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Field Trial Results in Coordinated Multi-Point Downlink Systems

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Field Trial Results in Coordinated Multi-Point Downlink Systems

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Abstract

The extension of cellular communication standards with multiple transmit and receive antennas is constantly crossing new technological frontiers from point-to-point towards spatially distributed communication links. This thesis investigates a coordinated multi-point transmission system in the downlink to overcome the limitations from spatial interference observed by several terminals. It will be shown that especially cell-edge users profit from the joint-transmission amongst the base stations if the cellular network operates on the same carrier frequency. The central results are gained from field trials within a cellular testbed where different spatial configurations are compared to interference limited systems in terms of the spectral efficiency.

At first, the system model of OFDM is introduced and the implications of distributed radio channel links especially onto the synchronization mechanisms are emphasized. Then, the model for the spatial transmission system is outlined where also the performance of precoding algorithms is related to spatial channel parameters. This derives the connection to the field trial experiments.

The second part concentrates on the measurement campaigns. Implementation details are presented for the transmit Wiener filter as an order-recursive precoding algorithm. It provides a low-complex solution and enables spatial configurations

from multiple transmission streams over several terminals down to the single-user case. Then, the entire measurement system and experiments are portrayed including a comparison to the downlink of 3GPP LTE Rel. 8 as reference technology. But also the shortcomings of the prototyping hardware are illustrated which restrict the closed-loop real-time experiments to intra-site measurements.

The results within this thesis are gained by a two-fold approach: It is shown that data-rates over multiple modulation and coding schemes match to observed post-equalization signal-to-interference-and-noise ratios and enable the prediction of SINRs solely based on physical channel coefficients. Further field trials gathered physical channel coefficients to anticipate the spectral efficiency at the cell-edge.

From these field trials, a spectral efficiency gain by base station cooperation at the cell-edges of at least 100 % could be observed, but also the relative cell-edge size must be considered. The results confirm the trade-off between the amount of spatial streams to the interference of multiple users and additional streams especially under line-of-sight conditions. Furthermore, an observation is made that the transmission concepts without full cooperation are valuable alternatives only if the cell-edge will not be considered. Then, the achieved performance gains may not justify the large implementation and signaling overhead of the realized precoding scheme. Although the system achieved homogenous performance results over the entire cell, appropriate scenarios with precise synchronization and fine-granular channel knowledge are required.

Zusammenfassung

Mit der stetigen Erweiterung zellularer Mobilfunknetze werden punkt-zu-punkt Mehrantennensysteme zu räumlich verteilten und koordinierten Kommunikationssystemen gewandelt. Die vorliegende Arbeit untersucht die Mehrpunktkommunikation experimentell mit dem Ziel, die räumliche Interferenz zwischen Mobilfunkteilnehmern anhand der Abwärtsstrecke zu begrenzen. Es wird dargelegt, dass insbesondere die Teilnehmer am Zellrand von einer gemeinsamen Sendestrategie zwischen Basisstationen profitieren, wenn das zellulare Netzwerk dieselbe Trägerfrequenz verwendet. Die Hauptergebnisse dieser Arbeit wurden durch Übertragungsexperimente in einem Testbett gewonnen, in denen die spektralen Effizienzen verschiedener Antennenkonfigurationen verglichen werden, die auch interferenzbegrenzte Systeme umfassen.

Der erste Teil der Arbeit betrachtet das OFDM Systemmodel und beschreibt die Synchronisation unter verteilten Ausbreitungskanälen. Im Anschluss wird das Mehrantennensystemmodel vorgestellt, anhand dessen das Verhalten einiger Vorentzerrungsalgorithmen im Zusammenhang verschiedener Ausbreitungsbedingungen erläutert wird, um das Verständnis zu den Experimenten herzustellen.

Der zweite Teil konzentriert sich auf die Messkampagnen. Hierzu werden die Implementierungsdetails des Wiener Sendefilters als ordnungsrekursiven Vorentzer-

rungsalgorithmus beschrieben. Dieser bietet eine einfache technische Realisierung und ermöglicht das Umschalten zwischen verschiedenen Antennenkonfigurationen sowie mehreren Datenströmen über verschiedene Teilnehmer. Danach wird das Messsystem wie auch -vorgehen erläutert und von der 3GPP LTE Rel. 8 Referenz abgegrenzt. Hierbei wird auch auf die technischen Defizite des Prototyps eingegangen. Die Echtzeitexperimente mit rückgeführten Kanalkoeffizienten sind auf die Durchführung innerhalb eines Standortes beschränkt, wobei die Signalverarbeitung in mehreren Basisstationen getrennt erfolgt.

