

# RF Imperfections in High-rate Wireless Systems

Impact and Digital Compensation

*by*

**Tim Schenk**

*Philips Research, Eindhoven  
The Netherlands*

 Springer

# Contents

|                                                    |      |
|----------------------------------------------------|------|
| Foreword                                           | xi   |
| Preface                                            | xiii |
| 1. INTRODUCTION                                    | 1    |
| 1.1 Wireless communications                        | 1    |
| 1.2 OFDM                                           | 3    |
| 1.3 MIMO                                           | 4    |
| 1.4 RF transceiver impairments                     | 6    |
| 1.5 Outline of the book                            | 9    |
| 2. MULTIPLE-ANTENNA OFDM SYSTEMS                   | 11   |
| 2.1 Introduction                                   | 11   |
| 2.2 Channel modelling                              | 11   |
| 2.2.1 Multipath propagation                        | 12   |
| 2.2.2 Stochastic channel model                     | 16   |
| 2.3 System modelling                               | 18   |
| 2.3.1 MIMO                                         | 19   |
| 2.3.2 OFDM                                         | 22   |
| 2.3.3 MIMO OFDM                                    | 26   |
| 2.4 Conclusions                                    | 29   |
| 3. DESIGN AND IMPLEMENTATION OF A MIMO OFDM SYSTEM | 31   |
| 3.1 Introduction                                   | 31   |
| 3.2 Transmission format and preamble design        | 32   |
| 3.2.1 IEEE 802.11a                                 | 32   |
| 3.2.2 MIMO OFDM                                    | 34   |

|       |                                             |     |
|-------|---------------------------------------------|-----|
| 3.3   | Frequency synchronisation                   | 39  |
| 3.3.1 | Influence of CFO                            | 40  |
| 3.3.2 | Algorithm description                       | 42  |
| 3.3.3 | Performance analysis                        | 44  |
| 3.3.4 | Numerical results                           | 47  |
| 3.3.5 | Summary                                     | 51  |
| 3.4   | Channel estimation                          | 52  |
| 3.4.1 | Algorithm and performance analysis          | 52  |
| 3.4.2 | Numerical results                           | 58  |
| 3.4.3 | Summary                                     | 62  |
| 3.5   | Timing synchronisation                      | 62  |
| 3.5.1 | System description                          | 63  |
| 3.5.2 | Algorithm description                       | 66  |
| 3.5.3 | Numerical results                           | 68  |
| 3.5.4 | Summary and discussion                      | 72  |
| 3.6   | Multiple-antenna OFDM system implementation | 73  |
| 3.6.1 | Test system description                     | 73  |
| 3.6.2 | Baseband design                             | 74  |
| 3.6.3 | Measurement results                         | 76  |
| 3.6.4 | Comparison with simulation results          | 79  |
| 3.7   | Conclusions                                 | 81  |
| 4.    | PHASE NOISE                                 | 83  |
| 4.1   | Introduction                                | 83  |
| 4.2   | System and phase noise modelling            | 84  |
| 4.2.1 | Oscillator modelling                        | 85  |
| 4.2.2 | Influence on signal model                   | 88  |
| 4.3   | Impact and distribution of the ICI term     | 91  |
| 4.3.1 | System model                                | 91  |
| 4.3.2 | Bit-error probabilities                     | 94  |
| 4.3.3 | Properties of the ICI term                  | 95  |
| 4.3.4 | Simulation results                          | 104 |
| 4.3.5 | Summary                                     | 107 |
| 4.4   | ICI-caused error term in MIMO OFDM          | 108 |
| 4.4.1 | Transmitter phase noise                     | 109 |
| 4.4.2 | Receiver phase noise                        | 110 |

|       |                                                    |     |
|-------|----------------------------------------------------|-----|
| 4.4.3 | Phase noise process                                | 112 |
| 4.4.4 | Numerical results                                  | 113 |
| 4.4.5 | Summary and discussion                             | 116 |
| 4.5   | Compensation of the CPE                            | 117 |
| 4.5.1 | Maximum-likelihood estimator                       | 117 |
| 4.5.2 | MLE optimisation algorithm                         | 119 |
| 4.5.3 | Sub-optimal estimator                              | 121 |
| 4.5.4 | Cramér-Rao lower bound                             | 122 |
| 4.5.5 | Numerical results                                  | 124 |
| 4.5.6 | Summary                                            | 130 |
| 4.6   | Compensation of the ICI                            | 130 |
| 4.6.1 | Suppression algorithm                              | 131 |
| 4.6.2 | Numerical results                                  | 134 |
| 4.6.3 | Summary                                            | 136 |
| 4.7   | Conclusions                                        | 137 |
| 5.    | <b>IQ IMBALANCE</b>                                | 139 |
| 5.1   | Introduction                                       | 139 |
| 5.2   | System and IQ imbalance modelling                  | 140 |
| 5.2.1 | TX/RX front-end architecture                       | 141 |
| 5.2.2 | IQ mismatch                                        | 143 |
| 5.2.3 | Influence on MIMO signal model                     | 145 |
| 5.2.4 | RX filter imbalance                                | 148 |
| 5.3   | Impact of IQ imbalance on system performance       | 150 |
| 5.3.1 | Error in symbol detection                          | 150 |
| 5.3.2 | Probability of erroneous detection<br>for $M$ -QAM | 152 |
| 5.3.3 | Numerical results                                  | 159 |
| 5.3.4 | Summary and discussion                             | 163 |
| 5.4   | Preamble based estimation and mitigation           | 163 |
| 5.4.1 | Preamble design                                    | 164 |
| 5.4.2 | TX IQ imbalance estimation                         | 166 |
| 5.4.3 | RX IQ imbalance estimation                         | 167 |
| 5.4.4 | TX and RX IQ imbalance estimation                  | 168 |
| 5.4.5 | Iterative TX and RX IQ imbalance estimation        | 170 |
| 5.4.6 | Numerical results                                  | 172 |
| 5.4.7 | Summary                                            | 177 |

