

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.



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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

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Coordinated Multi-Point in Mobile Communications

From Theory to Practice

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Contents

| | |
|---|------------------|
| <i>List of Contributors</i> | <i>page</i> xiii |
| <i>Acknowledgements</i> | xvii |
| <i>List of Abbreviations</i> | xviii |
| <i>Nomenclature and Notation</i> | xxiv |
| Part I Motivation and Basics | 1 |
| 1 Introduction | 3 |
| 1.1 Motivation | 3 |
| 1.2 Aim of this Book | 5 |
| 1.3 Classes of CoMP Considered | 5 |
| 1.4 Outline of this Book | 6 |
| 2 An Operator’s Point of View | 7 |
| 2.1 The Mobile Internet - A Success Story so far | 7 |
| 2.2 Requirements on Future Networks and Upcoming Challenges | 8 |
| 2.3 The Role of CoMP | 9 |
| 2.4 The Role of Field Trials | 10 |
| 3 Information-Theoretic Basics | 11 |
| 3.1 Observed Cellular Scenarios | 11 |
| 3.2 Usage of OFDMA for Broadband Wireless Communications | 11 |
| 3.3 Multi-Point Frequency-Flat Baseband Model Considered | 13 |
| 3.4 Uplink Transmission | 14 |
| 3.4.1 Basic Uplink Capacity Bounds | 15 |
| 3.4.2 Full Cooperation in the Uplink | 17 |
| 3.4.3 No Cooperation in the Uplink | 17 |
| 3.4.4 Numerical Example | 19 |
| 3.5 Downlink Transmission | 19 |
| 3.5.1 Basic Downlink Capacity Bounds | 20 |
| 3.5.2 Full Cooperation in the Downlink | 22 |
| 3.5.3 No Cooperation in the Downlink | 22 |
| 3.5.4 Numerical Example | 23 |

| | | |
|----------------|---|-----------|
| 3.6 | Summary | 24 |
| 4 | Gains and Trade-Offs of Multi-Cell Joint Signal Processing | 25 |
| 4.1 | Modeling Imperfect Channel State Information (CSI) | 25 |
| 4.1.1 | Imperfect CSI in the Uplink | 25 |
| 4.1.2 | Imperfect CSI in the Downlink | 27 |
| 4.2 | Gain of Joint Signal Processing under Imperfect CSI | 29 |
| 4.3 | Trade-Offs in Uplink Multi-Cell Joint Signal Processing | 32 |
| 4.3.1 | Different Information Exchange and Cooperation Schemes | 32 |
| 4.3.2 | Numerical Results | 35 |
| 4.3.3 | Parallels between Theory and Practical Cooperation Schemes | 37 |
| 4.4 | Degrees of Freedom in Downlink Joint Signal Processing | 37 |
| 4.5 | Summary | 38 |
| Part II | Practical CoMP Schemes | 39 |
| 5 | CoMP Schemes Based on Interf.-Aware Transceivers or Interf. Coord. | 41 |
| 5.1 | DL Multi-User Beamforming with IRC | 41 |
| 5.1.1 | Introduction | 41 |
| 5.1.2 | Downlink System Model | 43 |
| 5.1.3 | Linear Receivers | 44 |
| 5.1.4 | Imperfect Channel Estimation | 45 |
| 5.1.5 | Resource Allocation and Fair User Selection | 46 |
| 5.1.6 | Single-Cell Performance | 48 |
| 5.1.7 | Multi-Cell Performance under Perfect CSI | 50 |
| 5.1.8 | Multi-Cell Performance under Imperfect CSI | 52 |
| 5.1.9 | Summary | 54 |
| 5.2 | Uplink Joint Scheduling and Cooperative Interference Prediction | 54 |
| 5.2.1 | Interference-Aware Joint Scheduling | 56 |
| 5.2.2 | Cooperative Interference Prediction | 61 |
| 5.2.3 | Practical Considerations | 64 |
| 5.2.4 | Applicability of Both Schemes to the Downlink | 66 |
| 5.2.5 | Summary | 67 |
| 5.3 | Downlink Coordinated Beamforming | 68 |
| 5.3.1 | Introduction | 68 |
| 5.3.2 | Single Receive Antenna at the Terminal | 70 |
| 5.3.3 | Multiple Receive Antennas at the Terminal | 74 |
| 5.3.4 | Summary | 80 |
| 6 | CoMP Schemes Based on Multi-Cell Joint Signal Processing | 81 |
| 6.1 | Uplink Centralized Joint Detection | 81 |
| 6.1.1 | Introduction | 81 |
| 6.1.2 | Joint Detection Algorithms | 82 |