Die Ergebnisse dieser Arbeit wurden auf zwei Arten gewonnen: Zunächst erfolgte ein Abgleich gemessener Datenraten unter verschiedenen Modulations- und Kodierschemata zu beobachteten Signal-zu-Interferenz-und-Rauschverhältnissen. Das ermöglicht die Prädiktion von Messergebnissen basierend auf physikalischen Kanalkoeffizienten. Während weiteren Messfahrten wurden diese Koeffizienten dann großflächig bestimmt, um spektrale Effizienzen in Zellrandszenarien zu erhalten.

Es konnte ein Gewinn an spektraler Effizienz von mehr als 100 % an Zellrändern erzielt werden, wobei zusätzlich der Anteil des Zellrandes an der Gesamtfläche zu berücksichtigen ist. Die Ergebnisse bestätigen den Kompromiss zwischen der Anzahl der verwendeten Datenströme und der räumlichen Mehrnutzerinterferenz, weil die Ausbreitungsbedingungen häufig eine Sichtverbindung zwischen Sendern und Empfängern aufwiesen. Außerdem stellen die Verfahren ohne volle Kooperation einen guten technischen Kompromiss dar, wenn die Ergebnisse auf die gesamte Zellfläche bezogen werden. Die Verfahren ohne volle Kooperation einen guten technischen Kompromiss nur dar, wenn die Ergebnisse nicht auf die gesamte Zellfläche bezogen werden. Dann rechtfertigen die erreichten Datenraten mitunter nicht den zusätzlichen Implementierungsaufwand und die Signalisierung für den verwendeten Vorentzerrungsalgorithmus. Das Messsystem erreicht eine homogene Verteilung der Datenraten innerhalb der Zelle. Aber das Übertraungsverfahren beschränkt sich auf ausgewählte Nutzungsszenarien und bedingt eine präzise Synchronisation mit feingranularer Kanalkenntnis.

Acknowledgment

This thesis is the result of four years at the Vodafone Chair Mobile Communications Systems at the Technische Universität Dresden. I look back with pride onto Professor Gerhard Fettweis' chair, my colleagues and also the time in the laboratory to develop the radio hardware. In particularly, I want to thank Gerhard for those years. He always offered confidence and encouraged all of us to challenge the upcoming tasks. Here, I experienced the direct impact of research onto standardization committees and the telecommunication industry where we often presented the testbed with live and offline demonstrations at a whole bunch of conferences. I also thank Professor Gerhard Bauch to accept the second supervision of my thesis.

I appreciate the fruitful discussions with the head of my research group Dr. Wolfgang Rave. He gave important advices to reflect the outcome of experiments under a critical view. He always remembered me to focus only on a reduced set of results but with a clear understanding of their insights. I also acknowledge the chair's backbone where Steffen Watzek, Dr. Patrick Marsch, Kathrin Fromke and Sylvia Steppat overtook the organizational work of Easy-C.

Nevertheless, my results would not be possible with colleagues and students. At first, I want to mention the inner circle of the downlink transmission team namely Vincent Kotzsch, Ainoa Navarro Caldevilla and Erik Fischer. Also Eckhard Ohlmer, Ines Riedel, Michael Grieger and Hermann Hensel contributed with discussions and implementation work. Then, I thank Sven-Einar Breuer, Joachim Heft and Matthias Pötschke who administrated the testbed. My former students Martin Oemus, Julius Hoffmann and particularly Martin Danneberg supported the testbed automation which saved a significant amount of time to verify measurement results.

Finally, I am very grateful to my family for their support and encouragement to finalize this thesis. Especially my dear Denise and my daughters Lara and Alina pulled me back on the ground where I spend my time with a fantastic family.

