

# Contents

|          |                                                                  |           |
|----------|------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                              | <b>1</b>  |
| 1.1      | Radio Channel Behavior                                           | 2         |
| 1.2      | Basics of the OFDM Transmission Technique                        | 5         |
| 1.3      | OFDM Combined with Multiple Access Schemes                       | 10        |
| <b>2</b> | <b>Channel Modeling</b>                                          | <b>15</b> |
| 2.1      | Joint Space-Time-Frequency Representation                        | 16        |
| 2.1.1    | Multidimensional Channel Sounding                                | 17        |
| 2.1.2    | Extraction of Parameters for Dominant MPCs                       | 17        |
| 2.2      | Deterministic Modeling                                           | 18        |
| 2.2.1    | Relevant GTD/UTD Aspects                                         | 18        |
| 2.2.2    | Vehicle2X Channel Modeling                                       | 19        |
| 2.3      | Stochastic Driving of Multi-Path Model                           | 20        |
| 2.3.1    | Usage of the Large-Scale Parameters for Channel Characterization | 21        |
| 2.3.2    | Relaying                                                         | 24        |
| 2.3.3    | Cooperative Downlink                                             | 24        |
| <b>3</b> | <b>Link-Level Aspects</b>                                        | <b>33</b> |
| 3.1      | OFDM Data Detection and Channel Estimation                       | 33        |
| 3.1.1    | Introduction                                                     | 33        |
| 3.1.2    | Data Detection in the Presence of Nonlinear Distortions          | 33        |
| 3.1.3    | Joint Data Detection and Channel Estimation                      | 39        |
| 3.2      | Spreading                                                        | 47        |
| 3.2.1    | Introduction                                                     | 47        |
| 3.2.2    | MC-CDM and MC-CAFS                                               | 48        |
| 3.2.3    | Simulation Results                                               | 49        |
| 3.2.4    | Concluding Remarks                                               | 51        |

|       |                                                                                               |     |
|-------|-----------------------------------------------------------------------------------------------|-----|
| 3.3   | Iterative Diversity Reception for Coded OFDM<br>Transmission Over Fading Channels. . . . .    | 54  |
| 3.3.1 | Introduction. . . . .                                                                         | 54  |
| 3.3.2 | Turbo Diversity. . . . .                                                                      | 55  |
| 3.3.3 | Optimization for Turbo Diversity. . . . .                                                     | 56  |
| 3.3.4 | Performance Evaluation. . . . .                                                               | 57  |
| 3.3.5 | Summary. . . . .                                                                              | 59  |
| 3.4   | MMSE-based Turbo Equalization Principles for Frequency<br>Selective Fading Channels . . . . . | 61  |
| 3.4.1 | Introduction. . . . .                                                                         | 61  |
| 3.4.2 | System Model . . . . .                                                                        | 61  |
| 3.4.3 | MMSE Turbo Equalization Principles. . . . .                                                   | 62  |
| 3.4.4 | Summary. . . . .                                                                              | 66  |
| 3.5   | Peak-to-Average Power Ratio Reduction in Multi-Antenna<br>Scenarios . . . . .                 | 69  |
| 3.5.1 | Introduction and Overview on PAR<br>Reduction Schemes . . . . .                               | 69  |
| 3.5.2 | PAR Reduction Schemes for MIMO<br>Transmission . . . . .                                      | 71  |
| 3.5.3 | Numerical Results . . . . .                                                                   | 74  |
| 3.5.4 | Summary. . . . .                                                                              | 74  |
| 3.6   | Single- vs. Multicarrier Transmission in MIMO<br>and Multiuser Scenarios . . . . .            | 81  |
| 3.6.1 | Introduction. . . . .                                                                         | 81  |
| 3.6.2 | Point-to-Point MIMO Transmission. . . . .                                                     | 81  |
| 3.6.3 | Up- and Downlink Scenarios in Multiuser<br>Transmission . . . . .                             | 82  |
| 3.6.4 | Aspects of Channel Coding. . . . .                                                            | 84  |
| 3.6.5 | Summary. . . . .                                                                              | 85  |
| 3.7   | Successive Bit Loading Concept . . . . .                                                      | 90  |
| 3.7.1 | Introduction. . . . .                                                                         | 90  |
| 3.7.2 | System Model . . . . .                                                                        | 91  |
| 3.7.3 | Bit Loading Algorithm. . . . .                                                                | 92  |
| 3.7.4 | Results. . . . .                                                                              | 94  |
| 3.7.5 | Summary. . . . .                                                                              | 96  |
| 3.8   | Adaptive Transmission Techniques. . . . .                                                     | 98  |
| 3.8.1 | Introduction. . . . .                                                                         | 98  |
| 3.8.2 | Adaptive Modulation and Coding. . . . .                                                       | 98  |
| 3.8.3 | Adaptive MIMO Transmission. . . . .                                                           | 99  |
| 3.8.4 | Signaling of the Bit Allocation Table . . . . .                                               | 102 |
| 3.8.5 | Automatic Modulation Classification . . . . .                                                 | 103 |
| 3.8.6 | Summary. . . . .                                                                              | 105 |

