Coordinated Multi-Point in Mobile Communications

From Theory to Practice

A self-contained guide to coordinated multi-point (CoMP), this comprehensive book covers everything from theoretical basics to practical implementation. Addressing a wide range of topics, it highlights the potential gains of CoMP, the fundamental degrees of freedom involved, and the key challenges of using CoMP in practice. The editors and contributors bring unique real-world experience from running the world's first and largest test beds for LTE-Advanced, and recent field trial results are presented. With detailed insight into the realistic potential of CoMP as a key technology for LTE-Advanced and beyond, this is a must-read resource for professionals and students who want the big picture on CoMP or require in-depth knowledge of how to build cellular communication systems for the future.

Patrick Marsch was the technical project coordinator of the research project EASY-C, where the world's largest research test beds for LTE-Advanced were established and the first live demonstrations of CoMP were performed. He received his Dr.-Ing. degree from Technische Universität Dresden, where he later headed the system level group at the Vodafone Chair, focusing on optimizing spectral efficiency and energy efficiency in heterogeneous cellular deployments. He currently heads a radio research team within Nokia Siemens Networks in Wrocław, Poland.

Gerhard P. Fettweis is the Vodafone Chair Professor at Technische Universität Dresden, with 20 companies from around the world currently sponsoring his research on wireless transmission and chip design. An IEEE Fellow, he runs the world's largest cellular research test beds, coordinated the EASY-C project, and has received numerous awards. He began his career at IBM Research and has since developed nine start-up companies (so far).

Interference is the limiting factor in cellular communications and smart coordination of transmission can lead to significant improvements in quality of service. This book provides a strong outline and lays out some of the fundamental assumptions and theoretical models to treat the subject and supports the theory with results from system-level test benches and field measurements. I recommend this book to everyone interested in the topic.

Siavash M. Alamouti, Vodafone Group R&D Director

Coordinated Multi-Point in Mobile Communications

From Theory to Practice

Edited by

PATRICK MARSCH

Nokia Siemens Networks, Wrocław, Poland

GERHARD P. FETTWEIS

Technische Universität Dresden, Germany

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Tokyo, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9781107004115

First published 2011

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

ISBN 978-1-107-00411-5 Hardback

Additional resources for this publication at www.cambridge.org/9781107004115

Contents

List of Contributors

Amin, M. Awais	Qualcomm CDMA Technologies GmbH, Nuremberg, Germany
Bachl, Rainer	ST-Ericsson AT GmbH, Nuremberg, Germany
Bhagavatula, Ramya	University of Texas at Austin, TX, USA
Boccardi, Federico	Alcatel-Lucent Bell Labs, Stuttgart, Germany
Brown III, D. Richard	Worcester Polytechnic Institute, MA, USA
Brück, Stefan	Qualcomm CDMA Technologies GmbH, Nuremberg, Germany
Calin, Doru	Alcatel-Lucent Bell Labs, Murray Hill, NJ, USA
Chae, Chan-Byoung	Yonsei University, Korea
Dammann, Armin	Institute of Communications and Navigation, German Aerospace Center (DLR), Germany
Dekorsy, Armin	Institute for Telecomms. and High-Frequency Techniques, University of Bremen, Germany
Dietl, Guido	DOCOMO Euro-Labs, Munich, Germany
Doll, Mark	Alcatel-Lucent Bell Labs, Stuttgart, Germany
dos Santos, Ricardo B.	Federal University of Ceará, Brazil
Dötsch, Uwe	Alcatel-Lucent Bell Labs, Stuttgart, Germany
Droste, Heinz	Deutsche Telekom Laboratories, Darmstadt, Germany
Fahldieck, Torsten	Alcatel-Lucent Bell Labs, Stuttgart, Germany
Falconetti, Laetitia	Ericsson Research, Aachen, Germany
Fehske, Albrecht	Vodafone Chair, Technische Universität Dresden, Germany
Fettweis, Gerhard	Vodafone Chair, Technische Universität Dresden, Germany
Fischer, Erik	Vodafone Chair, Technische Universität Dresden, Germany
Forck, Andreas	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany

Frank, Philipp	Deutsche Telekom Laboratories, Berlin, Germany
Fritzsche, Richard	Vodafone Chair, Technische Universität Dresden, Germany
Garavaglia, Andrea	Qualcomm CDMA Technologies GmbH, Nuremberg, Germany
Gesbert, David	EURECOM - Mobile Communications Department, Sophia-Antipolis, France
Giese, Jochen	Qualcomm CDMA Technologies GmbH, Nuremberg, Germany
Grieger, Michael	Vodafone Chair, Technische Universität Dresden, Germany
Haustein, Thomas	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany
Heath Jr., Robert W.	University of Texas at Austin, TX, USA
Holfeld, Jörg	Vodafone Chair, Technische Universität Dresden, Germany
Hoymann, Christian	Ericsson Research, Aachen, Germany
Irmer, Ralf	Vodafone Group R&D, Newbury, UK
Jäckel, Stephan	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany
Jandura, Carsten	Actix GmbH, Dresden, Germany
Jungnickel, Volker	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany
Kadel, Gerhard	Deutsche Telekom Laboratories, Darmstadt, Germany
Klein, Andrew G.	Worcester Polytechnic Institute, MA, USA
Klein, Anja	Technische Universität Darmstadt, Germany
Koppenborg, Johannes	Alcatel-Lucent Bell Labs, Stuttgart, Germany
Kotzsch, Vincent	Vodafone Chair, Technische Universität Dresden, Germany
Maciel, Tarcisio F.	Federal University of Ceará, Brazil
Marsch, Patrick	Nokia Siemens Networks, Wrocław, Poland
Mayer, Hans-Peter	Alcatel-Lucent Bell Labs, Stuttgart, Germany
Mensing, Christian	Institute of Communications and Navigation, German Aerospace Center (DLR), Germany
Molisch, Andreas F.	Department of Electrical Engineering, University of Southern California, Los Angeles, CA, USA
Müller-Weinfurtner, Stefan	ST-Ericsson AT GmbH, Nuremberg, Germany

Müller, Andreas	Institute of Telecommunications, University of Stuttgart, Germany
Olbrich, Michael	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany
Palleit, Nico	Institute of Communications Engineering, University of Rostock, Germany
Rost, Peter	NEC Laboratories Europe, Heidelberg, Germany
Sand, Stephan	Institute of Communications and Navigation, German Aerospace Center (DLR), Germany
Schellmann, Malte	Huawei Technologies Düsseldorf GmbH, European Research Center, Munich, Germany
Schneider, Christian	Ilmenau University of Technology, Germany
Schulist, Matthias	Qualcomm CDMA Technologies GmbH, Nuremberg, Germany
Thiele, Lars	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany
Tian, Yafei	School of Electronics and Information Engineering, Beihang University, China
Tse, David	Wireless Foundations, University of California at Berkeley, CA, USA
Utschick, Wolfgang	Associate Institute for Signal Processing, Technische Universität München, Germany
Voigt, Jens	Actix GmbH, Dresden, Germany
Wachsmann, Udo	ST-Ericsson AT GmbH, Nuremberg, Germany
Wahls, Sander	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany
Wang, I-Hsiang	Wireless Foundations, University of California at Berkeley, CA, USA
Weber, Andreas	Alcatel-Lucent Bell Labs, Stuttgart, Germany
Weber, Ralf	Qualcomm CDMA Technologies GmbH, Nuremberg, Germany
Weber, Tobias	Institute of Communications Engineering, University of Rostock, Germany
Wei, Xinning	Institute of Communications Engineering, University of Rostock, Germany
Wild, Thorsten	Alcatel-Lucent Bell Labs, Stuttgart, Germany
Wirth, Thomas	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany
Yang, Chenyang	School of Electronics and Information Engineering, Beihang University, China

Zakhour, Randa	Electrical and Electronic Engineering Department, University of Melbourne, Australia
Zirwas, Wolfgang	Nokia Siemens Networks GmbH & Co. KG, Munich, Germany

Acknowledgements

This book is based on the knowledge and effort of a large number of authors, some of whom have been working in the field of CoMP for over a decade. The editors would like to thank all contributors for their great cooperation in the last months, their constructive discussions on contents, notation and nomenclature, and their patience in fine-tuning contents up to the last minute of editing.

The request for searching for new limits of cellular beyond 3G came from Vodafone Group R&D, initiating our research in the area of CoMP. As the sponsor of the Vodafone Chair at Technische Universität Dresden, Vodafone Group R&D has been instrumental in sharpening our view for CoMP schemes with practical impact. In particular Mike Walker, Trevor Gill and Luke Ibbetson among many others have been of great help in serving as a sounding board for our ideas. As a result, we have focused our research on theoretical limits as well as practical implementation challenges. The result of this view on CoMP technology has provided the basis for what has finally led to this book.

