Peter Rost

Opportunities, Benefits, and Constraints of Relaying in Mobile Communication Systems

Beiträge aus der Informationstechnik

Mobile Nachrichtenübertragung
Nr. 46

Peter Rost

Opportunities, Benefits, and Constraints of Relaying in Mobile Communication Systems

VOGT

Dresden 2009

Bibliografische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.ddb.de abrufbar.

Bibliographic Information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibiograpic data is available in the internet at http://dnb.ddb.de.

Zugl.: Dresden, Techn. Univ., Diss., 2009

Die vorliegende Arbeit stimmt mit dem Original der Dissertation „Opportunities, Benefits, and Constraints of Relaying in Mobile Communication Systems“ von Peter Rost überein.

Gesetzt vom Autor
Printed in Germany

ISBN 978-3-938860-23-6

Jörg Vogt Verlag
Niederwaldstr. 36
01277 Dresden
Germany

Phone: +49-(0)351-31403921
Telefax: +49-(0)351-31403918
e-mail: info@vogtverlag.de
Internet : www.vogtverlag.de

TECHNISCHE
UNIVERSITÄT
DRESDEN

Fakultät Elektrotechnik und Informationstechnik, Institut für Nachrichtentechnik

Opportunities, Benefits, and Constraints of Relaying in Mobile Communication Systems

Peter Matthias R. Rost

von der Fakultät Elektrotechnik und Informationstechnik
der Technischen Universität Dresden

zur Erlangung des akademischen Grades eines

Doktoringenieurs
(Dr.-Ing.)

genehmigte Dissertation

Vorsitzender:	Prof. Dr. techn. Klaus Janschek
Gutachter:	Prof. Dr.-Ing. Gerhard P. Fettweis
	Prof. J. Nicholas Laneman
Tag der Einreichung:	06. April 2009
Tag der Verteidigung:	24. Juni 2009

Abstract

Over the last decade wireless and mobile communication has become manifest in our everyday life. Furthermore, the development of ever increasing data rates, seamless mobility, and unlimited flexibility will not decline but rather accelerate. While existing mobile communication networks improved service quality and reached more users than ever before, new markets developed all over the world where mobile communication continues its success story with an unknown growth. Motivated by the chances and benefits, wireless and mobile communication systems undergo a change from only providing voice and other multimedia message services to systems which deliver internet to any place in the world. However, this ambitious goal cannot be accomplished with conventional cellular systems and instead requires new technologies such as multi-cell cooperation, movable radio access points without backhaul connection, and multiple-antenna transmission.

Among the most challenging problems in cellular networks is inter-cell interference. In order to assure sufficient quality of service, currently deployed systems try to avoid interference by coordinating resources such that two adjacent areas do not use the same spectrum. By contrast, multi-cell cooperation aims at exploiting interference instead of avoiding it, which is achieved by an additional cooperation among multiple radio access points instead of solely coordinating resources. Furthermore, the density of radio access points in currently deployed cellular networks increases in order to improve the reuse of available resources and to serve more user terminals at high data rates. This implies higher deployment costs which demands low-cost and flexible alternatives. In this thesis relaying is introduced as one possibility to increase the number of radio access points, to improve the resource reuse, and to organize cellular networks more flexibly. However, relay nodes also introduce more interference in the network, which demands more sophisticated interference mitigation algorithms.

This thesis discusses at first the full-duplex relay channel where multiple relay nodes support a single communication pair. Using this channel, coding strategies with different complexity and operating regions are introduced and evaluated in the context of a Gaussian system model. Through this performance analysis, simple high-performance protocols are identified and applied in the remainder of this thesis. Building on this analysis, the half-duplex relay channel introduces the orthogonality constraint, which prohibits simultaneous receiving and transmitting on the same time-frequency resource. Based upon this more practical consideration, different protocols are introduced, discussed, and again evaluated using a Gaussian system model.

Using the interference and broadcast channel, the half-duplex relay-channel is extended by a scenario with multiple communication pairs each supported by multiple relay nodes. With such a system model upcoming challenges in relay-based next generation mobile communication networks can be modeled and evaluated. For instance, protocols with coordination and cooperation on both source-to-relay and relay-to-user links are introduced and discussed. In order to analyze the extended relay-channel, the discussed protocols are applied to a setup, which uses a simplified channel model derived from a mobile communication system. The outcome is that a simple cascade of inter-source cooperation and inter-relay coordination achieves significant rate improvements over conventional systems while providing a significant amount of flexibility.

