

Contents

| | |
|------------------------------------|-------|
| Abstract | iii |
| Resumen | vii |
| Resum | xi |
| Acknowledgements | xv |
| Acronyms | xvii |
| Nomenclature | xxi |
| Contents | xxiii |
| List of Figures | xxvii |
| List of Tables | xxxi |
| 1 Introduction | 1 |
| 1.1 Motivation | 4 |
| 1.2 Objectives | 6 |
| 1.3 Contributions | 6 |
| 1.4 Organization | 7 |
| 2 Preliminaries | 11 |
| 2.1 MIMO systems | 11 |
| 2.1.1 Single-user | 12 |
| 2.1.2 Multiuser | 14 |
| 2.2 Coordinated systems | 19 |
| 2.3 Massive MIMO systems | 21 |

| | | |
|----------|---|-----------|
| 2.4 | MIMO-OFDM | 22 |
| 2.5 | Limited Feedback | 24 |
| 2.5.1 | Single-user | 24 |
| 2.5.2 | Multiuser | 26 |
| 2.6 | Channel models | 29 |
| 2.6.1 | Gaussian i.i.d. model | 30 |
| 2.6.2 | Kronecker model | 30 |
| 2.6.3 | Extended ITU model | 30 |
| 2.6.4 | Spatial channel model | 31 |
| 2.7 | Lattices | 33 |
| 2.7.1 | Introduction | 33 |
| 2.7.2 | Lattice reduction | 35 |
| I | Precoding | 39 |
| 3 | Precoding with Perfect CSIT | 41 |
| 3.1 | Zero-Forcing | 44 |
| 3.2 | Sphere encoder | 45 |
| 3.3 | Tomlinson-Harashima precoding | 46 |
| 3.4 | Lattice-Reduction-aided precoding | 48 |
| 3.4.1 | LRAP-linear | 48 |
| 3.4.2 | LRAP-VB | 49 |
| 3.4.3 | LR-THP | 50 |
| 3.5 | Performance | 51 |
| 3.6 | Complexity analysis | 54 |
| 3.6.1 | Preprocessing computational cost | 55 |
| 3.6.2 | Per-symbol-vector computational cost | 57 |
| 3.6.3 | Overall computational cost | 57 |
| 3.7 | Conclusion | 59 |
| 4 | Precoding with Imperfect CSIT | 61 |
| 4.1 | Zero-Forcing | 62 |
| 4.2 | Tomlinson-Harashima precoding | 63 |
| 4.3 | Lattice-Reduction-aided Tomlinson-Harashima precoding | 64 |
| 4.4 | Performance | 65 |
| 4.5 | Conclusion | 68 |
| 5 | Hardware Implementation | 69 |
| 5.1 | Introduction to GPU and CUDA | 70 |
| 5.1.1 | CUDA | 71 |

| | | |
|-----------|---|------------|
| 5.1.2 | Hardware considerations | 73 |
| 5.2 | GPU implementation of precoding algorithms | 74 |
| 5.2.1 | Implementation details | 74 |
| 5.2.2 | Results | 77 |
| 5.3 | Reconfigurable GPU implementation of THP | 80 |
| 5.3.1 | Reconfigurable THP scheme | 81 |
| 5.3.2 | Implementation details | 81 |
| 5.3.3 | Results | 82 |
| 5.4 | Parallelization of the LLL algorithm on GPU | 85 |
| 5.4.1 | Introduction to parallel lattice reduction strategies | 85 |
| 5.4.2 | Cost reduced all-swap LLL algorithm | 86 |
| 5.4.3 | Modified block LLL | 89 |
| 5.4.4 | Cost reduced modified block LLL | 91 |
| 5.4.5 | Implementation of MB-LLL and CRMB-LLL | 91 |
| 5.4.6 | Results | 95 |
| 5.5 | Conclusion | 101 |
| II | Limited Feedback | 103 |
| 6 | Limited Feedback exploiting Frequency Correlation | 105 |
| 6.1 | Introduction to quantization | 106 |
| 6.1.1 | Scalar quantization | 106 |
| 6.1.2 | Vector quantization | 113 |
| 6.2 | Vector quantization over CFR pilots | 117 |
| 6.2.1 | Channel estimation | 118 |
| 6.2.2 | Vector quantization | 119 |
| 6.2.3 | Numerical results | 121 |
| 6.2.4 | Conclusion | 124 |
| 6.3 | Channel quantization based on the KL transform | 124 |
| 6.3.1 | Time-domain quantization | 125 |
| 6.3.2 | Karhunen-Loève-Domain Quantization | 126 |
| 6.3.3 | Efficient eigendecomposition | 128 |
| 6.3.4 | Computational complexity | 129 |
| 6.3.5 | Numerical results | 130 |
| 6.3.6 | Conclusion | 134 |
| 6.4 | Conclusion | 134 |
| 7 | Limited Feedback exploiting Spatial Correlation | 135 |
| 7.1 | Quantization based on the spatial characterization of the SCM | 136 |
| 7.1.1 | System model | 136 |
| 7.1.2 | Statistical characterization of the spatial channel | 137 |

| | | |
|---------------------|---|------------|
| 7.1.3 | Proposed quantization scheme | 140 |
| 7.1.4 | Extension to CoMP | 141 |
| 7.1.5 | Numerical results | 143 |
| 7.1.6 | Conclusion | 150 |
| 7.2 | Quantization based on the spatial characterization of the Kronecker correlation model | 151 |
| 7.2.1 | System model | 152 |
| 7.2.2 | Statistical characterization of the spatial channel | 153 |
| 7.2.3 | Proposed quantization scheme | 158 |
| 7.2.4 | Alternative quantization scheme | 167 |
| 7.2.5 | Numerical results | 168 |
| 7.2.6 | Conclusion | 173 |
| 7.3 | Conclusion | 175 |
| 8 | Conclusions | 177 |
| 8.1 | Summary | 178 |
| 8.1.1 | Precoding | 178 |
| 8.1.2 | Limited feedback | 179 |
| 8.2 | Future work | 180 |
| 8.3 | Publications | 181 |
| Appendices | | 183 |
| A | CRAS-LLL: CUDA and OpenMP pseudocode | 185 |
| B | Conditional quantization codebook: details of calculations | 189 |
| Bibliography | | 193 |