|       |                                                |     |
|-------|------------------------------------------------|-----|
| 5.5   | Decision-directed mitigation                   | 178 |
| 5.5.1 | Adaptive filter based algorithm                | 178 |
| 5.5.2 | Numerical results                              | 180 |
| 5.6   | Conclusions                                    | 182 |
| 6.    | NONLINEARITIES                                 | 185 |
| 6.1   | Introduction                                   | 185 |
| 6.2   | System and nonlinearities modelling            | 187 |
| 6.2.1 | Nonlinearity modelling                         | 187 |
| 6.2.2 | Influence on signal model                      | 192 |
| 6.3   | Impact of nonlinearities on system performance | 195 |
| 6.3.1 | TX nonlinearities                              | 196 |
| 6.3.2 | RX nonlinearities                              | 201 |
| 6.3.3 | Numerical results                              | 203 |
| 6.3.4 | Summary and discussion                         | 207 |
| 6.4   | PAPR reduction by spatial shifting             | 208 |
| 6.4.1 | Signal modelling                               | 209 |
| 6.4.2 | Spatial shifting                               | 210 |
| 6.4.3 | Combining SS and PS                            | 211 |
| 6.4.4 | Subcarrier grouping schemes                    | 213 |
| 6.4.5 | Side information/Transparency                  | 213 |
| 6.4.6 | Numerical results                              | 215 |
| 6.4.7 | Summary and discussion                         | 217 |
| 6.5   | RX-based correction of nonlinearities          | 219 |
| 6.5.1 | Baseband amplitude clipping                    | 220 |
| 6.5.2 | Estimation of linear and nonlinear channel     | 221 |
| 6.5.3 | Postdistortion                                 | 230 |
| 6.5.4 | Iterative distortion removal                   | 231 |
| 6.5.5 | Simulation results                             | 233 |
| 6.5.6 | Summary                                        | 242 |
| 6.6   | Conclusions                                    | 242 |
| 7.    | A GENERALISED ERROR MODEL                      | 245 |
| 7.1   | Introduction                                   | 245 |
| 7.2   | Error model                                    | 246 |
| 7.2.1 | TX and RX impairment model                     | 247 |
| 7.2.2 | Mapping of RF impairments                      | 248 |
| 7.2.3 | Nonstationarity of the impairments             | 250 |
| 7.2.4 | Transmission structure                         | 252 |

|       |                                               |     |
|-------|-----------------------------------------------|-----|
| 7.3   | Performance evaluation                        | 252 |
| 7.3.1 | Preamble phase                                | 253 |
| 7.3.2 | Data phase                                    | 253 |
| 7.3.3 | Probability of error                          | 254 |
| 7.4   | Numerical results                             | 257 |
| 7.5   | Conclusions                                   | 261 |
| 8.    | DISCUSSION AND CONCLUSIONS                    | 263 |
| 8.1   | Summary and conclusions                       | 263 |
| 8.1.1 | Synchronisation for MIMO OFDM systems         | 264 |
| 8.1.2 | Multiple-antenna OFDM proof of concept        | 265 |
| 8.1.3 | Behavioural RF impairment modelling           | 265 |
| 8.1.4 | Performance impact of front-end imperfections | 266 |
| 8.1.5 | Mitigation approaches for RF impairments      | 267 |
| 8.1.6 | A generalised error model                     | 269 |
| 8.2   | Scope of future research                      | 270 |
| 8.2.1 | Influence of RF impairments                   | 270 |
| 8.2.2 | Mitigation approaches                         | 271 |
| 8.2.3 | Towards mm-wave systems                       | 272 |
|       | Glossary                                      | 275 |
|       | Appendices                                    | 281 |
| A     | MSE in CFO estimation                         | 281 |
| B     | MSE in channel estimation                     | 283 |
| B.1   | MSE in linear channel interpolation           | 283 |
| B.2   | MSE in linear channel extrapolation           | 284 |
| C     | Measurement setup                             | 287 |
| C.1   | Baseband                                      | 287 |
| C.2   | IF stages                                     | 289 |
| C.3   | Antennas                                      | 290 |
| D     | Proof of Theorem 4.1                          | 291 |
| E     | Orthonormal polynomial basis                  | 299 |
|       | References                                    | 301 |
|       | Index                                         | 315 |