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Nomenclature

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3 Notation

n	Lowercase letters denote scalar values.
$\underline{N}$	Vectors are underlined.
$\mathbf{N}$	Matrices are boldfaced.
$[\mathbf{M}]_{[m_1:m_2,n_1:n_2]}$	This operator selects submatrix from row m_1 to m_2 and column n_1 to n_2.
$()^*, ()^T, ()^H$	The conjugate, transpose and hermitian operator.
$\circledast$	Circular convolution as defined in equation (A.2.9).
Δ	Difference or distance between two quantities.
$\mathrm{dg}\,()$	The diagonal operator forms a vector into a diagonal matrix or selects the diagonal elements of a matrix.
$\mathrm{Tr}()$	The trace of a matrix.
$\mathrm{vec}\,()$	This stacks the columns from first to last of a matrix into one tall vector.
$\mathrm{E}\,\{\}$	The expectation over a random variable.
$\hat{x}$	An estimate of variable x.
σ_x^2	The variance of random variable x.
$R, \mathbf{R}$	The covariance and covariance matrix of random variables.
$\exp\{x\}$	e^x
δ	The dirac delta function.
$\mathcal{F}_x, \mathcal{F}_x^{-1}$	The Fourier transformation over variable x and its inverse operation.
$\mathrm{DFT}\{x\}, \mathrm{IDFT}\{x\}$	The discrete Fourier transformation over variable x and its inverse operation.

4 Symbols

In chapter 2:

Description	*Abbreviation*	*Index*
Sample duration	T_s	k
Sampling frequency	$f_\mathrm{s} = \frac{1}{T_\mathrm{s}}$	
Continuous time, delay and frequency	t, τ, f	$\sim, l, n$
Symbol duration	$T_\mathrm{O} = N_\mathrm{C} T_\mathrm{s}$	i
Number of subcarriers	N_C	n
Number cyclic prefix samples	N_CP	
Carrier and Doppler frequency	$f_\mathrm{c}, f_\mathrm{D}$	
Sampled channel length	L	l
Subcarrier spacing	$\Delta f_\mathrm{SC} = 1/T_\mathrm{O}$	$15\,\mathrm{kHz}$
Time-variant impulse response	$h(t, \tau)$	
The additive white Gaussian noise	$v(t)$	
Continuous/discrete transmit signal	$x(t), x[k]$	
Continuous/discrete receive signal	$y(t), y[k]$	
DFT-matrix and IDFT matrix	$\mathbf{F}, \mathbf{F}^H$	
Channel matrix in frequency domain	$\mathbf{H}$	
Circular channel matrix in time domain	$\mathbf{h}$	
Transmit symbol vector in FD and in TD	$\underline{X}, \underline{x}$	
Received symbol vector in FD and in TD	$\underline{Y}, \underline{y}$	
AWGN symbol vector in FD and in TD	$\underline{V}, \underline{y}$	
Channel's coherence bandwidth and time	$B_\mathrm{coh}, T_\mathrm{coh}$	
Channel's root mean squared delay spread	T_d	
Channel's excess delay	$\bar{\tau}$	

In chapter 3, 4 and 5 :

Description	*Abbreviation*	*Index*
Number of ...		
base stations	N_{Tx}	$l = 1, \ldots, N_{\mathrm{Tx}}$
transmit antennas at BS l	$N_{\mathrm{TxAnts},l}$	
Total no. of transmit antennas	$N_{\mathrm{Tot,TxAnts}}$	
mobile terminals (MTs)	N_{Rx}	$k, \overline{k} = 1, \ldots, N_{\mathrm{Rx}}$
receive antennas at MT k	$N_{\mathrm{RxAnts},k}$	
Total no. of receive Antennas	$N_{\mathrm{Tot,RxAnts}}$	
spatial streams for MT k	$N_{\mathrm{Sx},k}$	
Total number of streams	$N_{\mathrm{Tot,Sx}}$	
Local equalizer MT k	$\mathbf{G}_k$	$\in \mathbb{C}^{[N_{\mathrm{Sx},k} \times N_{\mathrm{RxAnts},k}]}$
Global spatial channel	$\mathbf{H}$	$\in \mathbb{C}^{[N_{\mathrm{Tot,RxAnts}} \times N_{\mathrm{Tot,TxAnts}}]}$
Local spatial channel	$\mathbf{H}_{k,l}$	$\in \mathbb{C}^{[N_{\mathrm{RxAnts},k} \times N_{\mathrm{TxAnts},l}]}$
Effective channel MT k	$\tilde{\mathbf{H}}_{k,k}$	$\in \mathbb{C}^{[N_{\mathrm{RxAnts},k} \times N_{\mathrm{Sx},k}]}$
Global precoder	$\mathbf{W}$	$\in \mathbb{C}^{[N_{\mathrm{Tot,TxAnts}} \times N_{\mathrm{Tot,Sx}}]}$
Local precoder for streams		
k to l-th BS	$\mathbf{W}_{l,k}$	$\in \mathbb{C}^{[N_{\mathrm{TxAnts},l} \times N_{\mathrm{Sx},k}]}$
Spatial streams of MTs k	$\underline{s}_k$	$\in \mathbb{C}^{[N_{\mathrm{Sx},k} \times 1]}$
Estimated spatial streams MT k	$\hat{\underline{s}}_k$	$\in \mathbb{C}^{[N_{\mathrm{Sx},k} \times 1]}$
Spatial noise at MT k	$\underline{v}_k$	$\in \mathbb{C}^{[N_{\mathrm{RxAnts},k} \times 1]}$