The analysis is rounded off with a system-level evaluation, which applies the previously derived protocols to a mobile communication system. For instance, an urban macro and micro-cellular scenario are discussed using the achievable rates and throughput within the respective scenario. Furthermore, a cost-benefit analysis is carried out, which focuses on the tradeoff between necessary costs to deploy relay nodes and achieved benefits through relaying. Using this evaluation, this work provides a proof-of-concept for relaying as an integral part of next generation mobile communication systems.

This thesis develops step-by-step a proposal for a relay-based mobile communication system. It shows that simple protocols, which decode and forward the source message appear favorable in a mobile communication system with fixed relay nodes. A cooperative access from source nodes to relay nodes is able to improve data rates on the feederlink and therefore counteract the loss caused by the half-duplex channel access of relay nodes. Thereafter, using multiple micro-cells relay nodes can improve the spectrum reuse while keeping the additional deployment costs low. Hence, for the analyzed scenarios relaying appears to be an interesting and viable possibility to improve data rates and flexibility in next generation mobile communication networks.

Zusammenfassung

In den letzten Jahren konnte sich drahtlose und mobile Kommunikation als fester Bestandteil unseres täglichen Lebens etablieren, wobei die Entwicklung hin zu immer höheren Datenraten, grenzenloser Mobilität, sowie unbegrenzter Flexibilität keinen Abbruch nimmt sondern stetig ansteigt. Während bestehende Mobilfunknetzwerke die erreichbaren Raten und die Anzahl unterstützter Nutzer erhöhen, werden immer neue Märkte erschlossen in denen die Mobilfunkkommunikation ihren Siegeszug fortsetzt. Drahtlose und mobile Funknetze durchlaufen eine Entwicklung von Sprach- oder Multimediadiensten hin zu Systemen, welche den primären Anschluss an das Internet darstellen. Um dieses anspruchsvolle Ziel zu erreichen, werden neue Technologien benötigt, wie z. B. Kooperation mehrerer Zellen, bewegliche Zugriffsknoten ohne Festnetzanbindung an das Datennetzwerk sowie Mehrantennenübertragung.

Zu den herausfordensten Problemen in zellularen Funknetzen gehört wohl die Interferenz zwischen den einzelnen Zellen. Um eine hinreichende Dienstequalität zu gewährleisten, koordinieren heutige Netze ihre Ressourcen so, dass zwei sich angrenzende Zellen unterschiedliche spektrale Ressourcen verwenden. Im Gegensatz dazu nutzt man Interferenz in Systemen mit Mehrzellenkooperation aus, indem z. B. mehrere Basisstationen kooperativ Nutzer versorgen anstatt lediglich die verwendeten Ressourcen zu koordinieren. Zudem wird die Dichte an Zugriffsknoten in derzeit verwendeten Systemen stetig erhöht, um die Wiederverwendung des Spektrums zu verbessern und die Anzahl der versorgten Nutzer zu erhöhen. Die Erhöhung der Knotendichte bedeutet jedoch eine Zunahme der notwendigen Aufbaukosten und erfordert darüber hinaus flexible und kostengünstige Alternativen zu bestehenden Technologien. In dieser Arbeit wird Relaying als eine solche Möglichkeit eingeführt, um die Dichte der Zugriffsknoten zu erhöhen, die Wiederverwendung des Spektrums zu verbessern sowie die Organisation des Netzwerkes flexibler zu gestalten. Nichtsdestotrotz verursacht Relaying auch eine Zunahme der Interferenz innerhalb der einzelnen Zellen, wodurch neue Algorithm zur Interferenzunterdrückung notwendig sind.

Zunächst führt diese Arbeit den Vollduplex-Relaykanal ein, in dem ein einzelnes Kommunikationspaar durch mehrere Vollduplex-Relayknoten unterstützt wird. Mit Hilfe dieses Kanals werden Kodierstrategien mit unterschiedlicher Komplexität und Wirkungsregionen eingeführt und anschliessend für ein Systemmodell mit Gaussch'schen Rauschen evaluiert. Diese Analyse identifiziert einfache Protokolle mit hinreichender Leistung, welche auch im weiteren Verlauf der Arbeit verwendet werden. Aufbauend auf dieser Analyse führt anschliessend der Halbduplex-Relaykanal die Orthogonalitätsbedingung ein, welche besagt, dass ein Relayknoten nicht auf der gleichen Zeit-Frequenzresource senden und empfangen kann. Auch für diesen Kanal werden verschiedene Protokolle vorgestellt, diskusiert sowie mit Hilfe eines Kanals mit Gauss'scher Signalisierung evaluiert.

