Shahid Khattak

Base Station Cooperation Strategies for Multi-user Detection in Interference Limited Cellular Systems

Beiträge aus der Informationstechnik

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VOGT

Dresden 2008

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., 2008

Die vorliegende Arbeit stimmt mit dem Original der Dissertation
„Base Station Cooperation Strategies for Multi-user Detection in Interference Limited Cellular Systems“
von Shahid Khattak überein.

Gesetzt vom Autor
Printed in Germany

ISBN 978-3-938860-20-5

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

Base Station Cooperation Strategies for Multi-user detection in Interference Limited Cellular Systems.

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von der
Fakultät Elektrotechnik und Informationstechnik
der Technischen Universität Dresden

zur Erlangung des akademischen Grades eines

Doktoringenieurs
(Dr.-Ing.)

genehmigte Dissertation

Vorsitzender: Prof. Dr.-Ing. habil. Frank Ellinger (TU Dresden)
Gutachter: Prof. Dr.-Ing. Gerhard Fettweis (TU Dresden)
Prof. Dr.-Ing. habil. Tobias Weber (Uni. Rostock)
Prof. Dr.-Ing. Eduard Jorswieck (TU Dresden)

Tag der Einreichung: 09.06.2008
Tag der Verteidigung: 30.09.2008

Abstract

An ever growing demand for high data rate broadband services requires either an increase in the system bandwidth or an improvement in the spectral efficiency. Since the mobile bandwidth is an expensive and scarce resource, it seems likely that a high frequency reuse is employed in the future cellular networks to increase their spectral efficiency. Such a setup by its very nature is interference limited. Most of this interference originates from outside the cell, and requires strategic base station cooperation schemes for its cancellation.

This thesis investigates different multiuser detection schemes for uplink cellular systems to mitigate interference between adjacent cells through exchange of information between the base stations. As such, it can be considered an extension/improvement over the existing SINR enhancing schemes employed in 3GPP standards, which combines signals from multiple cells during soft/softer handover. The investigated cooperative detection schemes are further classified into centralized and decentralized approaches, depending on whether the processing is done jointly at a single central point or locally at each base station in a distributed manner. The objective is to identify different receive algorithms that give the best complexity-performance tradeoff while keeping a low backhaul traffic between the base stations. Additionally, user positions within a cellular system need to be effectively modelled, so that their effect on the receiver performance can be investigated.

The information available at each base station has to be quantized before being exchanged. This introduces additional noise into the system and degrades the receiver performance for a given SNR. Since the centralized and distributed strategies exchange the received information in different forms, i.e., baseband signals or Log-Likelihood ratios, the quantization strategy and information exchange mechanism is also different. In our presented work, we try to identify the best quantization strategy for the received baseband signal exchanged during centralized processing so as to minimize the performance loss for a given number of quantization bits. Similarly, we also investigate efficient quantization strategies for reliability values exchanged between the base stations during distributed processing.

The strategic approaches for multiuser detection are well justified by information theoretic analysis, suggesting MIMO-like gains in the system capacity. The achievable rate per user significantly exceeds that of a conventional cellular system. We conclude that the system becomes fairer as not only the difference between the ergodic and outage capacities of a single user become smaller, but also the difference in performance between the users positioned at different locations within a cell is reduced. We also observe that, although, the performance of centralized processing schemes is superior to distributed ones it normally requires higher backhaul traffic. We therefore suggest using it in conjunction with distributed detection schemes through a scheduler in order to reach any required performance-backhaul tradeoff.

Another main conclusion to be drawn from this work is that the optimal quantization for the reliability values can be closely approached by minimizing the mean square quantization error in the soft bit domain. Contrary to that, performing complex optimal quantization of baseband signals does not give us any significant advantage, and uniform quantization with clipping appears to be adequate.