5 List of Acronyms

3GPP	3rd Generation Partnership Project
AWGN	additive white Gaussian noise
BS	base station
cdf	cumulative distribution function
CFO	carrier frequency offset
CIR	channel impulse response
Cl-WF	closed-loop water filling
CoMP	coordinated multi-point
Coord. BF	coordinated beam-forming
CP	cyclic prefix
CPE	common phase error
CR	code rate
CSI	channel state information
CSI-RS	CSI reference symbol
CSIT	CSI at the transmitter
CTF	channel transfer function
DFT	discrete Fourier transformation
DM-RS	demodulation reference symbol
DL	downlink
DoA	direction of arrival
DoD	direction of departure
eNB	enhanced Node B
EVD	eigenvalue decomposition
FD	frequency domain
GF	geometry factor
GPS	Global Positioning System
i.i.d.	independent and identically distributed
ICI	inter-carrier interference
IDFT	inverse discrete Fourier transformation
ISI	inter-symbol interference
LD	linear detection
LMMSE	linear minimum mean-square error
LS	least-square
LO	local oscillator
LOS	line-of-sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MCS	modulation and coding scheme
MI	mutual information

MIMO	multiple-input multiple-output
MMSE	minimum mean-square error
MSE	mean-square error
MT	mobile terminal
MU	multi-user
MU w/o Prec.	multi-user reception without precoding
NLOS	non-line-of-sight
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
PDCCH	physical downlink control channel
pdf	probability density function
PDP	power delay profile
ppm	parts per million
PRB	physical resource block
PSD	power spectral density
PUSCH	physical uplink shared channel
PDSCH	physical downlink shared channel
QAM	quadrature amplitude modulation
rms	root mean squared
RS	reference symbol
Rx	receive
RxZF	receive zero forcing
RxWF	receive Wiener filter
SC	subcarrier
SCO	sampling clock offset
SIC	successive interference cancellation
SINR	signal-to-interference-and-noise ratio
SISO	single-input single-output
SNR	signal-to-noise ratio
STO	symbol timing offset
SU	single-user
SVD	singular value decomposition
TD	time domain
TDMA	time division multiple access
TTI	time transmit interval
TDOA	time difference of arrival
TUD	Technische Universität Dresden
Tx	transmit
TxBD	transmit block diagonalization filter
TxWF	transmit Wiener filter
TxZF	transmit zero forcing filter
UL	uplink

CHAPTER 1

Facing Cellular Multi-Point Transmission Experiments

1.1 Contributions

This thesis attempts to reduce the gap between theoretical results and field trial experiments in the area of cellular mobile communications including the conceptual understanding, prototype realization and verification. The extension of current technologies requires system engineering to verify the feasibility of fresh ideas. But already the exploration of such ideas draws new implications, changes the perspective and offers solutions or even alternatives. Practical suboptimal results will outperform complex ones. An additional challenge remains in the identification of hidden obstacles in upcoming systems that contain fundamental differences and even extensions compared to existing technologies. Often the complexity and also the error sensitivity raise and focus the attention towards the testability. Wireless communication evolves constantly at an increasing pace and integrates itself even more into the common habits. It became a fundamental property in the everyday life.

This thesis is intended to researchers in theory who want to broaden their view and include field experiences into own algorithm design from the beginning on. Also the prototype research may gain from the realization methods and performance metrics. Furthermore, industry may circumvent one-way road developments and reduce the time to market of product deployments.