Nothing would be possible without interaction with friends, colleagues, fellow researchers and cooperation partners. The mindset and openness of our scientific community is a platform for inspiration and motor for sharpening our minds. In particular, the team at the Vodafone Chair has been of invaluable help in creating scientific results and providing the framework for inspirations, discussions, and many new insights. Thanks to the whole team for this major help!

While most parts of this book were mutually reviewed by the authors themselves, the editors would like to thank the following external reviewers for their valuable feedback: Fabian Diehm, Alexandre Gouraud, Ines Kluge, Marco Krondorf, Eckhard Ohlmer, Simone Redana, Fred Richter, Hendrik Schöneich, Mikael Sternad, Vinay Suryaprakash, Tommy Svensson, Stefan Valentin, Raphael Visoz, Guillaume Vivier and Steffen Watzek. Also, the appearance of the book would not be as it is without the significant work of Katharina Philipp, who adapted the majority of figures in this book to the same look and feel.

Last but surely not least, the editors would like to thank Phil Meyler and Sarah Finlay from Cambridge University Press for making this book possible, and for the great and patient support during its creation.

Patrick Marsch and **Gerhard Fettweis** (Editors), *January 2011*

List of Abbreviations

ACK	acknowledgement
ADC	analog to digital conversion
AGC	automatic gain control
aGW	advanced gateway
ANR	automatic neighbor relation
AoA	angle of arrival
AWGN	additive white Gaussian noise
bpcu	bits per channel use
BC	broadcast channel
BER	bit error rate
BF	beamforming
BLER	block error rate
BPSK	binary phase shift keying
BS	base station
CAZAC	constant amplitude zero autocorrelation codes
CB	coordinated beamforming
CCU	CoMP central unit
CD	Cholesky decomposition
CDF	cumulative distribution function
CDI	channel direction indicator
CDM	code division multiplex
CDMA	code division multiple access
CFO	carrier frequency offset
CGI	cell global identifier
CIF	compressed interference forwarding
CIR	channel impulse response
CoMP	coordinated multi-point
CP	cyclic prefix
CPRI	common public radio interface
CQI	channel quality indicator
CRC	cyclic redundancy check
CRLB	Cramér-Rao lower bound
CRS	common reference signal
CS	coordinated scheduling

CS/CB	coordinated scheduling / coordinated beamforming
CSG	closed subscriber group
CSI	channel state information
CSIR	channel state information at the receiver
CSI RS	CSI reference signal
CSIT	channel state information at the transmitter
CSU	central scheduling unit
CT	conventional transmission
CTF	channel transfer function
CU	central unit
CVQ	channel vector quantization
DAS	distributed antenna system
DBA	dynamic bandwidth assignment
DF	decode-and-forward
DFT	discrete Fourier transform
DIS	distributed interference subtraction
DL	downlink
DM	device manager
DPC	dirty paper coding
DRS	demodulation reference signal
DSL	digital subscriber line
DSLAM	DSL access multiplexer
DSP	digital signal processor
EASY-C	Enables of Ambient Services and Systems - Part C
eNB	enhanced Node B
EOC	eigenmode-aware optimum combiner
ERC	eigenmode-aware receive combining
EPON	Ethernet PON
E-UTRAN	enhanced UMTS terrestrial radio access network
EVD	eigenvalue decomposition
EvDO	evolution data optimized
FDD	frequency division duplex
FDM	frequency division multiplex
FEC	forward error correction
FFT	fast Fourier transform
FIR	finite impulse response
FPGA	field programmable gate array
FTP	file transfer protocol
g.d.o.f.	generalized degrees of freedom
GF	geometry factor
GSM	global system for mobile communications
GPON	Gigabit-capable PON
GPRS	general packet radio service