Daran anschliessend wird der Halbduplex-Relaykanal mit mehreren, parallen Kommunikationspaaren auf Basis des Broadcast- und Interferenzkanals eingeführt. Mit Hilfe dieses Modells können die Probleme und Anforderungen in einem relaybasierten Mobilfunknetz modelliert und evaluiert werden. Unter anderem werden Protokolle basierend auf Koordination and Kooperation von Quell- und Relayknoten diskutiert. Weiterhin werden diese Protokolle auf ein vereinfachtes Kanalmodel eines Mobilfunknetzes angewandt und analysiert. Es zeigt sich, dass eine einfach Kaskade von Quellknotenkooperation und Relayknotenkoordination in der Lage ist, eine signifikante Verbesserung der Raten gegenüber einem gewöhnlichen Mobilfunknetz zu erreichen.

Die Analyse dieser Arbeit wird durch eine Analyse auf Systemlevel abgeschlossen, welche die zuvor eingeführten Protokolle in einem Mobilfunksystem anwendet. Unter anderem werden die erreichbaren Raten in städtischen Szenarien mit Mikro- bzw. Makrozellenstruktur diskutiert. Weiterhin wird die Leistung der eingeführten Protokolle in Abhängigkeit von den Kosten für den Aufbau eines Relaynetzwerkes analysiert. Mit Hilfe dieser Analyse ist es möglich, die Umsetzbarkeit von Relaying als zusätzliche Option eines Mobilfunksystems zu beurteilen.

In dieser Arbeit wird schrittweise ein Vorschlag für ein relaybasiertes Mobilfunknetz herausgearbeitet. Unter anderem wird gezeigt, dass einfache Protokolle, bei denen das Relay die vollständige Nachricht dekodiert und weiterleitet, eine sehr gute Leistung bieten und dennoch die Kodier- und Dekodierkomplexität hinreichend gering ist. Weiterhin kann der Flaschenhals eines Relaynetzwerkes, die Verbindung zwischen Quelle und Relay, mit Hilfe einer kooperativen Übertragung wesentlich verbessert werden. Aufgrund der parallen Verwendung mehrerer Relayknoten können zudem mehrere Mikrozellen zu jeder Basisstation zugeordnet und parallel versorgt werden. Durch die mehrfache Verwendung der gleichen Resourcen innerhalb einer Zelle, kann Relaying in Mobilfunknetzen der nächsten Generation signifikante Ratenverbesserungen erreichen und erscheint demzufole als ernsthafte Zusatzoption für diese Netze.

Acknowledgments

This thesis is the result of my work at the Vodafone Chair Mobile Communications Systems at Technische Universität Dresden. I am deeply grateful to Professor Gerhard Fettweis for providing so many exciting opportunities and guiding me over the past four years. Due to his motivation and support I was allowed to meet innumerable thrilling challenges and to advance not only but particularly my academic skills. It was also Gerhard who enabled an exciting research exchange at the University of Notre Dame and the group of Professor J. Nicholas Laneman. I would like to express my gratitude towards Professor Laneman for many fruitful discussions and his substantial support during and after visiting Notre Dame.

Since June 2005 I was allowed to become acquainted with so many admiring persons; two of them are Ernesto Zimmermann and Clemens Michalke, who had to answer many questions and never lost their patience. Furthermore, I would like to express my sincere appreciation to Marco Krondorf and Steffen Bittner for sharing their wisdom and scientific expertness as well as for the great time on our various business trips. Ernesto Zimmermann, Stefan Krone, and Patrick Marsch are the most critical and careful reviewers I met over the past four years. Even though you did not always agree in opinion, you never lost the ability to find solutions and sometimes also new problems. Your critical insights and merry nature made my thesis better and my work more pleasant. Thanks also go to Ines, Andre, Bastian, and Torsten for the unpayable foosball experience. Writing a thesis offers the possibility to met many, many more interesting people, who all together help a lot advancing your work. Even though each of them surely deserves particular attention, I am hopefully excused not mentioning everyone.

My time at the Vodafone Chair has been complemented with the enriching work in the European research project WINNER and the amazing experience, which I made while organizing IEEE ICC 2009. WINNER offered me the chance to meet many interesting people, to discuss and defend my work, and to learn aspects, which proved to be an important part of my Ph.D. thesis. In particular, I want to thank Klaus Doppler for the long and fruitful discussions. ICC 2009 allowed me to be part of a great team and to acquire insights I never thought of before. I learned many important lessons beyond my academic education while working with an excellent local organizing team, technical program committee, and the organizing team of the IEEE Communications Society. In addition, I want to express my particular appreciation of the support of the German Academic Exchange Service (DAAD), which partly financed my research visit at Notre Dame. Furthermore, I highly appreciate the support of the Center for Information Services and High Performance Computing (ZIH), which provided the necessary computing power.