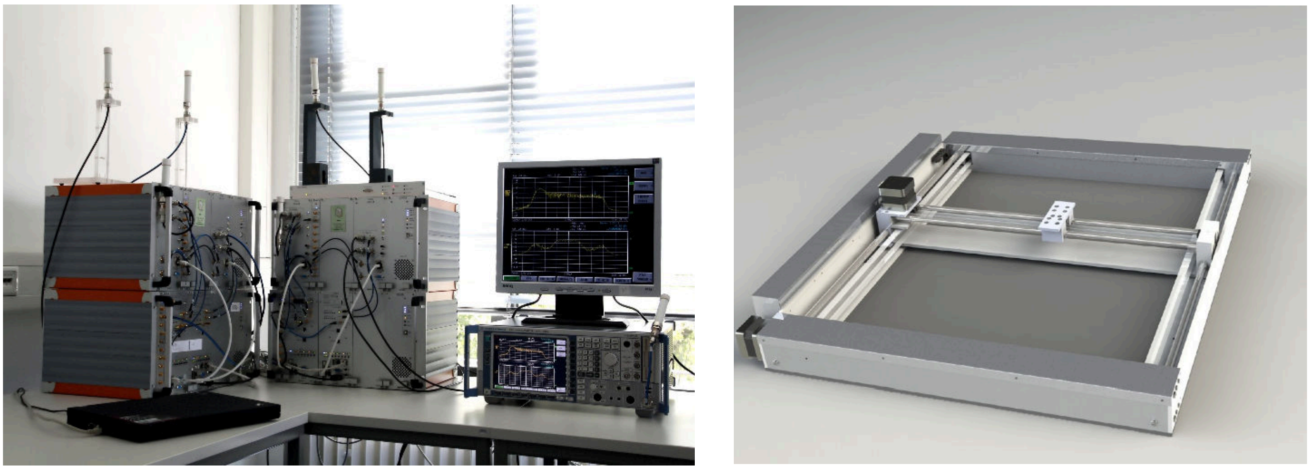
This thesis presents the realization and publishes field trial results for cell-edge and cell-center terminals which were gained within a cellular base station testbed. Different spatial configurations of linear downlink (DL) precoding are compared to an uncoordinated transmission. The effort to characterize such a closed-loop system in a cellular environment is tremendously high. Therefore, an evaluation approach will be presented that verifies the closed-loop procedure on selected positions with predicted results from measured channel transfer functions. With this method, testbed results are anticipated from channels of the entire area. The coordinated multi-point (CoMP) performance gains are weighted by the geometry factor proportions of the entire cluster to draw a comparison to conventional cellular systems.

The Vodafone chair conducted the installation and administration of the testbed in downtown Dresden, Germany, where fortunately commercial base station sites could be used. The author's contribution covers the definition of the linear precoder as an extension of 3GPP LTE Rel. 8 enhanced Node Bs (eNBs) which were acquired from National Instruments Dresden GmbH, formerly known as Signalion GmbH. This step includes the algorithm and its transformation into the fixed-point number description as pre-condition for a VHDL implementation given in chapter 4. The real-time precoder's counterpart realizes the channel state information feedback at terminal side, figure 1.1 on the facing page. While the system evolved into a 3×3 CoMP DL setup, a multitude of testing and verifications has been conducted. In addition, the author accomplished with the help of students an automatic measurement setup that includes the Global Positioning System (GPS) and the construction of measurement tables, figure 1.2.

Beside these steps, the setup was presented to a broad scientific, standardization and even commercial audience, for example at the ICC2009 conference with the first running 2×2 real-time demo [20], an International Telecommunication Union workshop [19] or at the Easy-C workshop with the first 3×3 CoMP DL intra-

Figure 1.1: The mobile terminal measurement equipment.

cell transmission [18]. Finally, the author elaborated the planning, execution and evaluation of the field trials in chapter 5.



(a) The base station equipment *(left)* and spectrum analyzer *(right)*.

(b) The measurement table for two-dimensional terminal antenna positioning.

Figure 1.2: The base station in the laboratory and antenna positioning table at terminal side.

1.2 The Challenge of Downlink CoMP Testbed Measurements

Conducting and evaluating field measurements is the end of a long journey and covers a wide and complex field. The start of the entire projects goes back to the year 2007 where the decision to build a testbed from scratch for a new generation of cellular radio was made. The profound planning of the entire steps was followed by labor-intensive engineering to build the first prototypes of base stations and terminals. The first enthusiastic ideas, how to demonstrate the capabilities of cooperating mobile networks, were steadily reduced onto the core algorithms that reflect the goals. Ideas were quickly raised but with each new implementation detail, their realization turned out to be tougher than expected. A limitation that could be extended was followed by an even harder one which was hidden by the previous stage. An often underestimated fact of such projects is the team coordination. No one can expect to know all the details and the research personal at university changes quickly. Especially the possibilities for students were often limited since their short term labor contracts prohibited a longer examination with the prototypes. To the author's surprise, only a few students were able to handle the specific behavior of the hardware such that the outcome of results becomes larger than the spend effort. But the less who gained detailed insight emerged to valuable support personal.

