\mathrm{LOS}}[\mathrm{dB}] =& 40.0\log_{10}(d_1) + 9.45 - 17.3\log_{10}(h_{\mathrm{BS}} - 1.0) - 17.3\log_{10}(h_{\mathrm{MT}} - 1.0) \\
& + 2.7\log_{10}(f/5.0) + \sigma, \quad d_{\mathrm{BP}} < d_1 < 5\mathrm{km} \\
d_{\mathrm{BP}} =& 4(h_{\mathrm{BS}} - 1.0)(h_{\mathrm{MT}} - 1.0)f/c
\end{aligned} \tag{4.3}$$

where c denotes the speed of light and $\sigma = 3\mathrm{dB}$. For an antenna height of $h_{\mathrm{BS}} = 10\mathrm{m}$ and a MT antenna hight of $h_{\mathrm{MT}} = 1.5\mathrm{m}$, the breakpoint is at $d_{\mathrm{BP}} = 237\mathrm{m}$; $\mathrm{PL}_{\mathrm{Free}}$ is the path-loss in free space.

$$\begin{aligned}
\mathrm{PL}_{\mathrm{NLOS}}[\mathrm{dB}] &= \min(\mathrm{PL}(d_1, d_2), \mathrm{PL}(d_2, d_1)) \\
\mathrm{PL}(d_k, d_m) &= \mathrm{PL}_{\mathrm{LOS}}(d_k) + 20 - 12.5 n_j + 10 n_j \log_{10}(d_m) + 3\log_{10}(f/c) + \sigma \\
n_j &= \max\{(2.8 - 0.0024 d_k), 1.84\} \\
& k, m \,\epsilon\, \{1,2\}, \{2,1\} \\
& 10\mathrm{m} < d_1 < 5\mathrm{km} \\
& 10\mathrm{m} < d_2 < 2\mathrm{km}
\end{aligned} \tag{4.4}$$

where d_k denotes the distance traveled in the LOS street and $\mathrm{PL}_{\mathrm{LOS}}$ the corresponding pathloss as in (4.3). The distance traveled in the NLOS street is denoted as d_m and the standard deviation of the shadow fading σ equals 4dB.

The outdoor to indoor path-loss model consists of three components, the outdoor path-loss PL_{B1} as defined by the urban micro-cell (B1) model, the penetration loss into the building PL_w and the indoor path-loss PL_i. The path-loss equation is given as

$$\mathrm{PL}_{\mathrm{o2i}}[\mathrm{dB}] = \min_n\{\mathrm{PL}_{n,B1} + \mathrm{PL}_{n,w} + \mathrm{PL}_{n,i}\}, \quad n = 1, 2, 3, 4, \tag{4.5}$$

where the path-loss is calculated using the four points $n = 1, 2, 3$, and 4 of the outer walls of the building blocks that are closest to the indoor MT, and

$$\begin{aligned}
\mathrm{PL}_{n,B1}[\mathrm{dB}] &= \mathrm{PL}_{B1}(d_{n,o}) \\
\mathrm{PL}_{n,w}[\mathrm{dB}] &= 13 + 15\,(1 - \cos\Theta_n)^2 \\
\mathrm{PL}_{n,i}[\mathrm{dB}] &= 0.5\, d_{n,i}
\end{aligned}$$

Moreover, $d_{n,o}$ denotes the distance to the closest point in all four streets surrounding the building block. Please note that $d_{n,o}$ is the distance traveled in the streets to reach these points and that the B1 path-loss model distinguishes whether the two nodes are in the same street or not, i.e. line-of-sight (LOS) or NLOS path-loss model is used. Furthermore, Θ_n denotes the angle relative to the normal of the wall under which the signal is entering the building at the points closest to the MT, and $d_{n,i}$ denotes the distance to the MT inside the building block.

Table 4.2 summarizes the main parameters for the metropolitan area test scenario. Most of them can also be found in [123].

Table 4.2: Metropolitan Area Test Scenario

Size of Manhattan grid	11 x 12
Building Block Size	200m
Street Width	30m
BS Tx power	37dBm per sector
BS No. Sectors	2
BS No. Antennas per Sector	1
BS antenna gain	14dBi (75deg beamwidth)
RN transmit power	30dBm
RN No. Antennas	2
RN antenna gain towards MT	7dBi (omni)
RN antenna gain towards BS	14dBi (60°)
MT Tx power	23dBm
MT antenna gain	0dBi (omni)
Wrap around	no
Noise Figure at BS	5dB
Noise Figure at RN	5dB
Noise Figure at MT	7dB
Noise power spectral density	-174 dBm/Hz

4.4 Numerical Results

In this section we present first results on interference coordination in a metropolitan area relay network. Next we study the cost and performance of different BS and relay deployments in the metropolitan area test scenario. Thereafter we show an extensive set of results on interference coordination by soft frequency reuse (SFR) in the metropolitan area test scenario for both a BS only and relay based deployments. The studies on SFR include the proposed interference aware scheduling scheme as described in Chapter 3. Further, we present results for multiband operation. We consider a wide area scenario where the RNs extend the coverage of a high capacity band with high propagation loss and a sparse metropolitan area deployment where also the RN is equipped with a multiband scheduler.

The presented results have been obtained with the dynamic system simulation tool presented in Section 4.2 and the OFDMA parameters of the WINNER system. Table 4.3 presents the main parameters of the WINNER TDD physical layer mode. An overall system bandwidth of 100MHz was chosen in WINNER to meet the peak data rates of 100 Mbit/s for high and 1 Gbit/s for low mobility that were established as research targets for systems beyond IMT-2000 [1]. Our numerical evaluations have been carried out for a carrier frequency of 3.95GHz. Even though these assessment results have been obtained for WINNER OFDMA parameters, they give also insights on the potential benefits of relays for OFDMA based cellular systems like WiMAX, 3GPP Long Term Evolution (LTE) and 3GPP2 Ultra Mobile Broadband (UMB).

Table 4.3: WINNER TDD mode OFDMA parameters for Downlink [10].

Bandwidth	100MHz
Carrier Frequency	3.95GHz
Frame length	0.6912ms
OFDM symbols/frame	30
Subcarrier Spacing	48.828KHz
Cyclic Prefix	1.2μs
No. Used Subcarriers	1840
Signal Bandwidth	90MHz
No. Subcarriers/chunk	8
No. symbols/chunk	120
No. Chunks in DL/frame	230
Control and pilot symbols/Chunks	16
Duplex Guard Time	8.4us

4.4.1 Interference Coordination in Metropolitan Area Relay Networks

In this section we present results on interference coordination in a metropolitan area relay networks. The test scenario follows the assumptions as described in Section 4.3.1 but a different relay deployment as illustrated in Figure 4.5. This deployment adds a relay to every BS sector and was used as first test scenario in WINNER. We will present results both for outdoor users located in the streets and for indoor users inside the building blocks.

We start from a scenario with the most restrictive interference coordination, i.e. BS and RN do not serve MT at the same time and the RN use a frequency reuse of two (Hard mask). The RN marked as light gray in Figure 4.5 use half of the bandwidth and the RN marked in dark gray use the other half. This is the reference scenario and the performance of the other interference coordination options will be presented as relative increase or decrease in average user throughput and in the fifth percentile of the user throughput cumulative distribution function (CDF). The results are only collected from users that have been served by monitored cells for at least 75% of the time.

Please note that differently to the results in [22] all interference coordination options have been evaluated with two antennas at the RN. One directive antenna that points to the BS to communicate with the BS and a second directive antenna pointing away from the BS to serve MTs. Further, we also show results for a round robin time domain scheduling strategy.

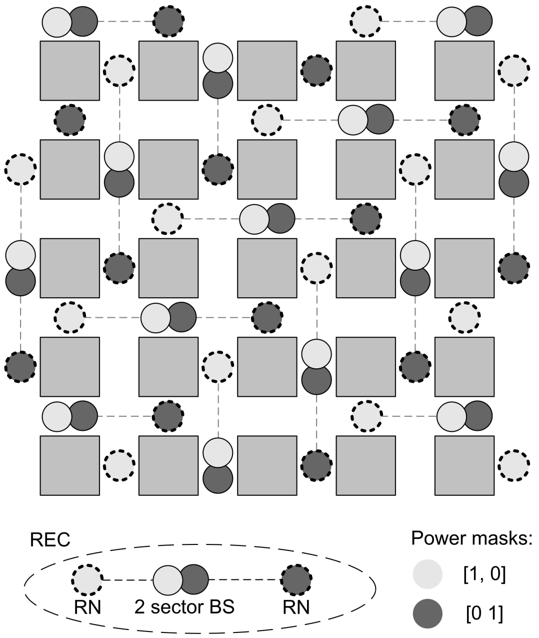


Figure 4.5: Metropolitan area relay deployment. The different colors show the relay grouping for reuse two in the frequency domain.

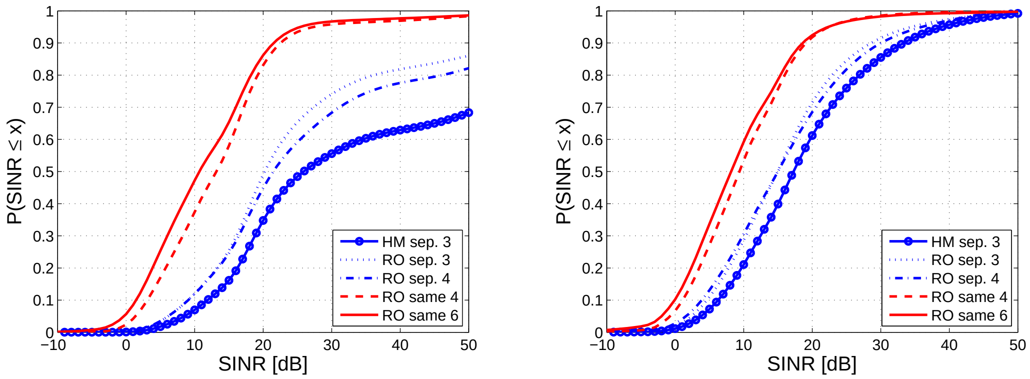
Table 4.4: Performance Impact on the average cell throughput and on the fifth percentile of the user throughput CDF for different Interference Coordination Options with Round Robin and Equal Throughput time domain fairness criteria.