| | | |
|--|--|------------|
| 6.1.3 | Local BS Processing with Limited Backhaul Constraint | 87 |
| 6.1.4 | Local or Partial Decoding with Limited Backhaul Constraint | 90 |
| 6.1.5 | Provisions for Uplink Joint Processing in WiMax and LTE | 92 |
| 6.1.6 | Summary | 93 |
| 6.2 | Uplink Decentralized Joint Detection | 94 |
| 6.2.1 | Practical Decentralized Interference Cancellation Scheme | 95 |
| 6.2.2 | Performance Assessment | 104 |
| 6.2.3 | Summary | 108 |
| 6.3 | DL Distributed CoMP Approaching Centralized Joint Transmission | 108 |
| 6.3.1 | System Model | 110 |
| 6.3.2 | Theoretical Limits for Static Clustering and DPC | 111 |
| 6.3.3 | Practical (Linear) Precoding | 113 |
| 6.3.4 | Scheme for Distributed, Centralized Joint Transmission | 115 |
| 6.3.5 | Summary | 121 |
| 6.4 | Downlink Decentralized Multi-User Transmission | 121 |
| 6.4.1 | Decentralized Beamforming with Limited CSIT | 122 |
| 6.4.2 | Multi-cell Beamforming with Limited Data Sharing | 130 |
| 6.4.3 | Summary | 136 |
| Part III Challenges Connected to CoMP | | 137 |
| 7 | Clustering | 139 |
| 7.1 | Static Clustering Concepts | 141 |
| 7.1.1 | Non-Overlapping Clusters | 142 |
| 7.1.2 | Overlapping Clusters | 145 |
| 7.1.3 | Resulting Geometries | 146 |
| 7.2 | Self-Organizing Clustering Concepts | 148 |
| 7.2.1 | Self-Organizing Network Concepts in 3GPP LTE | 148 |
| 7.2.2 | Adaptive Clustering Algorithms | 149 |
| 7.2.3 | Simulation Results | 152 |
| 7.2.4 | Signaling and Control Procedures | 157 |
| 7.3 | Summary | 159 |
| 8 | Synchronization | 161 |
| 8.1 | Synchronization Concepts | 161 |
| 8.1.1 | Synchronization Terminology | 161 |
| 8.1.2 | Network Synchronization | 163 |
| 8.1.3 | Satellite-Based Synchronization | 165 |
| 8.1.4 | Endogenous Distributed Wireless Carrier Synchronization | 166 |
| 8.1.5 | Summary | 170 |
| 8.2 | Imperfect Sync in Time: Perf. Degradation and Compensation | 170 |
| 8.2.1 | MIMO OFDM Transmission with Asynchronous Interference | 173 |
| 8.2.2 | Interf.-Aware Multi-User Joint Detection and Transmission | 176 |

| | | |
|--------|---|-----|
| 8.2.3 | System Level SINR Analysis | 178 |
| 8.2.4 | Summary | 181 |
| 8.3 | Imperfect Sync in Frequency: Perf. Degradation and Compensation | 181 |
| 8.3.1 | Downlink Analysis | 182 |
| 8.3.2 | Uplink Analysis | 189 |
| 8.3.3 | Summary | 192 |
| 9 | Channel Knowledge | 193 |
| 9.1 | Channel Estimation for CoMP | 193 |
| 9.1.1 | Channel Estimation - Single Link | 194 |
| 9.1.2 | Channel Estimation for CoMP | 202 |
| 9.1.3 | Multi-Cell Channel Estimation | 204 |
| 9.1.4 | Uplink Channel Estimation | 206 |
| 9.1.5 | Summary | 208 |
| 9.2 | Channel State Information Feedback to the Transmitter | 208 |
| 9.2.1 | Transmission Model | 210 |
| 9.2.2 | Sum-Rate Performance Measure | 211 |
| 9.2.3 | Channel Vector Quantization (CVQ) | 211 |
| 9.2.4 | Minimum Euclidean Distance Based CVQ | 213 |
| 9.2.5 | Maximum SINR Based CVQ | 214 |
| 9.2.6 | Pseudo-Maximum SINR based CVQ | 215 |
| 9.2.7 | Application to Zero-Forcing (ZF) Precoding | 216 |
| 9.2.8 | Resource Allocation | 216 |
| 9.2.9 | Simulation Results | 216 |
| 9.2.10 | Summary | 218 |
| 10 | Efficient and Robust Algorithm Implementation | 219 |
| 10.1 | Robust and Flexible Base Station Precoding Implementation | 219 |
| 10.1.1 | System Model | 220 |
| 10.1.2 | Transmit Filter Eigendecomposition | 221 |
| 10.1.3 | Transmit Filter Computations | 222 |
| 10.1.4 | The Order-Recursive Filter in Details | 224 |
| 10.1.5 | Example: SINR as Function of the Condition Number | 226 |
| 10.1.6 | Summary | 227 |
| 10.2 | Low-Complexity Terminal-Side Receiver Implementation | 227 |
| 10.2.1 | Introduction to Interference Rejection Combining (IRC) | 228 |
| 10.2.2 | IRC with Known Channel and Interference Covariance | 231 |
| 10.2.3 | Implementation Losses from Imperfect Channel Estimation | 233 |
| 10.2.4 | Losses from Spatial Interf.-and-Noise Covariance Estimation | 237 |
| 10.2.5 | Losses from Channel and Interference Estimation Errors | 241 |
| 10.2.6 | Summary | 241 |