GTC	GPON transmission convergence
GPS	global positioning system
GTP-U	GTP user plane
HARQ	hybrid automatic repeat request
H-BLAST	Horizontal Bell Laboratories Layered Space-Time Architecture
HK	Han-Kobayashi
HPBW	half-power beamwidth
HSPA	high-speed packet access
IAP	interference-aware precoding
IC	interference channel
ICI	inter-carrier interference
ICIN	inter-cell interference nulling
IDFT	inverse discrete Fourier transform
IF	intermediate frequency
i.i.d.	independently and identically distributed
IEEE	Institute of Electrical and Electronics Engineers
IFFT	inverse fast Fourier transform
INR	interference-to-noise ratio
IP	Internet protocol
IRC	interference rejection combining
ISD	inter-site distance
ISI	inter-symbol interference
JD	joint detection
JT	joint transmission
LAN	local area network
LDC	linear deterministic channel
LLR	log-likelihood ratio
LMMSE	linear minimum mean square error
LO	local oscillator
LOS	line-of-sight
LSP	large-scale parameters
LSU	LTE signal processing unit
LTE	Long Term Evolution
LTE-A	Long Term Evolution – Advanced
MAC	multiple access channel
MAN	metropolitan area network
MCS	modulation and coding scheme
MET	maximum Eigenvalue transmission
MIESM	mutual information equivalent SINR mapping
MIMO	multiple-input multiple-output
MISO	multiple-input single-output
MF	matched filter
ML	maximum likelihood
MLE	maximum likelihood estimator

MME	mobility management entity
MMSE	minimum mean square error
MPC	multi-path component
MRC	maximum ratio combining
MRM	measurement report message
MRT	maximum ratio transmission
MS	multiple stream
MSE	mean square error
MUI	multi-user interference
MU-MIMO	multi-user MIMO
NGMN	next generation mobile networks
NLOS	non line-of-sight
NMEA	National Marine Electronics Association
NR	neighbor relation
NRT	neighbor relation table
NTP	network time protocol
OAM	operation and maintenance
OC	optimum combining
OCXO	oven-controlled crystal oscillator
ODN	optical distribution network
OFDM	orthogonal frequency division multiplex
OFDMA	orthogonal frequency division multiple access
OLT	optical line termination
ONU	optical network unit
PA	power amplifier
PAPR	peak-to-average power ratio
PCI	physical cell identifier
PDF	probability distribution function
PDH	plesiochronous digital hierarchy
PDCCH	physical downlink control channel
PDSCH	physical downlink shared channel
PDP	power delay profile
PIC	parallel interference cancelation
PLL	phase-locked loop
PMI	precoding matrix indicator
ppb	parts per billion
ppm	parts per million
PPS	pulses per second
PON	passive optical network
POTS	plain old telephone service
PRB	physical resource block
PRS	positioning reference signal
PTP	precision time protocol
PUCCH	physical uplink control channel

PUSCH	physical uplink shared channel
QAM	quadrature amplitude modulation
QoE	quality of experience
QoS	quality of service
QPSK	quadrature phase shift keying
RAN	radio access network
RAP	radio access point
RB	resource block
RE	resource element
RF	radio frequency
RI	rank indicator
RHS	right-hand side
RMS	root mean square
RN	relay node
RNTI	radio network temporary identifier
RoF	radio over fibre
RRH	remote radio head
RRM	radio resource management
RS	reference signal
RSS	received signal strength
RSRP	reference signal received power
RTOA	round-trip time of arrival
RTT	round-trip time
SC	sub-carrier
SC-FDMA	single carrier frequency domain multiple access
SCM	spatial channel model
SCME	spatial channel model extended
SCTP	stream control transmission protocol
SDH	synchronous digital hierarchy
SDMA	spatial division multiple access
SDIV	spatial diversity
S-GW	serving gateway
SIC	successive interference cancelation
SINR	signal-to-interference-and-noise ratio
SIR	signal-to-interference ratio
SISO	single-input single-output
SMUX	spatial multiplexing
SON	self-organizing network
SONET	synchronous optical network
SS	single stream
SSB	single side band
SSP	smale-scale parameters
SNR	signal-to-noise ratio
SU-MIMO	single-user MIMO

SVD	singular value decomposition
SynchE	synchronous Ethernet
TB	transport block
TCI	target cell identifier
TDD	time division duplex
TDM	time division multiplex
TDMA	time division multiple access
TDOA	time delay of arrival
THP	Tomlinson-Harashima precoding
TOA	time of arrival
TTI	transmit time interval
UDP	user datagram protocol
UCA	uniform circular array
UE	user equipment
UL	uplink
ULA	uniform linear array
UMTS	universal mobile telecommunications standard
UTRAN	universal terrestrial RAN
VDSL	very-high-speed digital subscriber line
VID	VLAN identifier
VLAN	virtual local area network
VoIP	voice over IP
WAN	wide area network
WCDMA	wideband code division multiple access
WCI	worst companion indicator
WiMAX	Worldwide Interoperability for Microwave Access
WF	Wiener filter
WINNER	Wireless World Initiative New Radio
WSSUS	wide sense stationary uncorrelated scattering
XGPON	10-Gigabit-capable PON
ZF	zero-forcing