	Round robin		**Equal Throughput**	
Interference Coordination Option	Rel. Avg. cell TP [1]	5%ile of MT TP [1]	Rel. Avg. cell TP [1]	5%ile of MT TP [1]
Users in the street				
Reuse two in frequency domain (RN serves in 3 frames)	1	1	0.91	1.03
Reuse one in frequency domain (RN serves in 3 frames)	1.29	1.18	1.27	1.55
BS and RN serve MT at the same time (RN serves in 4 frames)	1.87	1.77	1.53	1.56
Optimal amount of frames where the RN serves MT	2.05	1.93	1.94	2.20
Users indoor				
Reuse two in frequency domain (RN serves in 3 frames)	1	1	0.89	1.16
Reuse one in frequency domain (RN serves in 3 frames)	1.41	1.52	1.33	1.52
Optimal amount of frames where the RN serves MT	2.21	1.94	2.02	1.80

Table 4.4 summarizes the relative average cell throughput and the fifth percentile of the user throughput CDF for the compared interference coordination options. Both the round robin and equal throughput time domain fairness criteria perform quite similar with some advantage in average cell throughput for the round robin scheduler. In the following

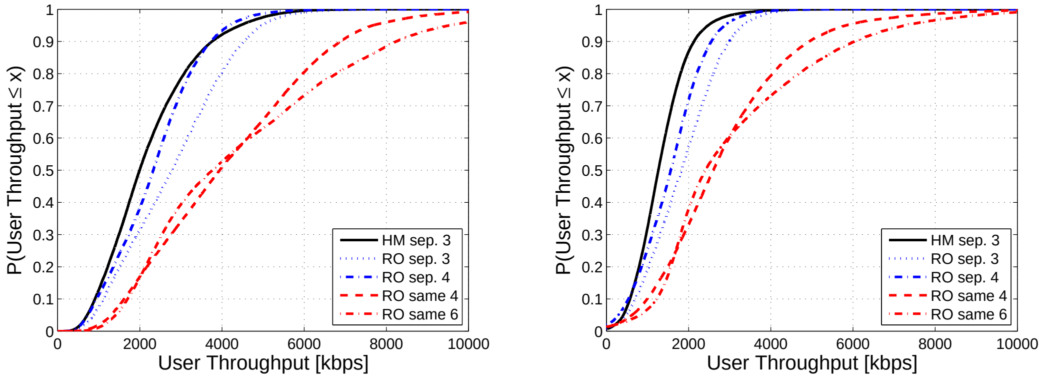
we will only discuss round robin results and we will start with the results for outdoor users.

Figure 4.6(a) compares the SINR of the received packets for different interference coordination options. The SINR of the received packets is clearly higher for the relay deployment with the reference scheme using a hard mask (reuse of two) for the two groups of RNs. For example, compared to the case where BS and RN transmit at the same time and the relay is active in 4 out of 8 frames, the median SINR is about 12dB higher and the difference increases even further for the higher parts of the CDF. Nevertheless, the SINR distribution also indicates that the performance of the relay deployment could be increased by a less restrictive interference coordination to allow more parallel transmissions while decreasing the SINR to a still tolerable value.



(a) Users in the streets.

(b) Users indoor.



(c) Users in the streets.

(d) Users indoor.

Figure 4.6: SINR of received packets and user throughput comparison of different interference coordination options for relay deployments with users in the streets and indoor.

Allowing all RNs to use the whole bandwidth increases the average cell throughput already by about 30%. More importantly not only the average cell throughput increases but also the lower percentiles of the user throughput CDF increases by 20% (see Figure 4.6(c)). Next, we allow both the BS and the RN to serve its MTs at the same time. This results in an improvement of 87% in the average cell throughput and 77% in the 5 percentile of the user throughput CDF. When assigning the optimal amount of frames to the RNs to serve MTs both the cell throughput and the fifth percentile of the user throughput CDF can be doubled compared to the reference scheme. This indicates that next to interference coordination in the frequency domain, the performance of relay deployments depends very much on the proper balance between the resources spent on the first hop between BS and RN and on the second hop between RN and MT.

In the reference case the best results are achieved when RNs serve users in 3 out of 8 frames. Due to the lower transmit power of the RNs the RN serves less MT and thus it is able to serve its MT in less than half of the frames. Especially when BS and RN serve MT at the same time the interference situation is more challenging as can be seen from Figure 4.7. Hence, it is beneficial, if the RN can serve its MTs in more frames. The best result was achieved when the RNs serve MTs in six out of eight frames. Since the RN uses a directive antenna towards the BS, the BS-RN link is significantly better than the RN-MT links and two frames are sufficient for the BS-RN communication.

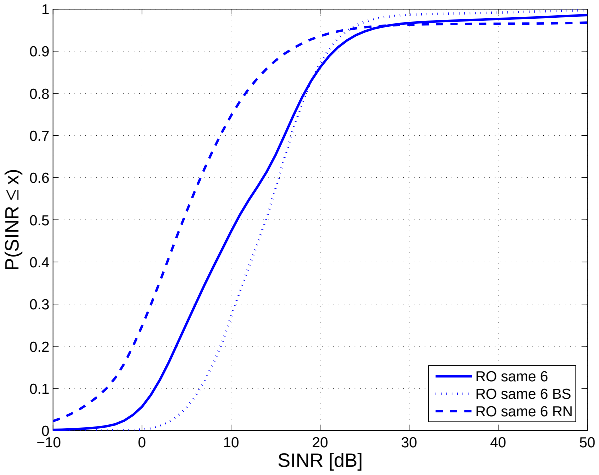


Figure 4.7: SINR of received packets when RN and BS serve users at the same time in 6 frames.

In addition to outdoor users, we simulated the same scenario but with only indoor users. The results in Table 4.4 and in Figure 4.6 for indoor users show that similar conclusions can be drawn from these results as for the previous case with users in the street. Again it is beneficial to use less restrictive interference coordination schemes. The best interference coordination scheme achieves 121% higher cell throughput and a 94% increase in the fifth percentile of the user throughput CDF.

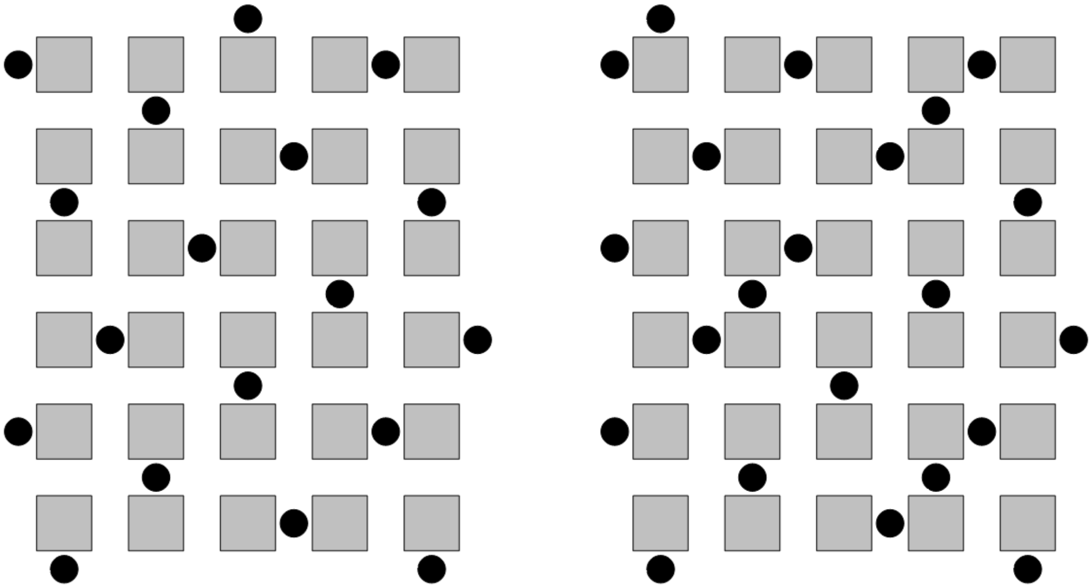
The number of frames in which RNs serve MTs is kept constant during the whole simulation and the same number is used within the whole network. It is for further studies, if the performance of the relay deployment can be improved by allowing RNs to individually adapt the number of frames in which they serve MTs.

The higher SINR of more restrictive RRM options could also be exploited by multi-stream transmission using MIMO techniques such as per-antenna rate control. However, the dense deployment of radio access points (BS or RN) assures a LOS or obstructed LOS link of the outdoor MT to the serving radio access points and the multi-stream support of the resulting MIMO channel will not be very good. In any case, we do not expect that the use of MIMO can more than double the cell throughput which would be required to outperform the best performing strategy.

4.4.2 Cost comparison between BS only and Relay based Deployments

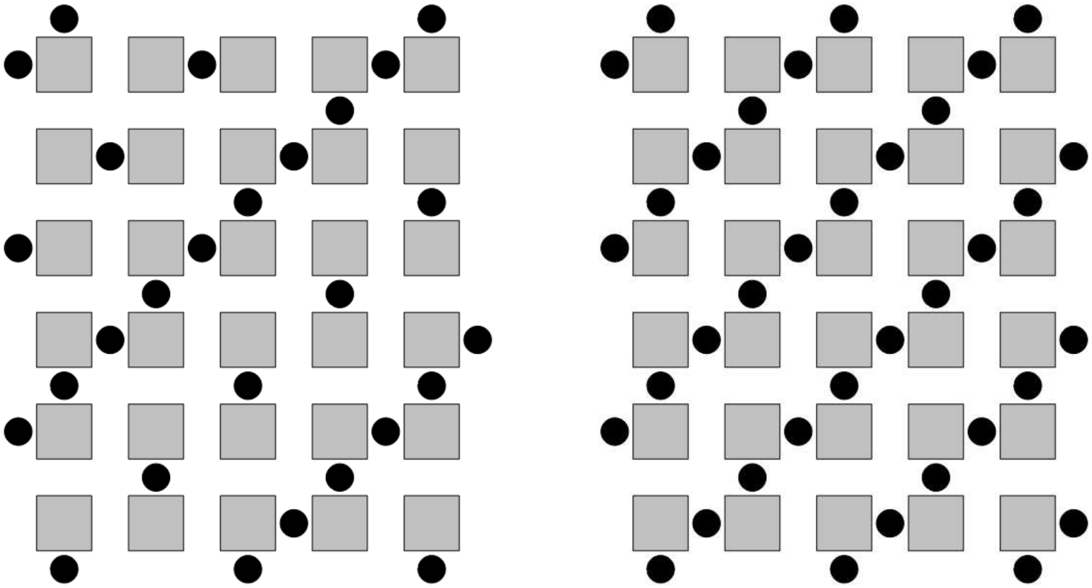
Cost considerations had a big influence on the choice of the RN properties. To achieve low cost relays with small physical size that can be mounted for example on lamp posts the relays operate with reduced transmit power and they are equipped with two antennas of limited size and gain.