Lastly but certainly not less importantly I want to thank my friends for their support, for proving that their is a life before death, and for their never ending tolerance. My parents Renate and Hans-Dieter as well as my sister Susanne always believed in me, supported all my decisions, and never lost the ability to make each day a little better. Kerstin is also part of this family but soon will head our own family – I cannot imagine that there is anyone, who could have been more patient and accepting, who could be a better friend, and who could be a better human than you are. You made this thesis possible and we both will master all other challenges, which lie ahead of us.

Contents

List of Figures

List of Tables

Abbreviations

AF Amplify-and-Forward

ARQ Automatic Repeat-Request

AWGN Additive White Gaussian Noise

BC Broadcast Channel

BICM Bit-Interleaved Coded Modulation

BLAST Bell-Labs Layered Space-Time

CDF Cumulative Distribution Function

CDMA Code-Division Multiple Access

CF Compress-and-Forward

CSI Channel State Information

DF Decode-and-Forward

DMT Diversity-Multiplexing-Tradeoff

DPC Dirty Paper Coding

ETW Etkin-Tse-Wang

FDD Frequency Division Duplex

FEC Forward Error Correction

HARQ Hybrid ARQ

HK Han-Kobayashi

IC Interference Channel

iCAR integrated Cellular Ad-hoc Relaying

LDPC Low-Density Parity-Check

LOS Line-of-Sight

MAC Multiple Access Channel

MANET Mobile Ad-Hoc Network

MCN Multihop Cellular Network

MCS Modulation and Coding Schemes

MIMO Multiple-Input Multiple-Output

OFDM Orthogonal Frequency Division Multiplex

OSI Open Systems Interconnection

PAPR Peak-to-Average-Power Ratio

PDF Partial Decode-and-Forward

PHY Physical Layer

QoS Quality-of-Service

RAP Radio Access Point

RRM Radio Resource Management

RC Relay Channel

SINR Signal-to-Interference-And-Noise Ratio

SNR Signal-to-Noise Ratio

STTC Space-Time Trellis Code

TDD Time Division Duplex

TDMA Time Division Multiple Access

VAA Virtual Antenna Array

WRN Wi-Fi Relay Network

ZF-DPC Zero-Forcing DPC

Nomenclature

Notation

n, N	Italic letters indicate scalars
X	Uppercase, non-italic letters denote random variables
$\mathcal{X}$	caligraphic letters denote an ordered set
$[b : b+t]$	denotes the ordered set of numbers $b, b+1, \cdots, b+t$ or $\emptyset$ if $t < 0$
$\mathbf{A}$	boldface characters denote matrices
$\underline{b}$	denotes the column vector $\underline{b}$
$[\mathbf{A}]_{i,j}$	denotes the element in the i-th row and j-th column of matrix $\mathbf{A}$
$[\underline{b}]_i$	denotes the i-th element of vector $\underline{b}$
$\underline{\mathrm{X}}^{(n)}$	abbreviation for the random sequence $\left\{\mathrm{X}^t\right\}_{t=1}^n$ which is used for the sake of readability
X^t	denotes the random variable at the t-th time index of a random sequence $\underline{\mathrm{X}}^{(n)}$
X_l	denotes the random variable assigned to the l-th terminal
$\underline{\mathrm{X}}_{\mathcal{C}}$	denotes the vector of random variables X_l with $l \in \mathcal{C}$
$\mathrm{X} \overset{n}{\sim} \mathrm{p}_{\mathrm{X}}(x)$	denotes that $\underline{\mathrm{X}}^{(n)}$ is drawn i.i.d. according to $\mathrm{p}_{\mathrm{X}}(x)$
$\Rightarrow$	denotes logical implication
$\mathrm{X} \leftrightarrow \mathrm{Y} \leftrightarrow \mathrm{Z}$	denotes that random variables $\mathrm{X}, \mathrm{Y}, \mathrm{Z}$ build a Markov chain

Symbols

$\underline{I}, \mathbf{I}$	Vector where each element is 1 and the identity matrix where each element on the diagonal is 1
ρ	Signal-to-Noise ratio (SNR)
$\mathrm{C}_{\mathrm{Site}}$	Cost of one site hosting multiple base stations
$\mathrm{C}_{\mathrm{Relay}}$	Cost of one relay node
θ	Pathloss exponent
σ_{X}^2	Variance of random variable X
$\mathbf{\Sigma}_{\underline{\mathrm{X}}}$	Covariance matrix of random vector $\underline{\mathrm{X}}$