Zusammenfassung

In den letzten Jahrzehnten erfuhr die drahtlose Kommunikation einen rasanten Aufschwung. Einerseits verfünffachte sich die Anzahl der Mobilfunk-Teilnehmer und andererseits wuchs der Bedarf an drahtlosen, breitbandigen Datenanbindungen exponentiell an. Der Erfolg zukünftiger drahtloser Kommunikationssysteme wird entscheidend davon abhüngen, inwieweit die Bedürfnisse und Anforderungen der Nutzer erfüllt und übertroffen werden. Viele zukünftige Anwendungen beinhalten hochratige Datendienste. Die Bereitstellung dieser Dienste erfordert entweder die Vergröerung der Systembandbreite oder die Verbesserung der spektralen Effizienz. Jedoch stellt die Bandbreite in der mobilen Kommunikation eine sehr knappe und folglich kostenintensive Ressource dar. Deshalb zeichnet sich der Trend ab, in zukünftigen Mobilfunknetzen eine höhere Frequenzwiederholung einzusetzen und somit die spektrale Effizienz zu steigern. Jedoch ist die Leistungsfähigkeit solcher Konzepte inhärent durch die Interferenz begrenzt, deren dominanter Anteil durch benachbarte Zellen hervorgerufen wird. Deshalb werden Kooperationsstrategien zwischen den Basisstationen benötigt, um die Interferenz zwischen Zellen zu senken, um eine bis zu 8-fach höhere spektrale Effizienz zu erzielen als in der zweiten und dritten Mobilfunkgeneration.

In dieser Arbeit werden verschiedene Mehrnutzer-Detektionsverfahren für den Uplink in zellularen Mobilfunksystemen untersucht, welche die Interferenz zwischen benachbarten Mobilfunkzellen mithilfe des Informationsaustausches zwischen den Basisstationen kompensiert. Solche Verfahren werden nachfolgend in zentralisierte und dezentralisierte Verfahren, abhängig davon, ob die Verarbeitung von einer zentralen Einheit oder verteilt in den beteiligten Basisstationen ausgeführt wird, unterteilt. Zielsetzung ist es, verschiedene Empfangsalgorithmen zu bestimmen, welche den besten Kompromiss zwischen Komplexität und Leistungsfähigkeit erzielen und gleichzeitig den zusätzlichen Informationsaustausch zwischen den Basisstationen gering halten. Zudem müssen die Nutzerpositionen im zellularen Mobilfunknetz effektiv modelliert werden, um den Einfluss der Nutzer auf die Leistungsfähigkeit der Empfänger untersuchen zu können.

Die Information, welche jede Basisstation aus ihren Uplink-Verbindungen gewinnt, kann nur quantisiert mit anderen Basisstationen ausgetauscht werden. Aufgrund dieser Quantisierung wird zusätzliches Rauschen in das System eingefügt und verschlechtert somit die Leistungsfähigkeit des Empfängers bei einem bestimmten Signal-zu-Rausch Verhältnis. Da zentralisierte sowie auch verteilte Ansätze die Empfangsinformation auf unterschiedliche Weise austauschen können, z.B. Basisband Signale oder Log-Likelihood Verhältnisse, existieren auch unterschiedliche Ansätze für die Quantisierung und den Informationsaustausch. Diese Arbeit zielt darauf ab, für den zentralisierten Ansatz die besten Quantisierungsstrategie für den Austausch der empfangenen Basisbandsignale zu bestimmen, welche die geringste Verschlechterung der Leistungsfähigkeit bei einer gegebenen Anzahl von Quantisierungsbits erzielt. Ebenso werden für dezentralisierte Verfahren effiziente Quantisierungsstrategien für den Austausch der Zuverlässigkeitsinformation zwischen den Basisstationen untersucht.