In the following we give an example of the cost comparison between BS and RN using the cost figures in [123]. Please note that the actual cost comparison figures will vary significantly depending for example on the country and the pre-installed sites of an operator. Nevertheless, these figures provide a feeling about the costs of different deployments. The initial capital expenditure (CAPEX) of the RN has been assumed to be comparable to a pico BS which is 2.1kEUR. The hardware cost of a two sector micro BS is 7.5kEUR and together with the site acquisition cost it results in a CAPEX of 10.5kEUR. Further, we assume the same operational expenditure (OPEX) for the RN as for a pico BS which sums up to 3.9kEUR over 10 years excluding the cost for the backhaul connection. The OPEX for the micro BS include additionally the costs of the fixed line connections and the overall OPEX sum up to 29.5kEUR over 10 years. The overall costs including initial CAPEX and OPEX over 10 years are 6kEUR per RN and 40kEUR for the 2 sector micro BS, respectively. Thus, the cost ratio between RN and BS is less than one sixth in this case.



(a) BS only deployment in street with 2 sectors per BS (144Sec).

(b) BS only deployment in street with 2 sectors per BS (178Sec).

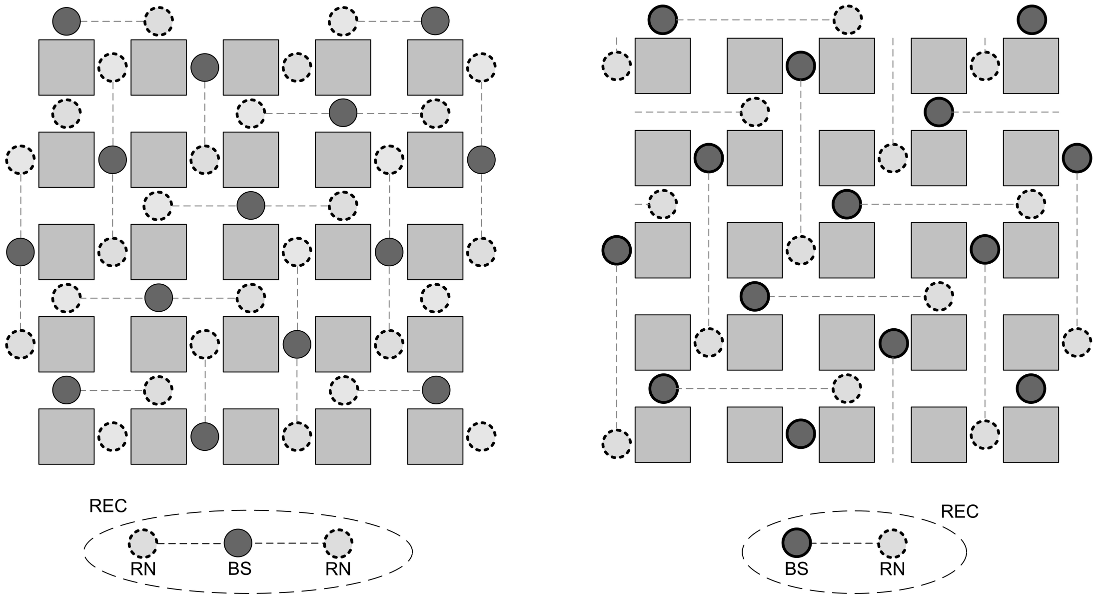


(c) BS only deployment in street with 2 sectors per BS (214Sec)

(d) BS only deployment in street with 2 sectors per BS (286Sec)

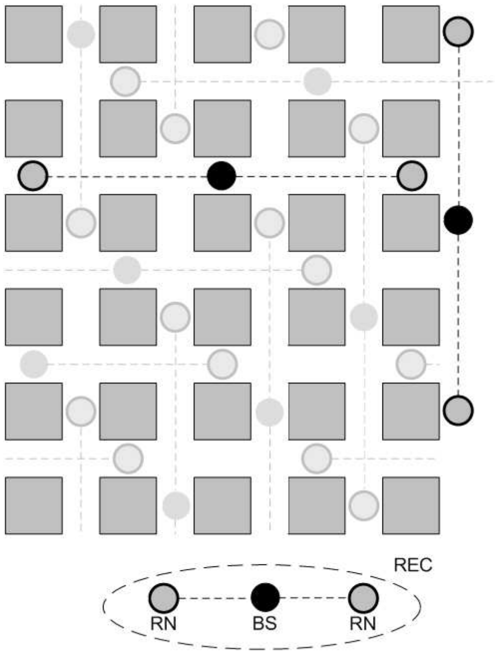
Figure 4.8: Deployment pattern for selected BS only deployments (zoom of the inner 5x6 blocks).

To compare the performance of BS only and relay deployments we evaluated selected BS only deployments depicted in Figure 4.8 and selected relay deployments in Figure 4.9. Please note that the 144 BS sectors 72 RN is the default relay deployment presented in Section 4.3.1 and the 144 BS sectors 144 RN is the same relay deployments as in Section 4.4.1.



(a) Relay deployment in street with 1 RN for each BS sector (144Sec 144RN)

(b) Relay deployment in street with 1RN for BS sector pointing down or to the right (144Sec 72RN).



(c) Relay deployment in street with 1RN for each BS sector (96Sec 96RN) without power masks.

Figure 4.9: Deployment pattern for selected relay deployments (zoom of the inner 5x6 blocks).

In these simulations we utilize the equal throughput time domain fairness criteria. The user density is kept constant at 470MT/km^2 in all scenarios and we evaluate the performance indicators only from the monitored center cells. The amount of monitored cells has been chosen such that a comparable monitored area for each scenario is obtained. It varies between four cells in the scenario illustrated in Figure 4.8(a) to eight cells for the scenario presented in Figure 4.8(d). To get comparable results, the throughput and the costs have been normalized over an area of one km^2. The MTs are randomly placed, move indoors and in areas served by the active cells at a maximum speed of 3km/h. The active cells cover about 2.2km^2 and the monitored cells about 0.3km^2. The RNs serve MTs in 6 out of 8 frames for both relay deployments.

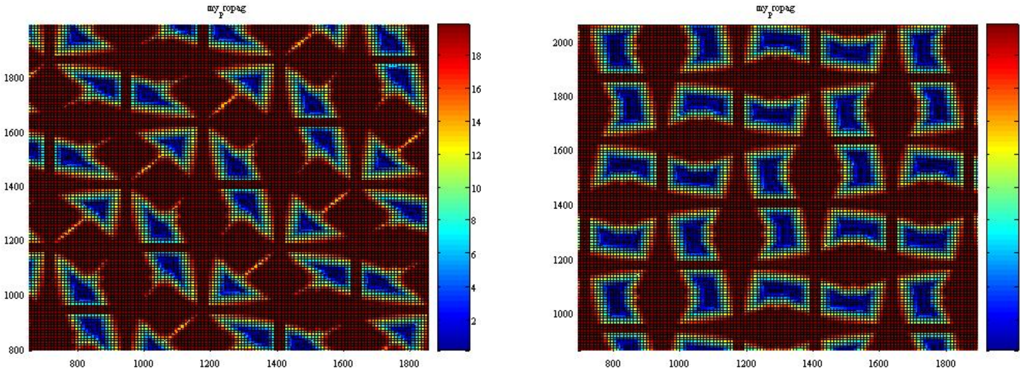
4.4.2.1 Coverage and cost comparison

In the coverage comparison we use the relay deployment illustrated in Figure 4.9(c) and the BS only deployment in Figure 4.8(a). The cost of both scenarios is similar for a RN/BS cost ratio of one fourth which is below the expected cost ratio of one sixth.

Figure 4.10(b) and Figure 4.10(a) illustrate the coverage area of the BS only and the relay deployment, respectively. We define the coverage area as area where the signal-to-noise ratio (SNR) provided by the radio access points is higher than 7dB and thus provides a spectral efficiency of 1b/s/Hz. Intuitively, it can be seen that the coverage area of the RN deployment is higher than the coverage area of the BS only deployment. In fact, the relay deployment can increase the covered area from 83.3% to 88.5% compared to a BS only deployment of similar cost. Both deployments cover all the streets but the relay deployments provides much better outdoor to indoor coverage, where it increases the indoor area coverage by 6%.

4.4.2.2 Performance and cost comparison

Table 4.5 compares the performance and the costs of the selected BS only and relay deployments. The scenarios are sorted by their average area throughput starting with the scenario that has the highest average throughput per km^2. In addition Table 4.5 contains the fifth percentile of the user throughput CDF and the costs per km^2 for each deployment following the cost figures presented in Section 4.4.2. Finally, the last row presents the relative cost figures for each deployment for a RN/BS cost ratio of one fourth and one third. Please note that the costs have been calculated based on the number of



(a) SNR of relay deployment 96BS96RN (zoom of center cells)

(b) SNR of BS only deployment 144BS (zoom of center cells).

Figure 4.10: Coverage comparison of relay and BS only deployment with similar costs.

monitored cells divided by the covered area. As both the 214BS and the 178BS scenarios follow irregular deployment pattern the costs do not scale linearly between the 144BS and the 286BS scenarios.

To select the most cost efficient deployment option for a given target performance, the cheapest deployment option that can meet the performance target has to be chosen. For example, when an area throughput of 250MByte/s/sqkm is targeted, the following deployments meet the performance target: the BS deployments with 107BS (214 sectors) and with 143BS (286 sectors), as well as the relay deployment with 72BS (144 sectors) and 72 RN, i.e. one RN per BS site. In this case the relay deployment with one RN per BS site is the most cost efficient. The next best BS only deployment that achieves the required performance target has about 30% higher costs per km^2 over 10 years. However, the average area throughput of the 214BS deployment is 23% higher than the area throughput of the relay deployments. To get the RN/BS cost ratio for which the relay deployment has the same cost as the BS only deployments we interpolate the cost and the area throughput between the 214BS and the 178BS scenario. In this comparison the 144BS72RN scenario is still cheaper than the BS only deployments for a RN/BS cost ratio of 1/4 and they have similar costs for a RN/BS cost ratio of 1/3. Please note that in our cost comparison in [21] the 144BS144RN scenario slightly outperformed the 144BS72RN scenario because it utilized soft frequency reuse. At that time we had not found a good power mask assignment for the BS only and 144BS72RN scenario yet and therefore SFR was selected only for the 144BS144RN scenario. As our later studies will show SFR provides also advantages for the BS only and the 144BS72RN scenario and to keep fairness we have now only compared reuse one results.