N	Receiver noise power
P	Transmit power
$d_{l,l'}$	Denotes the distance between two nodes l and l'
l	Terminal index
t	Time index
b	Block index
k	Message level index
$\mathrm{X}_l^t, \mathrm{Y}_l^t, \mathrm{M}_l^t$	Channel input, output, and state at node l and time index t
$\hat{\mathrm{Y}}_{l,k}$	k-th refinement level of the quantization of Y_l
$\mathrm{U}_{s,k}$, $\mathrm{V}_{l,k}$, $R_{l,k}$	$\mathrm{U}_{s,k}$ is the message level k sent by the source and $\mathrm{V}_{l,k}$ is the message leve k by terminal l with rates $R_{s,k}$ and $R_{l,k}$, respectively
$\upsilon_{(l',l),k}$	fraction of power spent at node l' to coherently support message level k at node l ($\mathrm{U}_{s,k}$ if $l' = s$, $\mathrm{V}_{l',k}$ otherwise)
$\omega_{l,k}$	fraction of power spent at node l for broadcast message k, i. e. $\mathrm{W}_{l,k}$
$\Upsilon^k_{(l,l')}$	the overall received power at level l' for message $\mathrm{V}_{l,k}$
$\tilde{\Upsilon}^k_{l,(m,m')}$	cross-correlation of a particular message $\mathrm{V}_{l,k}$ received at two nodes m and m'
$\Omega_l^{(k,k')}$	power of broadcast messages received at node l after decoding the broadcast messages of levels $[k:k']$
$\mathbf{K}_{(s,l)}^{(j,j')}$	covariance matrix of Y_l and all decoded quantizations $\underline{\hat{\mathrm{Y}}}_{l' \in [1:j], \phi(l)}$ when decoding the partial source message $\mathrm{U}_{s,j+1}$ and knowing $\underline{\mathrm{U}}_{s,[1:j']}$
f_{reuse}	Reuse factor

Functions

$\mathrm{I}\left(\mathrm{X};\mathrm{Y} \mid \mathrm{Z}\right)$	Mutual information between X and Y given Z
$\mathrm{H}\left(\mathrm{X} \mid \mathrm{Y}\right), \mathrm{h}\left(\mathrm{X} \mid \mathrm{Y}\right)$	Entropy and differential entropy of X given Y
$\mathrm{C}\left(\rho\right)$	Ergodic capacity of an AWGN channel with Gaussian alphabets and SNR ρ, i. e. $\mathrm{C}\left(\rho\right) = \log_2\left(1+\rho\right)$
$\Pi\left(\mathcal{X}\right)$	power set of set $\mathcal{X}$
$\pi\left(\mathcal{X}\right)$	denotes the set of permutations of $\mathcal{X}$
$\mathcal{O}_l(i)$	Denotes the i-th element of ordering $\mathcal{O}_l$
$\phi_l(i)$	Denotes the inverse of $\mathcal{O}_l$, i. e., $\phi_l(\mathcal{O}_l(i)) = i$
$\Pr\left\{\mathrm{x}\right\}$	probability of event x
$\mathrm{E}\left\{\cdot\right\}$	Expectation
$\mathrm{Var}\left\{\cdot\right\}$	Variance
$\mathrm{Cov}\left\{\cdot\right\}$	Covariance
$\mathcal{A}_\epsilon^{(n)}$	Typical set (random variables are omitted if unambiguous from the context)
$\mathcal{A}_\epsilon^{*(n)}$	Strongly typical set (random variables are omitted if unambiguous from the context)
$1\left(\cdot\right)$	Indicator function returning 1 if its argument is true
$\Vert\mathbf{K}\Vert$	Determinant of matrix $\mathbf{K}$
$\underline{x}^\dagger$	Transpose of vector $\underline{x}$
$\mathbf{K}^{\mathrm{H}}$	Hermitian transpose of matrix $\mathbf{K}$

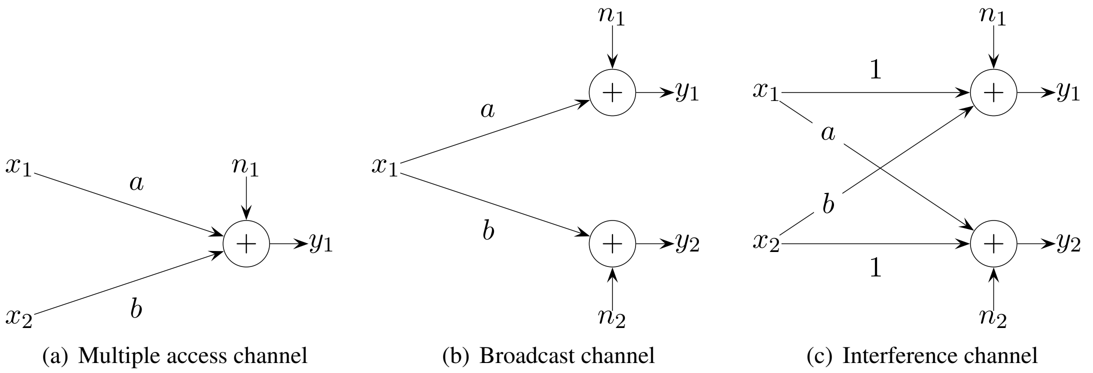
$\mathrm{Tr}(\mathbf{K})$	Trace of matrix $\mathbf{K}$
$\mathrm{Co}\,(\mathcal{S})$	Convex hull of set $\mathcal{S}$