|          |                                                                                                                   |            |
|----------|-------------------------------------------------------------------------------------------------------------------|------------|
| <b>4</b> | <b>System Level Aspects for Single Cell Scenarios</b>                                                             | <b>109</b> |
| 4.1      | Efficient Analysis of OFDM Channels                                                                               | 109        |
| 4.1.1    | Introduction                                                                                                      | 109        |
| 4.1.2    | The Channel Matrix $G$                                                                                            | 109        |
| 4.1.3    | Common Channel Operator Models                                                                                    | 111        |
| 4.1.4    | Computing the Channel Matrix $G$                                                                                  | 112        |
| 4.2      | Generic Description of a MIMO-OFDM-Radio-Transmission-Link                                                        | 115        |
| 4.2.1    | Introduction                                                                                                      | 115        |
| 4.2.2    | System Model                                                                                                      | 115        |
| 4.2.3    | Performance Analysis                                                                                              | 116        |
| 4.2.4    | Generic Model                                                                                                     | 118        |
| 4.2.5    | Summary and Further Work                                                                                          | 120        |
| 4.3      | Resource Allocation Using Broadcast Techniques                                                                    | 122        |
| 4.3.1    | Motivation                                                                                                        | 122        |
| 4.3.2    | Resource Allocation Algorithms                                                                                    | 122        |
| 4.4      | Rate Allocation for the 2-User Multiple Access Channel with MMSE Turbo Equalization                               | 128        |
| 4.4.1    | Introduction                                                                                                      | 128        |
| 4.4.2    | Turbo Equalization                                                                                                | 128        |
| 4.4.3    | Rate Allocation using EXIT Charts                                                                                 | 129        |
| 4.4.4    | Summary                                                                                                           | 131        |
| 4.5      | Coexistence of Systems                                                                                            | 133        |
| 4.6      | System Design for Time-Variant Channels                                                                           | 136        |
| 4.6.1    | Multicarrier Systems for Rapidly Moving Receivers                                                                 | 136        |
| 4.6.2    | Highly Mobile MIMO-OFDM-Transmission in Realistic Propagation Scenarios                                           | 138        |
| 4.7      | Combination of Adaptive and Non-Adaptive Multi-User OFDMA Schemes in the Presence of User-Dependent Imperfect CSI | 142        |
| 4.7.1    | Introduction                                                                                                      | 142        |
| 4.7.2    | Combining Transmission Schemes                                                                                    | 142        |
| 4.7.3    | Numerical Results                                                                                                 | 143        |
| 4.8      | Integration of COFDM Systems with Multiple Antennas and Design of Adaptive Medium Access Protocols                | 146        |
| 4.8.1    | Abstract                                                                                                          | 146        |
| 4.8.2    | MAC Frame for SDMA Operation and Spatial Grouping                                                                 | 146        |
| 4.8.3    | Hardware Implementation of COFDM Systems with Multiple Antennas                                                   | 147        |
| 4.9      | Large System Analysis of Nearly Optimum Low Complex Beamforming in Multicarrier Multiuser Multiantenna Systems    | 150        |