Table 4.5: Performance and Cost comparison for the selected deployments: the average throughput and the cost have been normalized per area

No. BS sectors No. RN	286	214	144 72	144 144	178	144
Cell TP [MB/s/km^2]	413	317	251	236	227	209
5%ile User TP [Mbit/s]	1.51	1.08	1.33	1.35	0.85	0.47
Cost [kEUR/km^2]	1052	737	565	605	568	526
RN/BS cost ratio 1/4	2	1.40	1.13	1.25	1.08	1
RN/BS cost ratio 1/3	2	1.40	1.17	1.33	1.08	1

Next to the average cell throughput also the fairness among users is an important figure of merit. Therefore we study also the 5 percentile of the user throughput CDF. 5% of the users experience a throughput of less than 0.47Mbit/s for the 144BS scenario and 0.85Mbit/s for the 178BS scenario compared to 1.51Mbit/s for the 286BS scenario. In the 144BS72RN scenario 5% of the users have less than 1.33Mbit/s throughput which is doubled compared to the 144BS scenario. On the other hand the average throughput increases only by 20% which indicates that the 144BS and the 178BS deployment do not provide sufficient coverage to offer high data rates to all the users in the scenario. All the other scenarios offer more than 1Mbit/s indicating that they provide sufficient outdoor to indoor coverage.

4.4.3 Soft Frequency Reuse in a Metropolitan Area Network

The metropolitan area test scenario is again modeled by the test scenario illustrated in Section 4.3.1. The building blocks provide strong shadowing from perpendicular streets. Thus, interference coordination is mainly needed at street crossings and at the border area between radio access points, whereas the border area is smaller than for a wide area deployment. For such a scenario we propose in Chapter 3 to use a resource assignment based on soft frequency reuse (SFR) that assigns power masks (in the frequency domain) to neighboring radio access points to coordinate the mutual interference. In the following we study the performance of SFR for a BS only deployment and a relay deployment.

For the BS only deployment we also compare the performance of SFR to Fractional Frequency Reuse (FFR). FFR is a competing interference coordination scheme where part of the bandwidth is operated as reuse one while the remaining bandwidth is split between groups of radio access points. Such a comparison has also been performed in [89] where SFR performs better than FFR both in residual packet error rate (PER) and in sustained traffic for a constant bit rate traffic model.

4.4.3.1 Soft-Frequency Reuse in a BS only deployment

The deployment pattern of the BS only scenario and the power mask assignment for the SFR and FFR case is illustrated in Figure 4.11. For SFR we subdivide the available OFDMA resource blocks (chunks) in the frequency domain into equal sized groups and assign one of the following power levels $P = \{1, 0.5, 0.25\}$ to each group. The power levels have not been optimized but a power mask step of 3dB was found to be the best choice when comparing several options (1, 2, 3, 4, 5dB) even though the difference in average cell throughput was less than 5%. In the FFR case two third of the chunks use reuse one and the rest is subdivided between the three groups of base station. Please note that FFR offers the possibility to adjust the amount of chunks with reduced interference. Selecting two third of the chunks for reuse one and having only one ninth with reduced interference for each base station works well in a metropolitan area, where relatively few MTs at street crossings experience the most challenging interference conditions. This selection would likely be different for macro-cellular scenarios. The simulations were performed with 2000 MTs moving in the streets inside the active area.

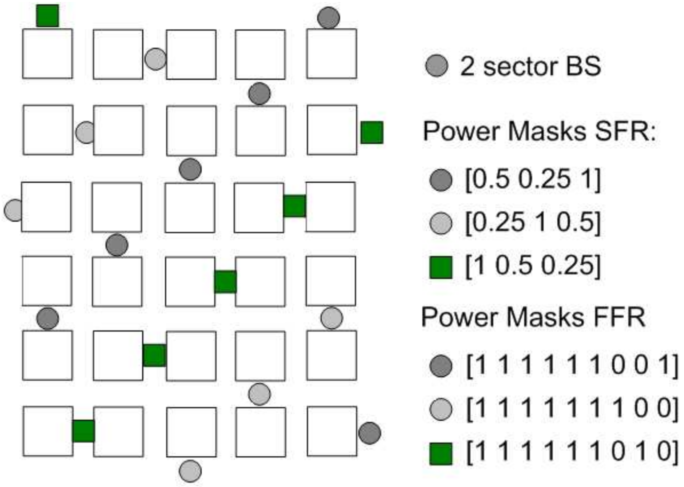


Figure 4.11: BS deployment and Power Mask Assignment (zoom).

Table 4.6 compares the fifth percentile of the user throughput cumulative distribution function (CDF) and the average cell throughput for reuse one, SFR and FFR with different scheduling options based on the two stage scheduling process described in Chapter 4.2. For the first stage time domain scheduler a round robin fairness criteria was used, except for two cases with an equal throughput criteria (ETP). The equal throughput criteria selects the MT with the lowest throughput in the last 50ms. Users of both groups are then selected for frequency domain scheduling.

ByUser, ByUser split, ByRB and ByRB split denote the frequency domain scheduling strategies as described in Chapter 3. ByUser denotes the frequency domain scheduling strategy that allocates the available chunks user by user. ByRB denotes the frequency domain scheduling strategy where the scheduler loops through the chunks and allocates each chunk to the user with the highest proportional fair metric for that chunk. Split denotes an option of the interference-aware scheduler where the time domain packet scheduler splits the users into groups of users with high and low SINR. The share of MTs allocated to the low SINR group K is listed in Table 4.6 for cases where the MTs have been split into high and low SINR groups. $M = 4$ and $M = 2$ MTs have been selected from the low SINR group for SFR and FFR simulations, respectively. $L = 12$ MTs have been selected for each scheduling round. We also investigate the reduced feedback (red FB) option of the interference aware phased scheduler.

First, we compare the results for the byRB strategy. SFR in combination with the interference aware scheduler increases the fifth percentile of the user throughput CDF by more than 40% and the average cell throughput by 8%. When utilizing the reduced feedback option of the interference aware scheduler, the fifth percentile of the user throughput CDF reduces by 7% for $K = 0.25N$ while the average cell throughput stays the same. The reduction in the fifth percentile of the user throughput CDF can be explained by the reduced multi-user diversity because the scheduler can allocate one third of the chunks only to MTs in the low SINR group and the other two third of the chunks to MTs in the high SINR group. Nevertheless we believe that the benefits from the reduced feedback outweigh the moderate loss in the lower percentiles of the user throughput CDF. A smaller K than the default value of $0.33N$ gives more priority to the low SINR MT. Reducing it below $0.25N$ does not help the fifth percentile of the user throughput CDF. On the other hand $K = 0.4N$ reduces the 5 percentile already by 7% compared to $K = 0.33N$. Nevertheless, the average cell throughput stays essentially the same which shows that the proposed scheduling algorithm is robust to parameter changes.

Figure 4.12 compares the user throughput CDF for the reference byUser and the byRB

Table 4.6: 5 percentiles of user throughput CDF, average cell throughput for Reuse one, SFR and FFR with different scheduling options

Scheduler	5-%ile User TP CDF [kb/s]	Average Cell TP [Mb/s/sector]
Reuse one		
ByUser	1557	127.3
ByRB	1340	129.3
ByRB ETP	1585	118.5
SFR		
ByUser (reference)	2004	128.2
ByUser split $K = 0.33N$	2201	126.8
ByUser split $K = 0.33N$ red FB	1642	117.1
ByRB	1616	139.7
ByRB split $K = 0.33N$	1890	139.3
ByRB split ETP $K = 0.33N$	1658	124.5
ByRB split $K = 0.2N$ red FB	1754	137.3
ByRB split $K = 0.25N$ red FB	1767	138.4
ByRB split $K = 0.33N$ red FB	1698	139.4
ByRB split $K = 0.4N$ red FB	1575	139.0
FFR		
ByRB	1689	114.9
ByRB split $K = 1/6N$	1822	115.6
ByRB split $K = 1/6N$ red FB	1609	116.2

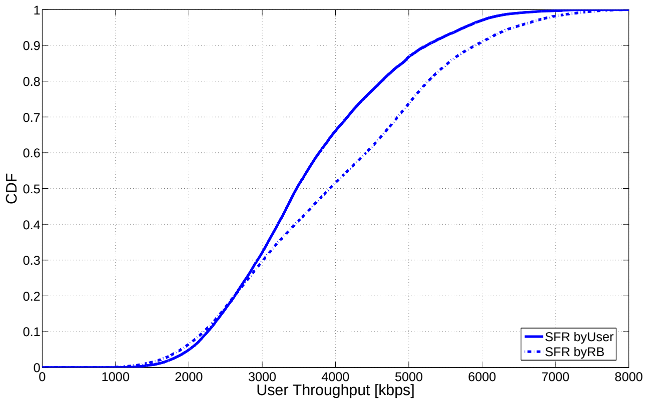
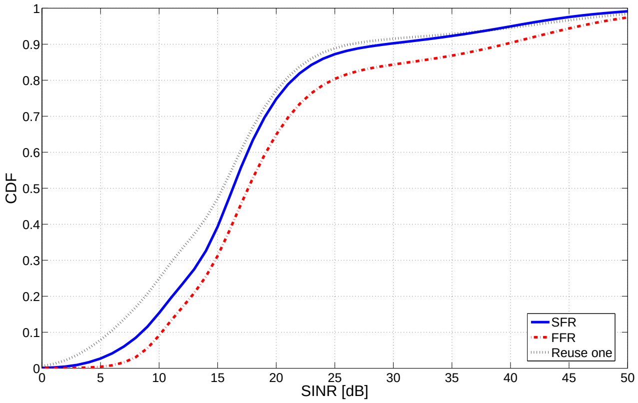