1 Introduction

Wireless communication systems and applications for wireless terminals such as PDAs, notebooks, and cellular phones are growing in importance and have become an integral part of everyday life. With the introduction of new standards, services, and hardware supporting more sophisticated applications, the demand for higher data rates has significantly increased. In the course of this development, the number of wireless terminals has also increased, which raises the question of how to efficiently operate networks, i. e., implement transmission protocols, which exploit the signal propagation characteristics in a network of wireless terminals.

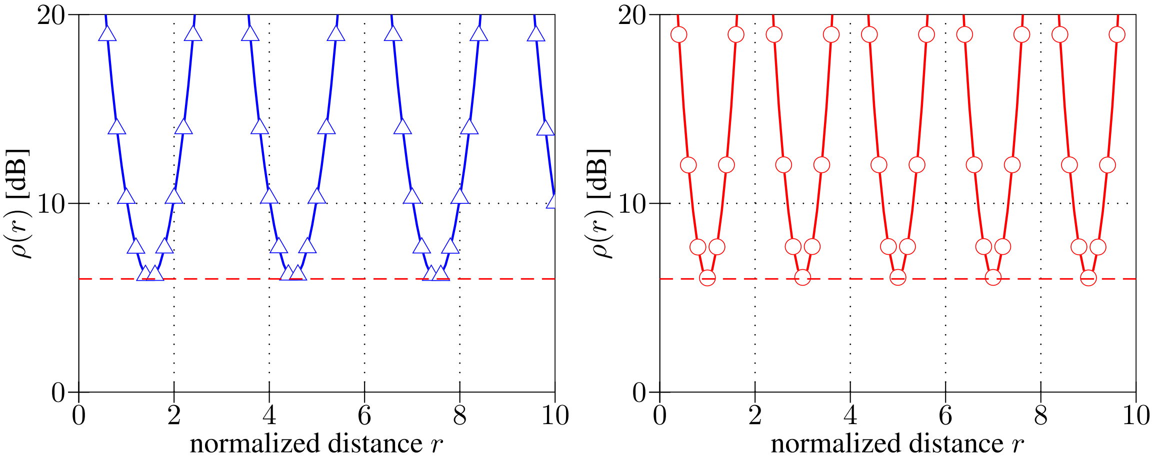
1.1 Motivation

Since Claude E. Shannon established the foundation of information theory in [Sha48, Sha49], major advances have been made in the field of point-to-point communication. However, network information theory, i. e., information theory for networks consisting of unicast and multicast-links, has not been as widely investigated. Even for networks with Additive White Gaussian Noise (AWGN) and without fading, the capacity is often not yet known. One reason for the difficulties arising during the analysis of



(a) Multiple access channel (b) Broadcast channel (c) Interference channel

Figure 1.1: Examples for three basic channels in the context of network information theory. x indicates the channel input of the source node(s), n denotes the additive noise, and y denotes the channel output at the destination node(s).



(a) Configuration A (b) Configuration B

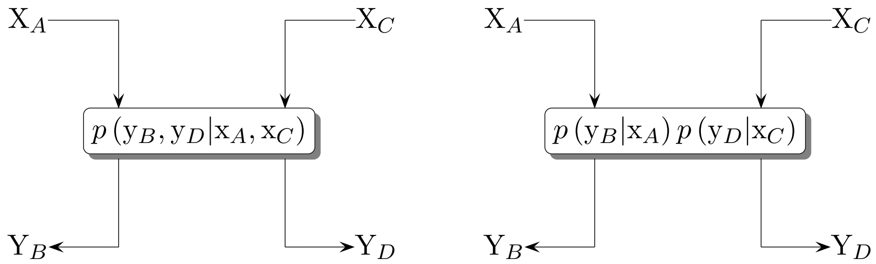
Figure 1.2: Power distribution over r for two different deployment scenarios

wireless networks is their broadcast nature. In comparison to wired networks, it is not possible that a certain transmission is only received by one dedicated receiver; it always introduces interference towards other terminals. Nonetheless, among the particular problems of network information theory, which have been solved thus far are the capacity region of the general Multiple Access Channel (MAC) which is illustrated in Figure 1.1(a), the Gaussian Broadcast Channel (BC) which is depicted in Figure 1.1(b) and, in parts of the Gaussian Interference Channel (IC) which is shown in Figure 1.1(c). Both MAC and BC are an integral part of today's wireless communication systems since the former represents the uplink channel from users to a Radio Access Point (RAP) and the latter the corresponding downlink. Nevertheless, among the unanswered questions are the Gaussian IC and the relay channel, which are both in the focus of this thesis.