Die entwickelten Mehrnutzer-Detektionsstrategien werden mit informationstheoretischen Analysen untermauert und bieten eine MIMO ähnliche Verbesserung der Systemkapazität. Die verfügbare Datenrate pro Nutzer übersteigt jene in konventionellen Mobilfunksystemen signifikant. Zusammenfassend kann gesagt werden, dass die Fairness in dem System erhöht wird, da sich nicht nur die Differenz zwischen ergodischer Kapazität und der Kapazität mit Outage eines einzelnen Nutzers verringert, sondern auch die Unterschiede in der Performance zwischen an unterschiedlichen Positionen innerhalb einer Zelle befindlichen Nutzern reduziert werden Es zeigt sich, dass zentralisierte Verarbeitungsansätze einerseits eine bessere Performance erzielen als die verteilten Verarbeitungsansätze. Andererseits verursachen sie eine höhere Verkehrslast auf Verbindungsnetzen (Backhaul). Deshalb wird ein zentralisierter Verarbeitungsansatz mit verteilten Detektionsschemata, kontrolliert von einem Steueralgorithmus, vorgeschlagen, um einen beliebigen Abtausch zwischen Performance und Backhaul-Traffic zu erzielen.

Eine andere Hauptschlussfolgerung dieser Arbeit ist, dass die optimale Quantisierung der Zuverlässigkeitswerte fast erreicht werden kann, indem der mittlere quadratische Quantisierungsfehler im Soft Bit-Wertebereich minimiert wird. Dem entgegen bietet die komplexe optimale Quantisierung der Basisbandsignale keinen signifikanten Vorteil, sodass die lineare Quantisierung mit Wertebeschränkung die adäquate Lösung darstellt.

Acknowledgement

This thesis results from my work at the Vodafone Chair Mobile Communications Systems at Technische Universität Dresden from 2004 to 2008.

I am particularly grateful to Professor Gerhard Fettweis for giving me the opportunity to join his group. His invaluable guidance and constant motivation through out my stay here was instrumental in enabling me to finish my work in time. Besides, he gave me the opportunity to work on different interesting projects, thereby broadening my outlook of mobile communications.

I would also like to express my gratitude to Dr. Wolfgang Rave for his valuable scientific guidance and for many fruitful discussions. He always found time to listen to my ideas and guided, corrected and inspired me through out my four year stay at the chair.

Moreover, I am very grateful to Prof. Tobias Weber and Prof. Eduard Jorswieck for acting as referees for this thesis.

During my stay at the chair, I have been extremely lucky to be associated with a group of very talented individuals, working together with whom has contributed greatly to my scientific knowhow. I would particularly like to mention Patrick Marsch for all his scientific input into my work, and for providing me with a different perspective on it. Dr. Ernesto Zimmermann, who was always very generous in sharing his knowledge and ideas. I also thank Steffen Bittner and André Fonseca dos Santos for reviewing this manuscript and giving useful comments. I also like to extend special thanks to Dr. Ralf Irmer for guiding me and helping me settle down at the chair and in Germany.

Finally, I would like to thank my family: my parents, who have supported and encouraged me over the years; my wife, who has been very patient and tolerant; and my kids for all their smiles and hugs.

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Abbreviations

1-D	One dimensional
2-D	Two dimensional
3GPP	Third generation partnership project
4G	4^{th} generation
APP	A-posteriori probability
AWGN	Additive white gaussian noise
BCJR	Bahl, Cocke, Jelinek, and Raviv
BER	Bit error rate
BICM	Bit interleaved coded modulation
BICM-ID	Bit interleaved coded modulation with iterative detection
BPSK	Binary phase shift keying
BS	Base station
CC	Convolutional codes
CCDF	Complementary cumulative distribution function
CDF	Cumulative distribution function
CDMA	Code division multiple access
CP	Cyclic Prefix
CSI	Channel state information
CU	Central Unit
dB	Decibel
DAS	Distributed antenna system
DFE	Decision feedback equalization
DFT	Discrete fourier transform
DID	Distributed iterative detection
DSD	Distributed successive detection
FER	Frame error rate
FFT	Fast fourier transform
HSPA	High speed packet access
ICI	Intra cell interference
IDFT	Inverse discrete fourier transform
IEEE	Institute of Electrical and Electronics Engineers
IID	Independent identically distributed