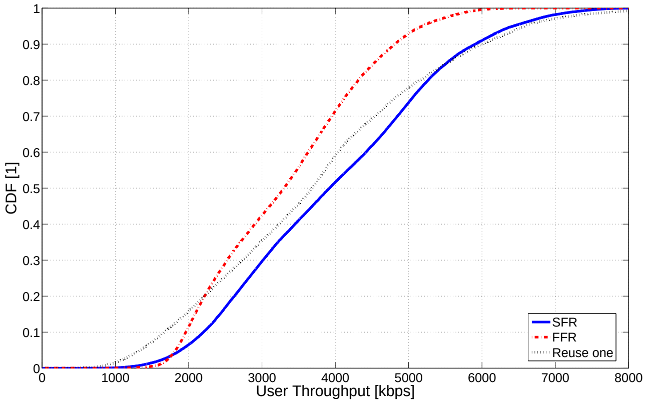
Figure 4.12: User Throughput CDF for SFR using byUser and byRB frequency domain scheduling.

strategy for SFR with $K = 0.33N$ and without using the reduced feedback option of the interference aware scheduler. Both cases are similar in the lower percentiles but the byRB strategy improves the higher percentiles and thereby increases the average cell throughput by 8%. This clearly illustrates that the additional degrees of freedom introduced by the byRB strategy are beneficial compared to allocating resource blocks user by user, as proposed in [89]. When utilizing the phased byUser scheduler instead of the reference byUser strategy, the 5 percentile of the user throughput CDF increases by 10% while the average throughput decreases by 1% compared to the reference byUser strategy. However the reduced feedback option does not perform as well for the byUser strategy as for the byRB strategy.

A time domain fairness strategy (ETP) can be utilized to increase the lower percentiles of the user throughput CDF for reuse one. However the results for SFR in Table 4.6 show that the 5 percentile reduces by 12% and the average cell throughput by 11%. This shows that adding a time domain fairness strategy to SFR is counter productive.



(a) Effective SINR of received packets.



(b) User Throughput.

Figure 4.13: Comparison of Reuse One, Soft Frequency Reuse and Fractional Frequency Reuse.

Figure 4.13 compares the results for SFR, FFR and reuse one with byRB strategy and with split for SFR and FFR. Both SFR and FFR improve the effective SINR of the received packets significantly compared to reuse one. At the 5 percentile of the CDF the increase is 2.6dB for SFR and 5.1dB for FFR. The higher increase in SINR for FFR comes at the price of less resources available for scheduling which reduces the average cell throughput by 17% compared to SFR. On the contrary SFR has the whole resources available for scheduling and the scheduler can utilize the introduced SINR variations to support users with low SINR. The split in high and low SINR user groups and selecting MTs from both groups for frequency domain scheduling makes good use of the SINR variations which also increases the average cell throughput by 8% compared to reuse one.

4.4.3.2 Soft frequency reuse and interference aware scheduling in relay deployments

In this section we apply soft frequency reuse and the interference aware scheduler to the default metropolitan area relay deployment in Figure 4.4 with 1 RN added to each BS site. Next to the comparison of soft frequency reuse to reuse one we also compare the performance of the relay based deployment to the performance of the same deployments without RNs in Figure 4.11.

Indoor Users

Table 4.7 compares the fifth percentile of the user throughput CDF and the average cell throughput of the relay deployment to the BS only deployment. These results have been obtained for users located indoors whereas the outdoor-to-indoor micro-cell pathloss and channel models described in 4.3.1 have been utilized. To all scenarios we have applied reuse one and the different time domain and frequency domain scheduling options described in Chapter 3. The soft frequency reuse results for the BS only deployment are not directly comparable to the results in Section 4.4.3.1 because we have increased the user density in the active area. Due to the additional radio access points (relays) the memory consumption of the simulator increased and we had to decrease the active area to the four monitored cells. 400 users were uniformly distributed in this area.

When comparing the results for a BS deployment with reuse one to the relay deployment with reuse one, the relay deployment significantly increases the average cell throughput and the 5th percentile of the user throughput CDF. The average cell throughput increases by about 15% site for the round robin and by 34% for the equal throughput time domain fairness criteria. In the BS only case more than five percent of the users have zero throughput which reduces to 0.8% for the relay based deployment. The results show that relays are an effective way to deploy additional radio access points to compensate the high penetration loss into the building blocks as well as the higher pathloss inside the building blocks. It should also be noted that the performance increase has been achieved by adding RNs with a 7dB lower transmit power than a BS sector. Further, we consider a two sector BS which offers double the capacity compared to a single sector BS. Users with zero throughput do not get resources allocated by the scheduler and the resources are distributed among the remaining users. Thus, the average cell throughput increases. If the only figure of merit is the average cell throughput, e.g. the five percent of users with lowest SINR should be removed from scheduling in the relay deployment for a fair comparison. This would further increase the average cell throughput for the relay deployment and increase the performance difference to the BS only deployment.

Table 4.7: 5 percentiles of user throughput CDF and average cell throughput for BS and relay deployments with/without SFR for indoor users and different Interference Aware scheduler parameters.

	BS only		**1 RN per BS**	
Scheduler	5-%ile User TP CDF [kb/s]	Average Cell TP [Mb/s/site]	5-%ile User TP CDF [kb/s]	Average Cell TP [Mb/s/site]
Reuse One				
ByRB	0	217	615	243
ByRB ETP	0	151	575	202
SFR				
ByRB	171	221	624	245
ByRB split $K = 0.2N$	28	207	718	235
ByRB split $K = 0.33N$	141	218	697	242
ByRB split $K = 0.4N$	162	221	644	243
ByRB split $K = 0.2N$ red FB	182	209	679	237
ByRB split $K = 0.33N$ red FB	123	217	625	242
ByRB split $K = 0.4N$ red FB	161	219	558	244
ByRB ETP	201	145	575	194
ByRB split ETP $K = 0.2N$	217	158	626	200
ByRB split ETP $K = 0.33N$	182	177	575	211
ByRB split ETP $K = 0.4N$	124	185	580	217
ByRB split ETP $K = 0.2N$ red FB	162	148	597	195
ByRB split ETP $K = 0.33N$ red FB	158	168	594	210
ByRB split ETP $K = 0.4N$ red FB	177	179	586	211

Next we discuss the results for the relay deployment with soft frequency reuse (SFR) and the interference aware scheduling scheme described in Chapter 3. For a round robin time domain fairness criteria the fifth percentile of the user throughput CDF increases by 13% (ByRB split $K = 0.33N$) while keeping the same average cell throughput compared to reuse one. In addition also the number of users with zero throughput is slightly reduced to 0.5%. Even though the performance increase is moderate, using the reduced feedback option of the interference aware scheduling scheme will reduce the feedback load.

For the equal throughput time domain fairness criteria, SFR with the interference aware scheduler increases the average cell throughput by 7% while keeping the fifth percentile of the user throughput CDF at the same level.

A more significant increase in performance can be observed for BS only deployments. For the round robin time domain scheduler, SFR increases the average cell throughput by 2% and the number of zero throughput users reduces from more than 5% to 3%. This clearly shows that for the BS only deployment SFR together with an appropriate scheduling scheme is able to utilize the chunks with increased power and reduced interference to support users with low SINR inside building blocks where the coverage is limited.

Figure 4.14 compares the user throughput CDF of the BS only deployment to the relay deployment for both reuse one and SFR with the interference aware scheduler. The relay based deployment more than triples the fifth percentile of the user throughput CDF. The tenth percentile is still doubled which shows that the relay deployment not only supports the very low percentiles but a wide range of low throughput users. SFR in combination with the interference aware scheduler slightly improves both the lower percentiles and the higher percentiles of the user throughput CDF. Thereby it supports the users with low throughput and it can increase the average cell throughput.

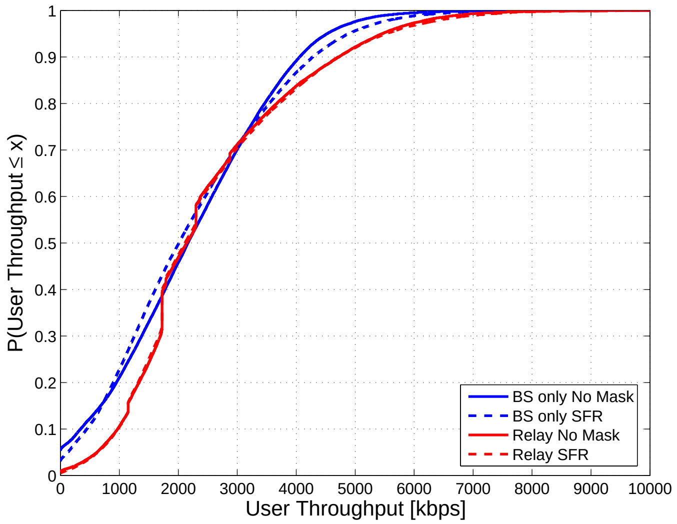


Figure 4.14: User throughput comparison of BS only and relay deployments for reuse one and soft frequency reuse with indoor users.

Figure 4.15 compares the SINR CDF of the received packets for the BS only deployment and the relay deployment with reuse one and SFR with the interference aware scheduler. For SFR with the interference aware scheduler the SINR slightly increases in the lower percentile whereas it slightly decreases in the higher percentiles.

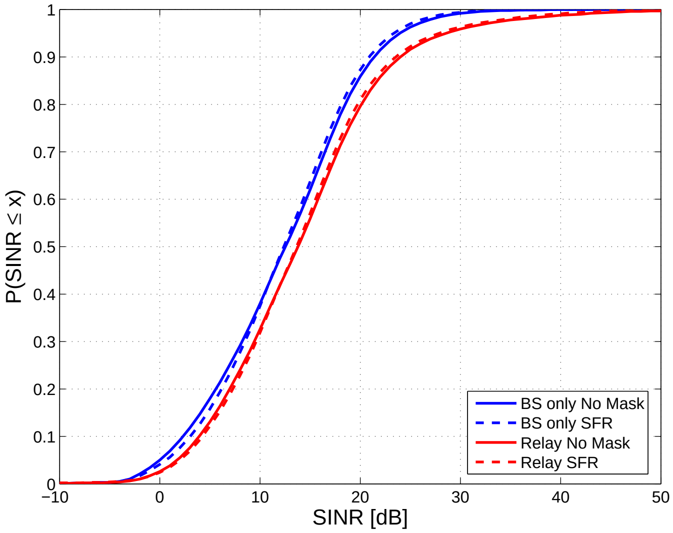


Figure 4.15: SINR of received packets comparison of BS only and relay deployments for reuse one and soft frequency reuse with indoor users.