To achieve the demanding goals of current and next generation wireless communication systems such as higher data rates, better connectivity, increased reliability, and more fairness, we need to address their basic challenge: interference. In comparison to a wired network where new cables can be deployed to increase the available resources, wireless networks must share the same spectrum, which makes the available bandwidth a scarce and expensive resource. In order to use the available resources as efficiently as possible, wireless communication networks must reuse them in the spatial domain; this requires sophisticated resource management algorithms. For conventional systems, spectrum reuse also implies the necessity to deploy additional base stations connected to a wired backhaul network, which significantly increases network setup and operation expenditure.

A challenging property as well as opportunity of the wireless channel is the nonlinear signal attenuation (path loss), which offers the possibility to concentrate power on certain points in the network. On the other hand, it also requires that either the density of RAPs or the transmission power must increase with the signal attenuation, which is of particular interest in wireless networks where interference plays an important role. Compared to currently deployed systems, next generation networks tend to use higher carrier frequencies where path loss becomes an even more important issue.

Consider an AWGN channel with a path loss exponent $\theta = 4$, receiver noise power N, and transmission power P. Given these qualities, the received Signal-to-Noise Ratio (SNR) at a normalized distance r is given by $\rho(r) = \sum_i P/N \cdot |r_i - r|^{-\theta}$ where r_i is the position of the i-th RAP. Figure 1.2 compares the



(a) Repeater (b) Switch

Figure 1.3: Comparison of repeaters and switches in wired networks.

received SNR in two different configurations of a wireless line network:

A: RAPs are deployed at $r_i = [0, 3, 6, \cdots, i \cdot 3]$ and each transmits with power P_{A} such that $P_{\mathrm{A}}/N = 10$,

B: RAPs are deployed at $r_i = [0, 2, 4, \cdots, i \cdot 2]$ and each transmits with power P_{B} such that $P_{\mathrm{B}}/N = 2$.

Configuration B deploys 1.5 times as many RAPs as configuration A but its RAPs transmit with one-fifth the power P_{A}. Therefore, the total energy consumption of the latter configuration is less than half of the energy consumption in configuration A, but both achieve the same minimum SNR. This example illustrates the well-known fact that densely deployed networks need less total transmission power and are able to improve fairness due to a more homogeneous power distribution. On the other hand, they face severe challenges to cope with the increased number of interfering terminals, the partly increased interference power level, and the more complex user scheduling. Another problem is the necessity to connect RAPs through a backhaul using out-of-band resources. Backhaul requirements such as the availability of a high-speed wired connection or micro-wave links to a central server diminish deployment flexibility and raise necessary expenditure. Hence, deployment and transmission strategies in next generation networks should exploit the opportunities and benefits in wireless *networks* while being able to mitigate the increased number of interferers caused by smaller cells and cost issues caused by the higher RAP density.

1.2 Relaying

One promising strategy to achieve the previously defined goals is to add intermediate nodes (known as *relay nodes*) supporting individual communication pairs. The idea of relaying is well known from wired networks where repeaters and switches are used to connect networks. Repeaters operate on the physical layer and amplify the received signal before it is forwarded. In contrast, switches operate on the medium access layer and are able to route packets to their dedicated receivers [U.S96]. Hence, switches are able to separate networks on the physical layer as illustrated in Figure 1.3 for the case where node A communicates with node B and node C communicates with node D. In the case of repeaters we have one joint pdf of *both* channel outputs depending on *both* channel inputs, whereas in case of switches, the joint pdf can be factorized such that the channel output of each destination node only depends on the channel input of the corresponding source node.

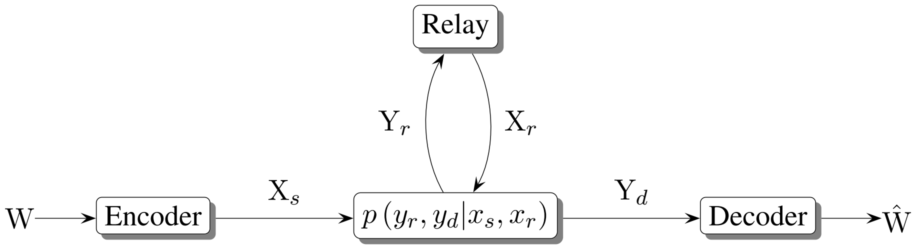


Figure 1.4: The three-terminal relay channel with channel inputs X_s and X_r and channel outputs Y_r and Y_d defined over the conditional probability density function $p(y_r, y_d|x_s, x_r)$.