ISI	Inter-symbol interference
ITU	International telecommunication union
JMLD	Joint maximum likelihood detection
LLR	Log-likelihood ratios
LTE	Long term evalution
MAP	Maximum a-posteriori probability
MI	Mutual information
MIMO	Multiple-input multiple-output
ML	Maximum likelihood
MLD	Maximum likelihood detection
MLSE	Maximum likelihood sequence estimation
MMSE	Minimum mean-square error
M-QAM	M-ary quadrature amplitude modulation
MSE	Mean squared error
MSEW	Minimum squared Euclidean weight
MSP	Modified set partitioning
MT	Mobile terminal
MUD	Multi-user detection
OCI	Other cell interference
OFDM	Orthogonal frequency division multiplexing
PAM	Pulse amplitude modulation
PAPR	Peak to average power ratio
PBC	Periodic boundary condition
pccc	Parallel concatenated convolutional codes
PDF	Probability density function
PIC	Parallel interference cancellation
QAM	Quadrature amplitude modulation
SAIC	Single antenna interference cancellation
SCCC	Serial concatenated convolutional codes
SIC	Successive interference cancellation
SINR	Signal-to-interference and noise power ratio
SIR	Signal-to-interference power ratio
SISO	Soft-input soft-output
SISO	Single-input single-output
SNR	Signal-to-noise power ratio
SP	Set partitioning
SSP	Semi set partitioning
SUD	Single user detection
WCDMA	Wideband code division multiple access
ZF	Zero forcing

Symbols

Multi-user Detection and Decoding

δ_{0k}	Kronecker Delta
$\Delta_{LD}, \Delta_{SIC}, \cdots$	Spatial diversity gain for different detection schemes
$\mathbf{\Phi}_{nn}$, $\mathbf{\Phi}_{ss}$, $\mathbf{\Phi}_{rr}$	Noise, transmit signal, and receive signal covariance matrix
$\mathbf{\Psi}$	Scaling matrix in unbiased MMSE
ρ	Relative path-loss between the MTs and BSs
σ_n^2	Variance of the AWGN receiver noise
σ_s^2	Variance of the transmitted symbols
σ_{eff}^2	Effective noise variance after initial pre-processing

$\mathbb{A}$	Set of modulation alphabet
$\mathbb{C}$	Set of all complex numbers
$\mathbb{I}_{l,i}$, $\bar{\mathbb{I}}_{l,i}$	Set of significant and non-significant interferers at BS l
$\mathbb{I}_l$	Set of all the interferers at BS l
$\mathbb{X}_{k,\pm 1}$, $\mathbb{Y}_{k,\pm 1}$	Set of hypotheses for the k^{th} bit at the soft demapper, decoder

b	No of bits per transmitted symbol
e , $\mathbf{e}$	Error, error vector,
E_b	Energy per bit
$\mathbf{G}$	MIMO channel matrix/Linear pre-filtering matrix
h_{lm}, $\mathbf{h}_l$, $\mathbf{H}$	Channel coefficient, channel vector, channel matrix
L_e	Channel impulse response length
L^d	A-posteriori LLR values at the output of a detector/decoder
L^a	A-priori information at the detector/decoder input
L^e	Extrinsic information
L^{tot}	Combined reliability infomation
m_d	Number of jointly detected data streams
m_l	Number of dominant interferers at BS l
N_0	Noise power spectral density
n_F	Frequency spacing between sub-carriers
n, $\mathbf{n}$, N	Receiver noise, noise vector, noise random variable
n_T, n_R	Number of transmit, receive antennas