In the case of relay deployments the active users are distributed among the BS sectors and RNs and each radio access point will serve less active users. The RNs have a lower coverage area than the BS and will also serve less users. We select the same amount of users ($L = 12$) at each radio access point for both the BS only and the relay deployment in each scheduling round, i.e. for the relay deployment each radio access point has less users to select from. Hence, the relay deployment will not gain as much as the BS only deployment from splitting the users into low and high SINR groups and the gain from the interference aware scheduler is less than in the BS only case.

Users in the streets

Table 4.8 illustrates the results for outdoor users with otherwise similar assumptions as for the indoor user case. Since the signal propagates very well in the street canyons and BSs are deployed in every street, there are clearly no coverage limitations and the scenario is interference limited. In this scenario the relay based deployment cannot improve the performance of the network compared to the BS only based deployment. It even reduces the average cell throughput and the 5th percentile of the user throughput CDF compared to reuse one. These results show that adding low cost relays to dense BS deployments which are not coverage limited will very likely not improve the performance.

Table 4.8: 5 percentiles of user throughput CDF and average cell throughput for BS and relay deployments with/without SFR for outdoor users.

	BS only		**1 RN per BS**	
Scheduler	5-%ile User TP CDF [kb/s]	Average Cell TP [Mb/s/site]	5-%ile User TP CDF [kb/s]	Average Cell TP [Mb/s/site]
Round Robin				
ByRB RO	1267	316	1069	301
ByRB SFR	1536	325	1150	309
ByRB SFR IA	1757	326	1214	306

To sum up, the relay deployment provides advantages especially in scenarios with indoor users where the relays effectively increase the outdoor-to-indoor coverage. The improvements due to soft frequency reuse and the interference aware scheduler are lower compared to the BS only case.

4.4.4 Relays in Multiband Operation

In a multiband operation, RNs can for example be used to extend the coverage of the band with worse propagation characteristics. For the example spectrum allocation in Figure 4.16 a radio access point is able to provide wide area coverage on the basic (B) band at 860MHz. However, it cannot cover the same area with the shared extension (E) band at 3.4GHz because of the differences in the propagation loss due to the different carrier frequencies.

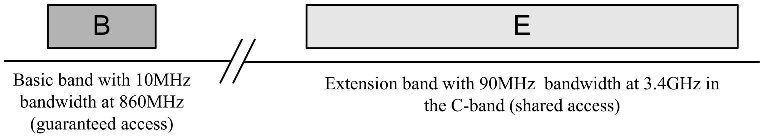


Figure 4.16: Possible spectrum allocation for IMT-Advanced in a multi band deployment.

We study the performance difference with and without RNs in the E band for the scenario presented in Figure 4.17. The BSs are equipped with both B band and E band radio interface. The Inter-Site Distance is 3km, and the BSs can provide the basic coverage for the B band at 860MHz using the pathloss model in [117]. Each BS sector has 6 RNs to extend the coverage area of the E band at 3.4GHz, two of them are evenly distributed on a circle around the BS with a radius of 500m and the other 4 are on a circle with a radius of 1000m as illustrated in Figure 4.17. We assume a line-of-sight (LOS) link between RN and BS and for the BS-MT and RN-MT links we assume a NLOS link.

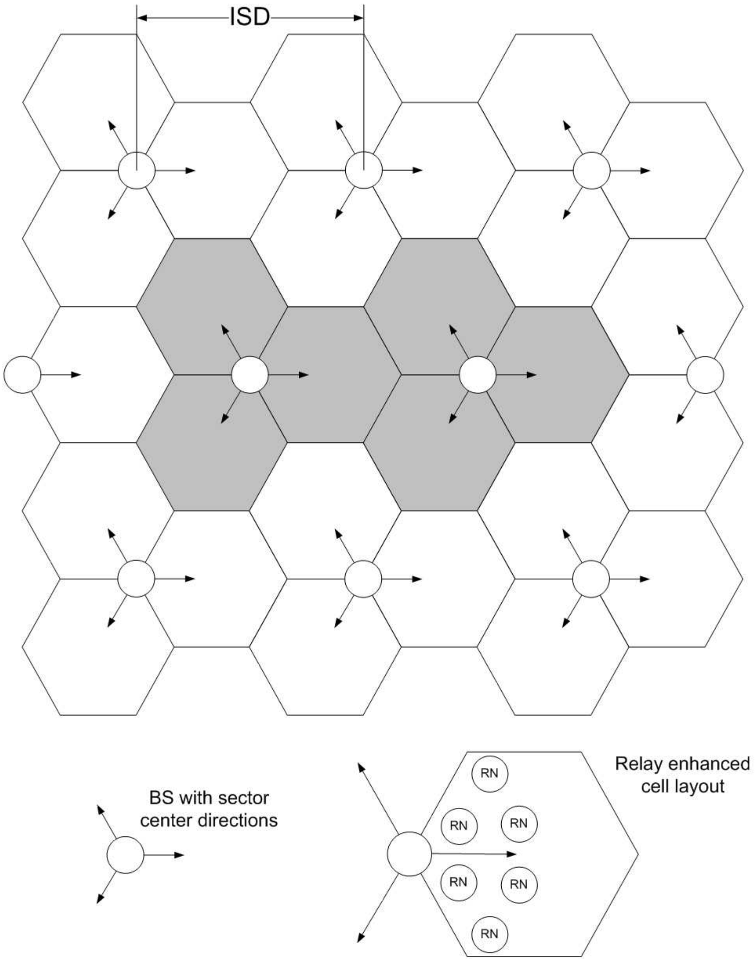


Figure 4.17: Multiband operation in wide area scenario. RNs extend the high bit rate coverage of the E band.

The corresponding channel and pathloss models can be found in [109]. The BS transmit power is 43dBm per sector and the RN transmit power is 37dBm. 2000 MTs move in the area at a speed of 3km/h. Table 4.9 compares the average cell throughput of the two center cells. Adding the E band to the B band at the BS increases the cell throughput seven fold. However, the high capacity E band is not available for most of the users in the cell and the increase does not fully scale with the increase in bandwidth. When using RNs to extend the E band coverage the throughput almost doubles. Further, the high capacity E band is available to most of the users in the cell.

Table 4.9: Cell throughput comparison with/without E band and RN

Scenario	Average cell throughput [Mbps]
Only B band BS	22
BS with both bands	150
BS with both bands and RN with E band	270

So far we have presented the multi-band operation in relay enhanced cells for RNs that operate only in the E band. However, some of the RNs might be equipped with both a B band and an E band radio interface.

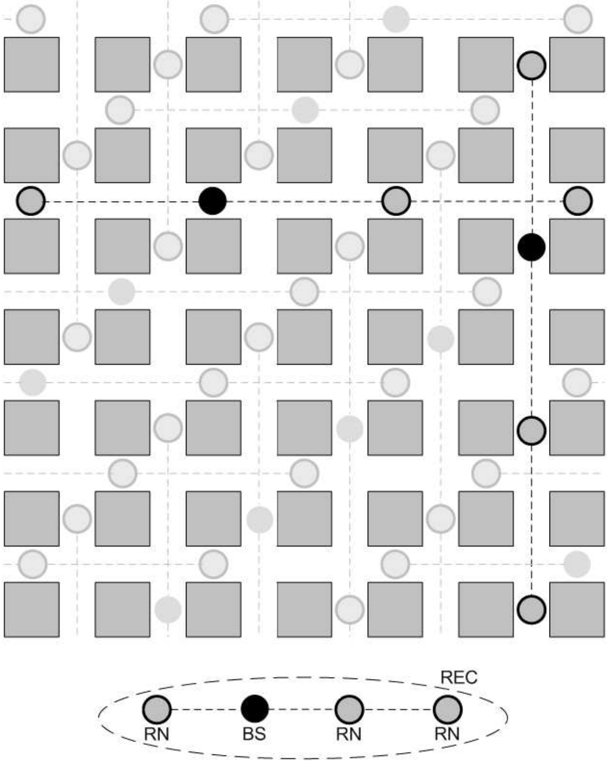


Figure 4.18: Multiband operation in metropolitan area scenario. The closer RNs right of and down from the BS are equipped with a Multiband Scheduler.

To investigate the potential benefits of RNs equipped with an MBS and a B band radio interface for the spectrum allocation in Figure 4.16 we study the coverage for indoor users in the scenario presented in Figure 4.18. Each BS is equipped with two sectors and they form together with three RNs in the same street a relay enhanced cell. The sectors to the right and down have two RNs whereas the RN closer to the BS is equipped with an MBS. The other RNs have only an E band radio interface. Table 4.10 compares the coverage area of the different bands for this scenario. The coverage area has been calculated using the pathloss models presented in Section 4.3.1 and in [109]. In particular we applied the B1 LOS model for points in the same street as the radio access point (BS or RN) and the B1 NLOS model for points in different streets. Inside the building blocks we use the B4 outdoor-to-indoor model, whereas we assume an indoor pathloss of 0.5dB/m for the E band (as specified by the model) and 0.3dB/m for the B band to take into account the lower indoor propagation losses at 860MHz than at 3.4GHz. In both cases the BS and RN use a transmit power of 30dBm and the BS is equipped with a 120 degree sector antenna having 11dBi antenna gain, whereas the RN is equipped with an omni-directional antenna and an antenna gain of 7dBi, following the assumptions in [123].