The match of theory and results is the most challenging part. This is the start to understand how the entire system runs in a non-artificial environment. It turns the technical demonstrator into a scientific tool. Here, a lot of hidden shortfalls are only offered at this stage. These kinds of faults are not those which are covered by tests of the single processing units or of the entire system which are based on rather artificial scenarios. The author learned that trouble shooting and error analysis covered the most research efforts. On the one hand, this is the most frustrating part and but is also the most interesting, if successful, on the other.

1.3 Structure of this Dissertation

The thesis is structured as follows: Chapter 2: *The Transmission Model, Synchronization and Channel Estimation* introduces the wireless channel models. On the one hand, the single-input single-output case for the time-frequency domain is given and on the other the spatial perspective. Then, the basic signal processing steps between the single antenna links describe the orthogonal frequency-division multiplexing transmission including channel estimation procedures and the enhanced CoMP DL synchronization.

Chapter 3: *The Coordinated Multi-Point Downlink System Model* embodies the notation in the spatial domain. Here, performance metrics are defined and different transmission strategies are considered from a theoretical point of view. System verification in field trials is almost infeasible since the operating point remains only an estimate which is limited to a single measurement position. Furthermore, a huge amount of field measurements has to be combined and summed up into a clear understanding. Due to the author's opinion, sanity checks relate the observed performance to physical parameters like the channel's eigenvalue structure. They also provide an outlook to alternatives from the realized and quite static hardware system.

The realized linear precoding algorithm is presented in chapter 4: *Precoding Implementation Challenges* and compared to other matrix computation candidates. The chosen order recursions are described step by step to map the algorithm into the pipelined hardware architecture.

Chapter 5: *Field Trials of Multi-Point Downlink Transmissions in Cellular Systems* covers a description of the testbed and the observed physical parameters. The measurement setup is stated also with its limitations. Then, the field trial methodology motivates the performance results with a discussion of the observed spectral efficiencies.

This thesis is finalized in chapter 6: *Summary and Conclusions* with a review and the key findings of this work.

1.4 The Evolution Towards LTE-Advanced and CoMP

The cellular communications represents a global success story. It goes back to the mid-1980s when its second generation entered the markets with digital transmission technology. Wireless telephone services have been enabled almost everywhere and at any time. Since the 1990s and still today, GSM operates as backbone particularly for voice services and limited data transmission. In the 2000s, UMTS and others of the third generation rose towards mobile broadband services and induced a constantly growing demand for high network throughput.

With the roll-out of 3GPP LTE Rel. 8 in the 2010s, a multiple-input multiple-output (MIMO)-orthogonal frequency-division multiple access (OFDMA) based broadband system enters the market which features high system capacity and coverage, low latency and bandwidth flexibility. But already with the standardization of 3GPP LTE Rel. 8, the necessity became obvious to overcome drawbacks and conduct technological extensions: Cell-edge users on the same time-frequency resources suffer from spatial multi-cell interference. Frequency planning still remains an obligation with the drawback of a decreased spectral efficiency. The International Telecommunication Union published a call for International Mobile Telecommunications-Advanced technology proposals with targets for future cellular systems in March 2008 [5/L08]. Some months later, the study phase for Long Term Evolution - Advanced (LTE-A) started. At the same time, the German Federal Ministry of Education and Research (BMBF) funded the Easy-C project with the ambition to investigate ideas for LTE-A in large scale testbeds, figure 1.3 and figure 1.4. The technological know-how in Europe and the collaboration between different players in the communication industry should be stimulated. One of the LTE-A enablers contains the multi-user (MU) interference mitigation in the downlink between distributed base stations by CoMP linear precoding. In theory, the CoMP DL transmission can lead to a significant increase in the spectral efficiency for cell-edge users, if channel state information at the transmitter is available, [GHH+10, IMW+09]. These concepts are reflected in the subsequent 3GPP LTE releases. The 3rd Generation Partnership Project (3GPP) consortium pushed the extension of 3GPP LTE to meet the requirement of a higher demand