$\mathbf{p}$, $\mathbf{P}$	Element-wise square-root path-loss vector/matrix
P_e	Bit error probability
Q	Cardinality of the modulation alphabet
r_l , $\mathbf{r}$, R	Received signal, signal vector, random variable
s_m , $\mathbf{s}$, S	Transmitted symbol, symbol vector, random variable
T	Sampling time
T_s, T_{cp}	OFDM symbol duration, cyclic prefix duration
u_l, $\mathbf{u}$	Information bits, vector
x_k, $\mathbf{x}$	Encoded bit, vector
$\tilde{(\cdot)}$	Hypothesis
$\hat{(\cdot)}$	Estimate

Information Theoretic Analysis and System level Simulations

$\eta_{DAS}^{out}, \eta_{DAS}^{erg}$	Outage and Ergodic spectral efficiencies for DAS
λ	Cell loading
μ	Frequency reuse
C_{AWGN}	AWGN capacity of a single input single output system
C_{DAS}	Capacity of a DAS
$C_{DAS}^{out}, C_{DAS}^{erg}$	Outage and Ergodic capacities for DAS
H	Entropy function
I	Mutual information
$\mathcal{L}$	Total number of co-channel interferers in a network
$\mathcal{N}$	Total number of cells in a network
N_s	Number of independent realizations of a channel
$\mathcal{R}_{DAS}$	Combined rate for all the jointly processed users in a DAS
$\mathcal{R}$	Rate per resource

Quantization of Exchanged Information

λ	Soft-bit
μ_L	Mean LLR values for each mode
σ_L^2	Variance of the LLR values for each mode
b_q	Number of quantization bits
D	Input clipping level
MSE_q	Quantization mean square error
SNR_q	Signal to quantization noise power ratio
d_i	Decision levels
r_i	Reconstruction levels
R	Number of reconstruction levels

Operators

$\bigodot$	Element-wise product
$*$	Linear convolution
$\otimes$	Circular convolution
$(\cdot)^*$	Complex conjugate
$(\cdot)^H$	Hermitian (conjugate transpose)
$\Vert\cdot\Vert$	Magnitude of a complex-valued quantity
$\vert\cdot\vert$	Cardinality of a set, Magnitude of a real-valued quantity
$\wedge$	Intersection
$\mathrm{dg}\{\cdot\}$	Forms a diagonal matrix from the leading diagonal of a matrix
$\mathcal{E}\{\cdot\}$	Expectation
$\Xi\{\cdot\}$	Forms a diagonal matrix from a vector

Chapter 1

Introduction

“**cooperation** - noun:
∼ *an act or instance of working or acting together for a common purpose or benefit; joint action*”

1.1 Motivation

The mobile and wireless communication has seen a tremendous growth over the recent years. Not only the global number of mobile users has increased almost five fold in the last ten years, but also the demand for broadband wireless data access has grown exponentially. The success of future mobile and wireless communications systems depends on meeting and exceeding the needs and requirements of consumers. Many future applications will involve data oriented broadband services with high data rates, and therefore require a higher bandwidth or spectral efficiency to satisfy the user expectations. Since the mobile bandwidth is expensive and a scarce resource, it seems likely that this will demand an increase in spectral efficiency over those provided by the second and third generation systems, perhaps 6-8 times larger than HSPA.