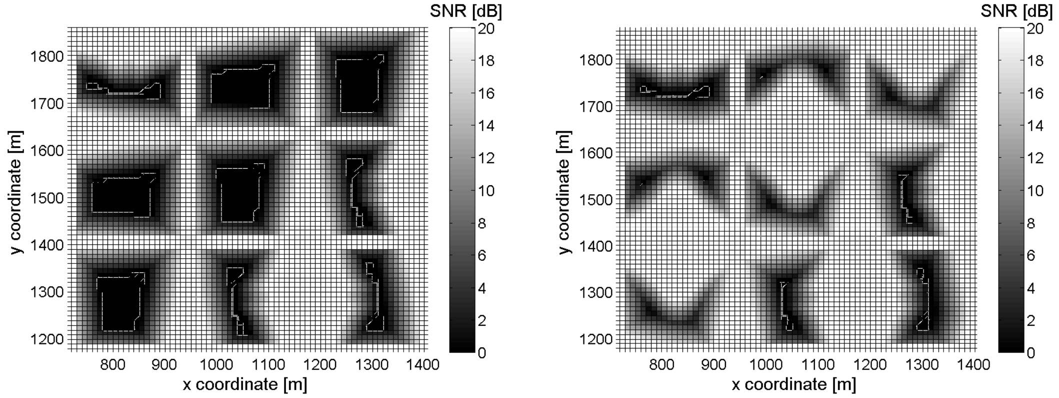
Table 4.10: Area with a spectral efficiency higher than 1bps/Hz

E band	60%
B band without RN	68%
B band with RN	83%

The E band can only provide a spectral efficiency of more than 1b/s/Hz in 60% of the area even though every radio access point is equipped with an E band interface. The BSs alone can already provide this spectral efficiency for the same area on the B band. However, since the bandwidth on the B band is only 10MHz, the capacity will be much lower. The coverage area can be further increased to 83% by equipping one third of the RNs with a B band interface.

The coverage for the B band in the center area of the scenario in Figure 4.18 is illustrated in Figure 4.19(a) and Figure 4.19(b) for the case when only BS have a B band radio interface and for the case where additionally one third of the RNs are equipped with a B band radio interface, respectively. This comparison clearly shows that the B band should be available at the RN as well to provide coverage. However, due to the lower bandwidth of the B band, the B band should only be used to serve MT that cannot be served on the E band but not for forwarding data to the RN. Therefore, the RN should be equipped with an MBS to be able to receive data on the E band and forward it on the B band to MTs that it serves on the B band.

On the other hand, for relay deployments with more than two hops the BS might be able to reach RNs via one hop on the B band and via multiple hops on the E band. In this case, it might be beneficial for delay sensitive traffic to send data on the B band to the RN, which forwards it then to the MT.



(a) Only BS equipped with Multiband Scheduler

(b) BS and every third RN equipped with Multiband Scheduler.

Figure 4.19: Coverage comparison of relay and BS only deployment with similar costs.

4.5 Comparison to related work

There are only few performance results available in literature for relays in a cellular network. In the following we will list some of these results, their main findings and we will compare their assumptions and evaluation tools to our work. The main focus of our work has been on the downlink of OFDMA systems. Therefore we will start with results on OFDMA systems and later only briefly discuss results on cellular systems which are not based on OFDMA and on results obtained for the uplink.

Table 4.11 compares our results to the results available in literature. The results have been obtained with very different assumptions, i.e. they are typically not directly comparable. The main focus of our work has been on the metropolitan area scenario. However, since there are no comparable results we also compare our results obtained with the same simulation tool in a wide area test scenario [26]. Similar to most results obtained in the wide area we assumed that the RN transforms a non line-of-sight (NLOS) BS-MT

Table 4.11: Summary of downlink performance comparisons of BS only and relay deployments in cellular OFDMA systems

	Cell TP	5 percentile User TP	Comments
Wide area			
DRS [25]	+45%	-	NLOS RN-MT
static resource assignment [82]	+25%	NA	non full buffer, LOS RN-MT
Dynamic resource assignment [124]	+100%	-	LOS RN-MT, 14 RN per site
Dynamic resource assignment [125]	+90%	NA	Non full buffer, no sectors at BS, macro RN 3dB less tx power
Our results [26]	+ 89%	+185%	LOS RN-MT, 12 RN per site
Metropolitan area			
Our results indoor users	+5%	+254%	1RN per site, BS and RN in street
Our results outdoor users	-6%	-32%	1RN per site, BS and RN in street
Directional antennas outdoor users [126] and [127]	-	-	No comparison with BS only, BS and RN at street crossing 4RN per site

link into two line-of-sight (LOS) BS-RN and RN-MT links. Table 4.11 shows that the our simulation show similar gains from relay deployments as other research groups.

The results in [82] and in [25] use the same test scenario as in our work. However, the studies in [82] do not include frequency adaptive scheduling and the resource assignment is not optimal which explains the lower gains from deploying relays. The results in [25] do not assume a LOS RN-MT link but utilize a sophisticated interference coordination scheme, called Dynamic Resource Sharing (DRS) [128], [85]. Even though the interference coordination scheme reduces the interference generated by the BS to the sub-cells formed by the RNs, the cell throughput increases only by 45% compared to 90% - 100% achieved with the LOS assumption.

The IEEE 802.16j has issued a standard [129] and first performance results for the downlink of such a system are available. In [124] a scenario with 14 RN added to each BS in a macro-cellular deployment with a cell radius of 1km is studied. The scenario is based on a wide area BS deployment modeled by a hexagonal grid augmented by micro-cells deployed below rooftop. Under the assumption of a LOS BS-RN and RN-MT link the relay deployment increases the downlink capacity of the cellular network by more than 100%.

In [125] different reuse pattern and path selection rules have been studied. The results show that a macro-cellular relay deployment can serve up to 90% more users than a BS based deployment. However, this comparison does not consider sectors at the BS and shadow fading as well as fast fading is not modeled. Further, the RN transmission power is only 3dB less than the BS transmission power, which would not result in significant cost savings due to the use of relays. The results in [130] indicate that for relays that do not extend the coverage area of a BS (transparent relays in IEEE 802.16j) the performance gains are below 5%.

Another set of assessment results for a WiMAX relay deployment in a metropolitan area is available in [126] and [127]. Unfortunately, there is no comparison with a BS only deployment but the results show significant gains from using directive antennas. In this work it is assumed that the BSs and RNs are deployed at street crossings with directional antennas covering the streets leading to the crossing. In practical deployments it will be hard to deploy a radio access point at street crossings and therefore our work focuses on a deployment in the streets which is also recommended by 3GPP in [117] and similar to [126] and [127] we also utilize directive antennas (sectors) at the BS. Secondly, the previous work in the metropolitan area has focused on outdoor users in the street whereas we consider also users inside the building blocks that typically account for most of the traffic in a cellular network.

In addition to multi-cell studies, several aspects of the cellular downlink of OFDMA systems have been studied for a single cell. In [81] the OFDMA resource allocation for a single cell with multiple users is analyzed. The results show that an independent max C/I scheduler at the BS and the RN with local channel knowledge looses only 10% compared to a centralized scheduler with channel knowledge of all the BS-MT, BS-RN and RN-MT links. In these studies the relay deployment achieves 15% higher data throughput and the outage probability is reduced from 30% to 20%. These results illustrate the potential of relay networks to distribute the high bit rate coverage more evenly over the cell. Moreover, most of the gain can already be achieved with local channel knowledge, i.e. the BS does not know the channel state information (CSI) of RN-MT links and it is not necessary to forward the CSI of RN-MT links to the BS. Using only local CSI information the RN can quicker respond to channel variations than a centralized scheduler at the BS. Further, the amount of control signaling between RN and BS is greatly reduced compared to a centralized scheduler at the BS.

In [131] it is shown that the optimization of the sub-frame duration (RN transmits to MT/RN receives from BS) together with sub-carrier allocation improves the overall cell throughput compared to sub-carrier allocation only as proposed in [132]. These single cell results confirm that the sub-frame duration should be flexible as proposed by our dynamic resource assignment.

In addition to the aforementioned results there are also results available for non-OFDMA systems. The performance results for the iCAR system in [77] show that the system can reduce the call blocking and dropping rate. For a scenario with 3 RN per cell which are placed at the cell border, the call blocking rate can drop from 10% to 1% by using RNs to offload traffic from a hot spot to cooler cells. The 1% call blocking rate is achieved when the RNs cover at least 20% of the cell area. The proposed relaying mechanism decreases also the call dropping rate due to mobility of the MTs. However, differently to the relays studied in WINNER the concept is based on out-of-band relays that require additional bandwidth. Further, in these studies the radio propagation was not modeled. Nevertheless, it shows that there are potentially big gains from load balancing between different cells by using relays.

The performance of a multihop cellular network architecture with mobile terminals as relays has been studied in [7]. When keeping the same base station density their analysis shows a system throughput increase of about 40% if all the traffic is between sources and destinations within the same cell. Further, these studies also suggest that multihop cellular networks with MTs as relays can be used to increase the coverage area of a cell. However, the results in [7] are not directly applicable to cellular networks because they do not take into account that BS and RN may have a different coverage area. Similar to the performance analysis for the iCAR studies also the radio propagation has not been modeled. Further, the results have been obtained for an 802.11 Request to send (RTS)/Clear to Send (CTS) protocol [133] which is not used in cellular networks. The reported throughput increase of 40% has been obtained for 100% of the traffic within the same cell and no performance increase could be obtained for traffic when the sources or destinations of the traffic are outside the cell. Since most of the traffic in current cellular network does not stay within a single cell, the expected gains from MT relays are low. In addition the overhead from route discovery and route maintenance is not modeled which can be significant in scenarios where the mobile relays are moving and when short response times are required. Finally, mobile relays cannot be used for coverage extension in the initial deployment of a cellular network since the mobile terminal density is low. These were also the main reasons why we considered only fixed infrastructure RNs in the WINNER project. However, there is a great potential of handling local traffic within a cell by allowing direct device-to-device communication between MTs [134], [135] and [136].

In [78] the performance of relays in an 1xEV-DO cellular network with a centralized scheduler has been studied. The results show that the aggregate downlink throughput can be increased by about 20-30% for relays with 20dB less transmit power than the BS, which is comparable to the scenario considered in our work. In these simulations it has been assumed that the BS knows for each mobile terminal the received signal strength for the two strongest relays, the current rate for these links and the buffer status of each relay. Based on this knowledge the BS selects the optimal route for each packet and the parallel transmissions which maximizes the rate in the cell. In these studies the relays operate only on the cellular downlink since they have to send feedback information on the uplink and cannot receive at the same time from MTs.

A comparison of the uplink capacity in a wide area scenario with and without relays for an IEEE802.16j system in [137] shows a 40% increase in capacity. Similar to our assumptions in the WINNER project, this paper assumes a favorable link between the BS and RN. Further, the amount of time slots used for BS-RN and RN-MT communication has been chosen such that the overall cell throughput is maximized. System performance results of relay based deployments for the cellular uplink for the WINNER system can be found in [80].