Nomenclature and Notation

Nomenclature

In this book, we generally consider the setup and involved nomenclature depicted in Fig. 3.1 on page 13. Please note that we assume a *site* to consist of three *sectors*, which are equivalent to *cells*. Each sector or cell is assumed to be served by one dedicated base station (BS), even though in practice multiple such BSs may be integrated into one physical device.

CoMP Scheme Classification

Throughout the book, CoMP schemes are classified on one hand according to the extent of cooperation between BSs. We here distinguish between

- interference-aware transmission and detection (possibly with estimation of interference, but without explicit BS cooperation)
- interference coordination (e.g. joint multi-cell scheduling, coordinated beamforming etc.)
- multi-cell joint signal processing (e.g. joint detection or joint transmission)

We further distinguish between *decentralized* and *centralized* CoMP schemes, depending on where the subject of cooperation takes place. This classification is applied to various schemes observed in this book in Table 1.

Notation

Unless stated otherwise, the following holds throughout most parts of the book:

- Calligraphic letters (e.g., $\mathcal{M}$) represent *sets*
- Capital, italic letters, (e.g. $P_{\max}$) denote *constants*
- Bold-face, capital letters (e.g. $\mathbf{H}$) represent *matrices*
- Bold-face, lowercase letters (e.g. $\mathbf{h}$) represent *vectors*
- Lowercase, italic letters represent *scalars*.
- Variables with a hat on top (e.g. $\hat{\mathbf{H}}$) denote *estimates*
- Variables with a bar on top (e.g. $\bar{\mathbf{H}}$) denote an *effective* expression
- Variables with a tilde on top (e.g. $\tilde{\mathbf{H}}$ denote expressions in *time domain*, whereas other expressions are usually in *frequency domain*, see Section 8.2).

Table 1. Classification of CoMP schemes.

	Decentralized	**Centralized**
Interference-aware transmission/ detection	→ DL multi-user beamforming with IRC (Sections 5.1, 13.3) → IRC (Section 10.2)	
Interference coordination	→ UL cooperative interf. prediction (Sections 5.2.2, 14.3) → DL coordinated sched. / beamforming (CS/CB) (Sections 5.3, 14.4.3)	→ UL joint scheduling (Sections 5.2.1, 14.3) → DL centralized joint scheduling (Section 11.1)
Multi-cell joint signal processing	→ UL decentralized joint detection (Sections 6.2, 13.1, 14.3) → UL distr. interference subtraction (Sections 4.3.1, 13.2) → DL distributed joint transmission (Sections 6.3, 13.3, 13.4)	→ UL centralized joint detection (Sections 6.1, 13.2) → DL centralized joint transmission (Sections 6.3,13.3)

The following variables are frequently used throughout the book:

- $\mathbf{H}$, $\mathbf{h}$, or h denote (matrices or vectors of) channel coefficients
- $\mathbf{x}$ or x are signals to be transmitted, *before* precoding
- $\mathbf{s}$ or s are signals to be transmitted, *after* precoding
- $\mathbf{y}$ or y are received signals
- $\mathbf{W}$ or $\mathbf{w}$ are transmit/receive filters used at the BS side
- $\mathbf{G}$ or $\mathbf{g}$ are transmit/receive filters used at the UE side
- c typically denotes a cluster index
- k and j typically denote user indices
- m typically denotes a base station index
- t, τ and i denote time indices, where t and τ are time-continuous, and i is a discrete sample index
- f and q denote frequency indices, where f is frequency-continuous, and q is a discrete sub-carrier index
- o denotes an OFDM symbol index

As in most publications, $(\cdot)^H$ denotes Hermitian matrix transpose, $\mathrm{tr}\{\cdot\}$ denotes the trace of a matrix, $|\cdot|$ denotes set size when applied to a set, or determinant when applied to a matrix. $E\{\cdot\}$ denotes expectation value. $\mathbf{I}$ is an identity matrix.