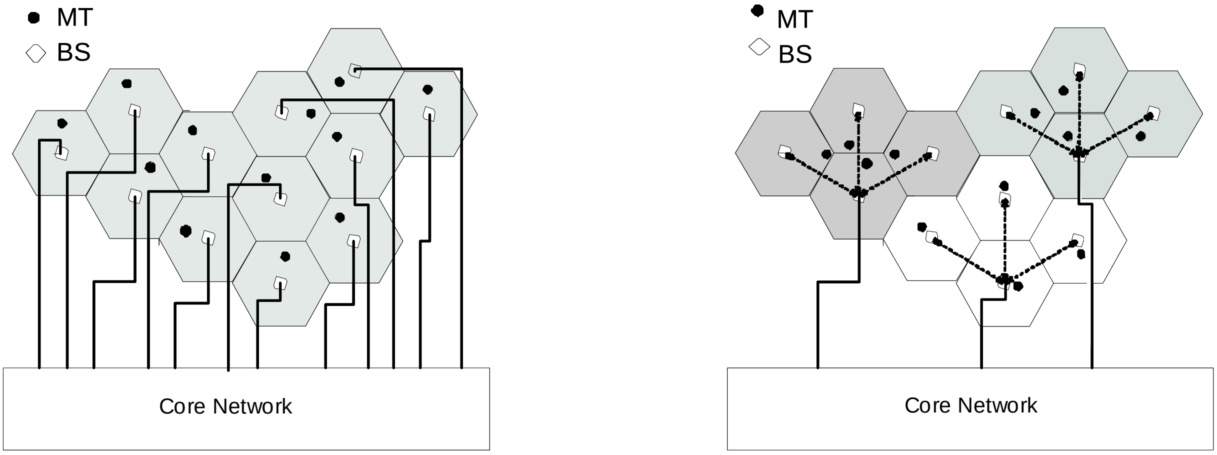
In their benchmark paper on information theoretic capacity of multi-receiver networks [HW93], Hanly and Whiting concluded that the cost of partitioning the frequency spectrum is more than the cost of interference when it is not done. A higher frequency reuse is therefore proposed to improve the spectral efficiency, resulting in the interference from co-channel users outside the cells to dominate, thereby forming a single most important factor limiting the system performance. This interference coming from the adjacent cells is commonly known as *other cell interference* (OCI). OCI has been treated in [And05], where it was suggested that advanced receiver and transmitter techniques can be employed together with strategic approaches to cancel the increased interference across the cell borders. The strategic approaches to handling OCI require co-operative signal processing between the *base stations* (BSs) through mutual exchange of the received information between them. The signal propagation across the borders can now be visualized as an additional source of diversity, and can contribute to the desired signal gain in both the uplink and the downlink. However, in this thesis we only consider the uplink scenarios for investigating the OCI mitigation through BS cooperation. Given that the *mobile terminals* (MT) are low cost, low power independent entities, and are not expected to cooperate to perform transmit or receive beamforming, they are assumed to be as simple as possible with most of the complex processing of a cellular system moved to the BSs.

The cooperative strategies in the uplink are further classified into centralized and decentralized approaches. In the centralized approaches, the BSs perform only the frontend RF processing and send the quantized baseband signals to a single *central unit* (CU) for joint detection and decoding. This idea of a super receiver in a cellular network, having all the information at the cooperative BSs available to it, was first conceived by Wyner in [Wyn94]. Assuming negligible information loss from the receive antenna to the CU, the radio interface can be considered similar to that for MIMO, but with different path-losses for each link. The information theoretic results for point-to-point MIMO channels are therefore also valid, suggesting impressive gains in channel capacity and spectrum efficiency as shown in [SW97, RP02a, MKF06]. The second approach of decentralized cooperative strategies perform the baseband processing of the desired signals locally at each BS, while exchanging processed reliability information between them [AEH, SWSW04]. The same potential capacity gains as in the centralized approaches are predicted, as long as the entire information content of the received signal is exchanged between the BSs. Fig. 1.1 compares a conventional cellular system with a cooperative centralized processing architecture.

Although the idea of cooperative signal processing has been around for some time now, it is only in the last few years that it has stirred up a greater interest in the scientific community. Among them are works by groups in Rostock and Kaiserslautern (Sklavos, Weber) [SWBC, WWA07], USA (Andrews, Dai, Paulraj) [And05, ZD04, RP02a], Australia (Grant) [GHEM04], Turkey(Aktas) [AEH06], Israel (Shamai, Shental) [SW97, SWSW04]. This is of course not the complete list of researchers in the area. In fact, cooperative signal processing between the base stations has also been proposed as the potential radio interface for the 4G cellular networks, capable for providing the targeted three fold spectral efficiency over LTE.