4.6 Summary and discussion

In this Chapter we presented an extensive set of system simulation results which evaluate the proposed technologies for relay networks. One of the main conclusions from these results is that relay deployments in a metropolitan area are cost efficient for a BS to RN cost ratio of about three when considering mainly outdoor-to-indoor coverage. We presented some example cost figures which indicate that using the WINNER assumptions on RNs the costs of a RN could be about one sixth of the costs of a two sector micro BS in this scenario. Hence, the relay deployment is clearly more cost efficient than the BS only deployment. Secondly our cost studies show that a relay deployment provides clearly a better high bit rate outdoor-to-indoor coverage than a BS deployment with similar costs.

When comparing different interference coordination options in a metropolitan area relay network, the results clearly indicate that a restrictive interference coordination is not needed and a frequency reuse of one should be targeted. Overly restrictive interference coordination schemes can lead to significant performance degradation, e.g. the average cell throughput of the most restrictive interference coordination scheme was less than half of the cell throughput of the best performing resource assignment.

Interference coordination based on soft frequency reuse (SFR) is well suited for metropolitan area networks. SFR together with our proposed interference aware scheduler increases the fifth percentile of the user throughput cumulative distribution function and reduces the indoor users with zero throughput. Our results also show that SFR clearly outperforms fractional frequency reuse a competing interference coordination scheme. The improvements due to SFR and the interference aware scheduler are higher in the BS only scenario than for the relay deployment.

Finally, we presented results for a network with multiband operation. The network uses 10MHz at 860MHz (B band) and 90MHz at 3.4GHz (E band). A macro BS deployment provides coverage at the lower frequency band and RNs are utilized to increase the coverage area of the higher frequency band. Adding the E band to the B band at the BS increases the cell throughput seven fold. However, the high capacity E band is not available for most of the users in the cell and the increase does not fully scale with the increase in bandwidth. When using RNs to extend the E band coverage the throughput increases twelve fold and more importantly the high capacity E band is available to most of the users in the cell.

Chapter 5

Conclusions

Cellular deployments based on in-band relays are a promising alternative for next generation communication systems. The relays extend the (high-bit rate) coverage of a base station and cover otherwise shadowed area. Relays enable a cost efficient deployment at carrier frequencies beyond 2GHz that can support high aggregate data rates of up to 1Gbit/s with a system bandwidth of up to 100MHz.

Our performance assessments show that relay deployments in a metropolitan area scenario are cost efficient for a BS to RN cost ratio of three which is significantly below the expected cost ratio of six for the studied relay properties. For the performance comparison we have chosen the important case of an operator that wants to upgrade an existing UMTS BS deployment to a next generation system with an increased bandwidth of 100MHz operating above 3GHz. Adding relays to such a BS deployment increases the outdoor to indoor coverage significantly and the fifth percentile of the user throughput cumulative distribution function more than triples.

The most promising next generation communication systems such as 3GPP Long Term Evolution, Worldwide Interoperability for Microwave Access (WiMAX) or 3GPP2 Ultra Mobile Broadband (UMB) are all based on Orthogonal Frequency Division Multiple Access (OFDMA). Therefore the integration of relays into OFDMA systems is of high interest. Not surprisingly relays as part of an infrastructure based network have already been standardised in the Technical Specification Group j (TSG j) of IEEE802.16j [5] and it is a study item in 3GPP.

In this thesis we have studied the main aspects to make relaying applicable to cellular networks. We have focused on selected functions which are crucial for the performance of cellular relay networks based on OFDMA. In particular we have presented our work on dynamic resource assignment in relay enhanced cells and the integration of cooperative relaying into an OFDMA based cellular system, based on the WINNER system concept. The dynamic resource assignment framework allows to flexibly assign the RN to act as a MT to communicate with the BS and to act as a BS to serve associated MTs. Next to this coordination in the time domain, the dynamic resource assignment framework enables a coordination in frequency and spatial domain to adapt to a wide range of scenarios. We have also shown that the framework can be applied to the IEEE 802.16j standard with small changes to allow coordination in the frequency domain.

We proposed a resource assignment based on soft frequency reuse for metropolitan area networks. Soft frequency reuse introduces signal to interference plus noise ratio (SINR) variations that can be exploited by the scheduler to schedule high power resources with reduced interference to MTs in the border area between radio access points and in areas with limited coverage. We have developed a novel interference aware scheduling algorithm that is able to exploit these SINR variations while reducing the feedback required from MTs to support the scheduler at the BS or RN. MTs with low SINR need to report channel quality information only from resource blocks with high power, e.g. one third of the resource blocks. In a BS only deployment with outdoor users soft frequency reuse with the interference aware scheduling strategy improves the 5 percentile of the user throughput cumulative distribution function by 41% and the average cell throughput by 8% compared to reuse one. For indoor users the number of users with zero throughput is reduced from more than 5% to 3%. For the default relay deployment and users in the street, the fifth percentile of the user throughput CDF increases by 14% and the average cell throughput by 2%. For indoor users the fifth percentile of the user throughput CDF increases by 13% while keeping the same average cell throughput. The number of indoor users with zero throughput decreases from 0.8% to 0.5%. Event though the improvements are not as big as in the BS only case it is still relevant and the reduced feedback option of the interference aware scheduler will reduce the feedback load for the MTs.

We have outlined how to integrate cooperative relaying into a cellular system. We proposed to give the control of the cooperative transmissions to the first common node in the tree topology. This node does not have to be involved in the cooperative transmissions. Using the first common node ensures short delays and gives flexibility in the nodes that can cooperate. For example cooperative relaying is not restricted to BS-RN cooperation and to avoid excessive system complexity a cooperation between nodes of neighboring cells is not supported. The cooperative relaying concepts allows the distributed use of all multi-antenna transmission schemes used in the network. However, sophisticated multi-user MIMO pre-coding schemes will require high quality links between BS and RNs to support the signalling overhead from such schemes. In order to reduce delays we introduced the serving radio access point concept for cooperative transmissions. The serving radio access point signals control information, such as the resource allocation to the cooperatively served MT and performs retransmissions which are not done cooperatively. This enables fast retransmissions on resources assigned to the serving radio access point since there is no coordination between the cooperating radio access points needed.

The integration of relays into a cellular network requires a careful cross-layer design and many other functions have to be designed with relays in mind. In particular we have presented an end-to-end relay ARQ scheme that ensures reliable data communications without excessive overhead. In addition to a reliable end-to-end connection, it allows the relay to send outer-ARQ acknowledgements to the previous node (BS or RN) to recover from HARQ errors on that hop, e.g. when a NACK is interpreted as ACK at the previous node (BS or RN). The relay uses only one bit to indicate that the feedback message is not sent from a MT but from a RN. The additional bit is only needed for RN-BS communication (and RN-RN communication for more than two hops) and it does not increase the amount of data transmitted by the MT.

The World Radiocommunications Conference (WRC'07) in 2007 has identified new spectrum for IMT systems in several bands. IMT-Advanced systems can also operate on bands that are currently allocated to 2nd and 3rd generation communication systems. Thus, it is foreseen that future systems will benefit from operating on multiple bands. We have presented a new concept called Multi-Band Scheduler (MBS) that enables a fast and seamless switch between different bands and it abstracts the PHY and MAC layer operation on multiple bands from the higher layers.

We discussed the operation of the MBS in detail for a relaying scenario with different propagation properties and thus different coverage area of the used bands. In this scenario RNs are used to extend the coverage of the high capacity extension band that has a higher propagation loss than the basic band. Our simulation results show that RNs are an effective way to balance the coverage of the bands. Thereby, they increase the overall capacity of the network by 80% and the high capacity band is available to most of the users in the cell. Further, our results show that multiband operation at both the BS and the RN increases the high bit rate coverage and enables to balance the network load on each hop by utilizing different bands.

In addition we have introduced the idea to utilize the amplify and forward (AF) within the cyclic prefix (CP) protocol for cellular relays in metropolitan area networks. Both the signal transmitted by the source and the relay arrive within the cyclic prefix at the destination and the receiver treats the signal transmitted by the relay simply as an additional multi-path component. Thereby, it avoids the rate loss from half-duplex relay operation but requires full-duplex operation of the relays. Even though this sounds promising there are implementation related challenges on how to provide sufficient isolation between transmit and receive antennas. In addition signal processing is needed to suppress the self-interference and the resulting delays together with the additional propagation delays have to be lower than the cyclic prefix. Nevertheless, these challenges can be overcome and AF within the CP is utilized for example by gap fillers in DVB-T and DVB-H broadcast systems. Similarly, it could be utilized to enhance a Multimedia Broadcast Multicast Service (MBMS) based on a cellular deployment.

To sum up, we have presented a selection of enabling technologies for an efficient and reliable operation of cellular relay networks. We have studied the proposed technologies in dynamic system simulations and our results show the great potential of relays that utilize the proposed enabling technologies for next generation communication systems.

There are plenty of possible topics to continue the work on in-band relays for next generation communication systems and in the following we will present some promising future research directions.

In our work we have mainly focused on the downlink but the potential gains from relaying are even greater in uplink. Relays reduce the distance to the serving AP for MTs which can improve the achievable uplink data rates especially for power limited MTs. Research questions that should be addressed include the radio resource management between BS and RN for the uplink, uplink scheduling strategies and related performance evaluations. Further, it should be studied, how to select the serving AP (BS or RN). Since BS and RN have significantly different transmit power, big differences in uplink and downlink link quality can be expected. This situation is similar to having co-channel deployments of wide area base stations and Femto base stations, which is currently studied within the heterogeneous networks study item in 3GPP.

Currently, our dynamic resource assignment concept assumes that the BS assigns the resources to the RN in its relay enhanced cells. This strategy should be compared to distributed solutions, e.g. building on our adaptive soft frequency reuse scheme with the suggested enhancements in this thesis. Further, it should be studied if there is potential gain from cooperation of multiple relay enhanced cells in the resource assignment. Another important aspect is the relay operation in the framework of LTE-Advanced which allows to aggregate multiple carriers. It should be studied how to optimally utilize the available carriers in the presence of relays.

Finally, there are possible directions to continue our work on cooperative relaying. The proposed cooperative relaying concept should be evaluated and the concept should be refined based on these evaluation results. In addition, the integration of cooperative relays with coordinated multi point transmissions of multiple BS should be studied.

Appendix A

List of publications

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