Van der Meulen [vdM68, vdM71] was the first to apply this idea to wireless communication systems and introduced the three-terminal relay channel as illustrated in Figure 1.4. A single source-destination communication pair is supported by a relay node, which receives the source transmission and transmits support information to the destination node. In [CG79] Cover and El Gamal presented two basic coding strategies for the three-terminal relay channel, which are still the basis for most relaying protocols today: Decode-and-Forward (DF) where the relay node decodes the source message and provides additional, redundant information to the destination and Compress-and-Forward (CF) where the relay node quantizes its channel output and forwards the quantization to the destination.

Relays using DF and CF are operating in a *digital* relaying mode, which affects both physical and medium access layer. *Analog* relays, by contrast, work as a repeater and simply amplify and forward the received signal. Neither modes are able to separate two wireless networks on the physical layer, however digital relays are able to separate networks on the medium access layer. The former mode offers more flexibility and opportunities with respect to coding and resource assignment strategies to alleviate the effects of interference between (relay-) cells. In addition, digital relays can be seen as a micro-base station without wired backhaul instead using in-band resources as feeder link. By replacing parts of the deployed base stations with additional relay nodes, both base stations and relay nodes are able to achieve a more homogeneous power distribution while reducing expenditures due to lower hardware costs and the less developed backhaul infrastructure. On the other hand, relay nodes utilize a portion of the available bandwidth which implies a loss of spectral efficiency and raises the question of whether the improved channel conditions and the more homogeneous power distribution can outweigh this loss.

1.3 Scope, Outline, and Contribution of this Work

The focus of this work is on wireless communication systems supported by relay nodes. In particular, this work considers mobile communication systems with wired infrastructure and centralized control. This work does not consider analog relaying; rather, it analyzes approaches that utilize the degrees of freedom offered by DF and CF. Although this work is concentrated on physical layer access, it also points out how relaying affects higher layer functions such as user scheduling and resource management in mobile communication systems.

This discussion begins with Chapter 2, which addresses the protocol complexity in relay networks employing multiple relay nodes to support a single source-destination pair. In order to justify the performance-complexity tradeoff of different relaying strategies, Chapter 2 uses a full-duplex system model and introduces a framework, which generalizes and combines DF and CF based relaying strategies. This framework is used to derive protocols of lower complexity and to compare their performance using a Gaussian relay channel model. Reflecting more practical constraints, Chapter 3 extends the previously used system model by an orthogonality constraint, which forces nodes to either listen or transmit on the same resource (but not both). The orthogonality constraint and the previously derived protocols are combined and are again analyzed with respect to their performance-complexity tradeoff. Among others Chapter 3 introduces a protocol where two relay nodes are alternately transmitting, which proves to be the preferable strategy in a half-duplex two-relay network.

In Chapters 2 and 3, the multiple relay channel with a single source-destination pair is investigated. Although this investigation is helpful to understand the performance-complexity tradeoff of protocols for multiple relay nodes, it ignores the effects of interference between multiple communication pairs. Thus, Chapter 4 extends the interference channel by multiple relay nodes in order to analyze how interference mitigation and cancellation schemes can be combined with relaying, and how relaying can be integrated in a scenario with multiple communication pairs. In the course of this analysis, a framework is presented which allows for a variety of protocols applicable in mobile communication systems.

Finally, Chapter 5 concludes the investigation by applying the previously derived results to a mobile communication system considering resource management as well as user scheduling, clustering, and fairness. In order to justify the previously derived protocols, the network and channel model of a next generation mobile communication system is used and the presented relaying approaches are integrated. Although this analysis concentrates on physical layer aspects, implications on higher layer functions are outlined and first algorithms using well-investigated standard techniques are presented. This thesis culminates with Chapter 6, which gives an outline for future work to integrate relaying in upcoming next generation networks.

Each individual chapter focuses on a small set of aspects and problems that arose during the course of developing this thesis. Therefore, many problems, results, and methods are not presented in detail. For the purpose of providing a more elaborate insight into the topic of relaying, each chapter gives in its last section an extensive list of further literature and discusses related topics. Furthermore, this thesis assumes that the reader knows terms such as *achievable rates*, *capacity*, *joint typicality*, or *Markov chain*. To avoid any misunderstanding while reading this thesis, Appendix A defines these terms using the notation applied herein.