Performing cooperative interference cancellation between the BSs causes a change in the current cellular network paradigm and brings forth new challenges requiring a vast amount of additional research. One of the foremost problems relates to the application of different receive strategies to efficiently overcome the OCI, while maintaining a low backhaul. In this context, the effect of cell loading and user position within a cell can be analyzed to give a better insight into the effect of user behavior on the receiver performance. This work can be further extended by exploring the issues related to channel estimation, thereby developing means to convey the channel information efficiently while accurately identifying all significant received signals. Additionally, the common MIMO assumption of perfect synchronization between all the received data streams breaks down for the considered cooperative networks, and schemes for improving frequency and time synchronization between different entities in a cellular network also need to be investigated.

Another interesting area for research is the optimal scheduling of the users for the co-



(a) A conventional cellular network (b) Cooperative base station processing

Figure 1.1: Comparing conventional and cooperative cellular network architectures.

operative processing under constrained backhaul with the objective to find the best compromise between the throughput and operating cost. It is well known that joint scheduling of users for cooperative networks is a complex optimization problem, and requires a huge amount of channel information to be sent repeatedly to a centrally located scheduler over the backhaul links. Distributed scheduling schemes therefore need to be investigated that work only on locally available channel knowledge.

The above discussion shows that even at a single glance the cooperative cellular architecture provides us with a multitude of interesting open questions. While some of these problems can be solved by simple extension to the existing theory, others are more involved and serve as potential research areas. The author hopes that this thesis can provide some contribution to few of these topics.

1.2 Objective of this Thesis

This thesis' objectives are to

- Investigate centralized cooperative multi-user detection
    - Study different multi-user algorithms in the context of joint processing.
    - Examine the effect of user position and cell loading on the effectiveness of joint processing.
    - Investigate the quantization of the received baseband signal and its effect on the receiver performance.
- Investigate decentralized cooperative multi-user detection

- Develop multi-user detection strategies using base station cooperation for decentralized processing, and find an upper bound for decentralized processing.
- Identify an efficient quantization strategy for reliability values available at the output of the decoder/demapper.

1.3 Outline

Chapters 2 and 3 establish the notation and familiarizes the reader with the basics. In chapter 2, we start with the description of the underlying transmission systems (single-carrier, multi-carrier) for which the methods to be developed later are applicable. We also look at the system setup for the centralized and decentralized multi-user detection schemes involving base station cooperation. Besides, the common set of parameters to be used throughout the thesis during the numerical analysis is identified. In Chapter 3, we look at different multi-user detection schemes, i.e., how the receiving side of a transmission system obtains the estimates for the transmitted data. Here, we provide results for only the linear and iterative detection schemes under uncoded transmission.

Chapter 4 looks at joint multi-user detection and decoding through base station cooperation. We start by investigating the information theoretic bounds on the joint processing. The performance of different centralized linear and iterative receivers is then presented together with the effect of user position and cell loading on its performance. Finally, different quantization schemes are applied to the baseband signal and their effect on the distributed antenna system receiver performance is studied.

Chapters 4 and 6 both deal with decentralized cooperative signal processing. In chapter 5, we focus on the distributed detection algorithms where the processed information available at the output of the detector/decoder is exchanged. The decentralized detection algorithms are again classified into two types, the first one requiring an iterative exchange of improving reliability values between the BSs, while the second one is based on a successive detection approach. Also, the optimal distributed detection scheme is identified under unconstrained backhaul. Chapter 6 develops tools to efficiently quantize the reliability values to be exchanged between the BSs in order to minimize the loss of information for any given number of quantization bits.

The thesis is concluded in chapter 7 with a summary of the main results and an outlook.