|          |                                                                                                                                     |            |
|----------|-------------------------------------------------------------------------------------------------------------------------------------|------------|
| 4.9.1    | Introduction . . . . .                                                                                                              | 150        |
| 4.9.2    | System Model . . . . .                                                                                                              | 150        |
| 4.9.3    | Description of Algorithms. . . . .                                                                                                  | 151        |
| 4.9.4    | Approximation of the Ergodic Sum Rate with<br>Large System Analysis . . . . .                                                       | 152        |
| 4.9.5    | Numerical Results . . . . .                                                                                                         | 154        |
| 4.10     | Combined Radar and Communication Systems<br>Using OFDM . . . . .                                                                    | 156        |
| 4.10.1   | Introduction. . . . .                                                                                                               | 156        |
| 4.10.2   | Signal Design . . . . .                                                                                                             | 156        |
| 4.10.3   | The Radar Subsystem . . . . .                                                                                                       | 158        |
| 4.10.4   | Measurements . . . . .                                                                                                              | 160        |
| 4.10.5   | Summary . . . . .                                                                                                                   | 163        |
| <b>5</b> | <b>System Level Aspects for Multiple Cell Scenarios. . . . .</b>                                                                    | <b>165</b> |
| 5.1      | Link Adaptation. . . . .                                                                                                            | 165        |
| 5.1.1    | Motivation. . . . .                                                                                                                 | 165        |
| 5.1.2    | Example of a Multiple Link Scenario . . . . .                                                                                       | 165        |
| 5.1.3    | Adaptation of Physical Link Parameters. . . . .                                                                                     | 169        |
| 5.1.4    | Cross-Layer Adaptation . . . . .                                                                                                    | 176        |
| 5.1.5    | Multiple Link Network - Overall Adaptation . . . . .                                                                                | 178        |
| 5.2      | System Concept for a MIMO-OFDM-Based Self-Organizing<br>Data Transmission Network . . . . .                                         | 180        |
| 5.2.1    | Introduction. . . . .                                                                                                               | 180        |
| 5.2.2    | Beamforming Concepts. . . . .                                                                                                       | 181        |
| 5.2.3    | System Concept . . . . .                                                                                                            | 182        |
| 5.2.4    | Summary . . . . .                                                                                                                   | 190        |
| 5.3      | Pricing Algorithms for Power Control, Beamformer Design,<br>and Interference Alignment in Interference<br>Limited Networks. . . . . | 192        |
| 5.3.1    | Introduction. . . . .                                                                                                               | 192        |
| 5.3.2    | System Model . . . . .                                                                                                              | 192        |
| 5.3.3    | Distributed Interference Pricing . . . . .                                                                                          | 193        |
| 5.3.4    | MIMO Interference Networks and<br>Interference Alignment. . . . .                                                                   | 196        |
| 5.3.5    | Summary . . . . .                                                                                                                   | 198        |
| 5.4      | Interference Reduction: Cooperative Communication<br>with Partial CST in Mobile Radio Cellular Networks . . . . .                   | 199        |
| 5.4.1    | Introduction. . . . .                                                                                                               | 199        |
| 5.4.2    | System Model and Reference Scenario . . . . .                                                                                       | 200        |
| 5.4.3    | Significant CSI Selection Algorithm and Channel<br>Matrix Formalism . . . . .                                                       | 203        |
| 5.4.4    | Decentralized JD/JT with Significant CSI for<br>Interference Reduction . . . . .                                                    | 205        |

|              |                                                                               |            |
|--------------|-------------------------------------------------------------------------------|------------|
| 5.4.5        | Impact of Imperfect CSI on Cooperative Communication Based on JD/JT . . . . . | 208        |
| 5.4.6        | Advanced Algorithm Based on Statistical Knowledge of Imperfect CSI . . . . .  | 210        |
| 5.4.7        | System Concept Based on Different Levels of Knowledge of CSI . . . . .        | 211        |
| 5.4.8        | Outlook . . . . .                                                             | 211        |
| <b>6</b>     | <b>OFDM/DMT for Wireline Communications . . . . .</b>                         | <b>215</b> |
| 6.1          | Discrete MultiTone (DMT) and Wireline Channel Properties . . . . .            | 215        |
| 6.1.1        | Properties of the Twisted-Pair Channel . . . . .                              | 215        |
| 6.1.2        | Discrete MultiTone (DMT) . . . . .                                            | 219        |
| 6.2          | Optical OFDM Transmission and Optical Channel Properties . . . . .            | 225        |
| 6.3          | Impulse-Noise Cancellation . . . . .                                          | 227        |
| 6.3.1        | Common Mode and Differential Mode . . . . .                                   | 227        |
| 6.3.2        | Coupling and Transfer Functions . . . . .                                     | 227        |
| 6.3.3        | Common-Mode Reference-Based Canceler . . . . .                                | 227        |
| 6.3.4        | Impulse Noise Detection and Cancellation . . . . .                            | 229        |
| 6.3.5        | Simulation Results . . . . .                                                  | 230        |
| 6.4          | Dual Polarization Optical OFDM Transmission . . . . .                         | 233        |
| 6.4.1        | Setup . . . . .                                                               | 233        |
| 6.4.2        | Noise Variance Estimation . . . . .                                           | 234        |
| 6.4.3        | ADC/DAC Resolution . . . . .                                                  | 237        |
| 6.5          | Forward Error Correction . . . . .                                            | 238        |
| 6.5.1        | BICM-ID System Model . . . . .                                                | 239        |
| 6.5.2        | Influence of the Applied Mapping . . . . .                                    | 241        |
| 6.5.3        | Simulations on the Performance of Coded OFDM . . . . .                        | 241        |
| 6.6          | Summary . . . . .                                                             | 243        |
| <b>Index</b> | <b>. . . . .</b>                                                              | <b>251</b> |