| | | |
|-----------|--|------------|
| 11 | Scheduling, Signaling and Adaptive Usage of CoMP | 243 |
| 11.1 | Centralized Scheduling for CoMP | 243 |
| 11.1.1 | Introduction | 243 |
| 11.1.2 | System Model | 244 |
| 11.1.3 | Centralized Scheduling Problems | 246 |
| 11.1.4 | Analyses and Results | 251 |
| 11.1.5 | Summary | 254 |
| 11.2 | Decentralized Radio Link Control and Inter-BS Signaling | 254 |
| 11.2.1 | Resource Allocation | 255 |
| 11.2.2 | Link Adaptation | 256 |
| 11.2.3 | Radio Link Measurements | 257 |
| 11.2.4 | Uplink Power Control | 258 |
| 11.2.5 | Uplink Timing Advance | 259 |
| 11.2.6 | HARQ-related Timing Constraints for UL CoMP | 259 |
| 11.2.7 | Handover | 262 |
| 11.2.8 | Inter-BS Signaling | 262 |
| 11.2.9 | Summary | 266 |
| 11.3 | Ad-hoc CoMP | 266 |
| 11.3.1 | Introduction | 267 |
| 11.3.2 | Ad-Hoc CoMP With More Accurate CSI | 269 |
| 11.3.3 | Ad-Hoc CoMP with CSI Impairments | 273 |
| 11.3.4 | Ad-Hoc CoMP and HARQ | 275 |
| 11.3.5 | Summary | 276 |
| 12 | Backhaul | 277 |
| 12.1 | Fund. Limits of Interf. Mitigation with Limited Backhaul Coop. | 277 |
| 12.1.1 | Introduction | 278 |
| 12.1.2 | Uplink Scenario: Receiver Cooperation | 281 |
| 12.1.3 | Downlink Scenario: Transmitter Cooperation | 286 |
| 12.1.4 | UL-DL Reciprocity and Generalized Degrees of Freedom | 287 |
| 12.1.5 | Summary | 291 |
| 12.2 | Backhaul Requirements of Practical CoMP Schemes | 291 |
| 12.2.1 | Types of Backhaul Data and Scaling Laws | 291 |
| 12.2.2 | Specific Backhaul Requirements of Exemplary CoMP Schemes | 294 |
| 12.2.3 | Backhaul Latency Requirements | 299 |
| 12.2.4 | Backhaul Topology Considerations | 300 |
| 12.2.5 | Summary | 300 |
| 12.3 | CoMP Backhaul Infrastructure Concepts | 301 |
| 12.3.1 | Ethernet | 301 |
| 12.3.2 | Passive Optical Network | 303 |
| 12.3.3 | Digital Subscriber Line | 305 |
| 12.3.4 | Microwave | 306 |
| 12.3.5 | The X2 Interface | 307 |
| 12.3.6 | Backhaul Topology Concepts | 307 |

x

| | | |
|---------------------------------------|---|------------|
| 12.3.7 | Summary | 310 |
| Part IV Performance Assessment | | 311 |
| 13 | Field Trial Results | 313 |
| 13.1 | Real-time Impl. and Trials of Adv. Receivers and UL CoMP | 313 |
| 13.1.1 | Real-time Implementation and Lab Tests | 314 |
| 13.1.2 | Uplink Successive Interference Cancelation (SIC) Receiver | 314 |
| 13.1.3 | Uplink Macro Diversity Trials with Distributed RRHs | 317 |
| 13.1.4 | Summary | 319 |
| 13.2 | Assessing the Gain of Uplink CoMP in a Large-Scale Field Trial | 319 |
| 13.2.1 | Measurement Setup | 320 |
| 13.2.2 | Signal Processing Architecture and Evaluation Concept | 321 |
| 13.2.3 | Noise Estimation | 322 |
| 13.2.4 | Channel Equalization | 322 |
| 13.2.5 | Field Trial Results | 325 |
| 13.2.6 | Summary | 330 |
| 13.3 | Real-time Implementation and Field Trials for Downlink CoMP | 331 |
| 13.3.1 | Introduction | 332 |
| 13.3.2 | Enabling Features | 334 |
| 13.3.3 | Real-time Implementation | 346 |
| 13.3.4 | Field Trials | 347 |
| 13.3.5 | Summary | 352 |
| 13.4 | Predicting Pract. Achievable DL CoMP Gains over Larger Areas | 353 |
| 13.4.1 | Setup and Closed-Loop System Design | 353 |
| 13.4.2 | Measurement and Evaluation Methodology | 356 |
| 13.4.3 | Measurement Campaign | 358 |
| 13.4.4 | Summary | 363 |
| 13.5 | Lessons Learnt Through Field Trials | 364 |
| 14 | Performance Prediction of CoMP in Large Cellular Systems | 367 |
| 14.1 | Simulation and Link-2-System Mapping Methodology | 367 |
| 14.1.1 | General Simulation Assumptions and Modeling | 368 |
| 14.1.2 | Channel Models and Antenna Models | 370 |
| 14.1.3 | Transceiver Techniques | 373 |
| 14.1.4 | Link-to-System Interface | 373 |
| 14.1.5 | Key Performance Indicators | 375 |
| 14.1.6 | Summary | 376 |
| 14.2 | Obtaining Chn. Model Params. via Chn. Sounding or Ray-Tracing | 376 |
| 14.2.1 | Large-Scale-Parameters | 377 |
| 14.2.2 | Measurement-based Parameter Estimation | 380 |
| 14.2.3 | Ray-Tracing based Parameter Simulation | 380 |
| 14.2.4 | Comparison between Measurements and Ray-Tracing | 382 |

| | | |
|---------------------------------------|--|------------|
| 14.2.5 | Summary | 387 |
| 14.3 | Uplink Simulation Results | 387 |
| 14.3.1 | Compared Schemes | 387 |
| 14.3.2 | Simulation Assumptions and Parameters | 389 |
| 14.3.3 | Backhaul Traffic | 391 |
| 14.3.4 | Simulation Results | 392 |
| 14.3.5 | Summary | 395 |
| 14.4 | Downlink Simulation Results | 396 |
| 14.4.1 | Compared Schemes | 396 |
| 14.4.2 | Simulation Assumptions and Parameters | 397 |
| 14.4.3 | Detailed Analysis of Coordinated Scheduling/Beamforming | 398 |
| 14.4.4 | Backhaul Traffic | 406 |
| 14.4.5 | Simulation Results | 406 |
| 14.4.6 | Summary | 408 |
| Part V Outlook and Conclusions | | 409 |
| 15 | Outlook | 411 |
| 15.1 | Using CoMP for Terminal Localization | 411 |
| 15.1.1 | Localization based on the Signal Propagation Delay | 412 |
| 15.1.2 | Further Localization Methods | 416 |
| 15.1.3 | Localization in B3G Standards | 418 |
| 15.1.4 | Summary | 422 |
| 15.2 | Relay-Assisted Mobile Communication using CoMP | 423 |
| 15.2.1 | Introduction | 423 |
| 15.2.2 | Reference Scenario | 424 |
| 15.2.3 | System and Protocol Description | 425 |
| 15.2.4 | Trade-Offs in Relay Networks | 427 |
| 15.2.5 | Numerical Evaluation of CoMP and Relaying | 428 |
| 15.2.6 | Cost/Benefit Trade-Off | 428 |
| 15.2.7 | Energy/Benefit Trade-Off | 429 |
| 15.2.8 | Computation/Transmission Power Trade-Off | 430 |
| 15.2.9 | Summary | 432 |
| 15.3 | Next Generation Cellular Network Planning and Optimization | 432 |
| 15.3.1 | Introduction | 432 |
| 15.3.2 | Classical Cellular Network Planning and Optimization | 433 |
| 15.3.3 | Physical Characterization of Capacity Gains through CoMP | 435 |
| 15.3.4 | Summary | 443 |
| 15.4 | Energy-Efficiency Aspects of CoMP | 444 |
| 15.4.1 | System Model | 445 |
| 15.4.2 | Effective Transmission Rates | 447 |
| 15.4.3 | Backhauling | 448 |
| 15.4.4 | Energy Consumption of Cellular Base Stations | 449 |

| | | |
|-----------|--|-----|
| | 15.4.5 System Evaluation | 451 |
| | 15.4.6 Summary | 453 |
| 16 | Summary and Conclusions | 455 |
| | 16.1 Summary of this Book | 455 |
| | 16.1.1 Most Promising CoMP Schemes and Potential Gains | 455 |
| | 16.1.2 Key Challenges Identified | 457 |
| | 16.2 Conclusions | 458 |
| | 16.2.1 About this Book | 459 |
| | 16.2.2 CoMP’s Place in the LTE-Advanced Roadmap and Beyond | 460 |
| | <i>References</i> | 461 |
| | <i>Index</i> | 479 |

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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 | small-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 beam-forming 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, $\text{tr}\{\cdot\}$ 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.