Contents

Abstract i

Kurzfassung iii

I. Introduction 1

1. Inductively Coupled Microsensor Networks 3
1.1. The Paradigm of Microsensor Networks . . . 3
1.1.1. Requirements and Challenges . . . 4
1.1.2. Physical Layer Technologies . . . 6
1.2. Inductively Coupled Microsensor Networks . . . 9
1.3. Contributions and Outline . . . 13

2. A Primer in Linear N-port Network Theory 17
2.1. N-port Networks . . . 17
2.2. Port Reduction . . . 20
2.2.1. Port Reduction for S-Parameter Measurement . . . 22
2.3. Networks with Internal Sources . . . 24
2.4. Noisy Networks . . . 25
2.5. Time-Variant Networks . . . 27

3. Inductive Coupling as Physical Layer 29
3.1. Inductive Coupling . . . 29
3.1.1. Definition of Coordinate System . . . 31
3.1.2. Self- and Mutual Inductance in the MQS Regime . . . 32
3.1.3. Dipole Approximation of Mutual Inductance . . . 35
3.1.4. Comparison of Inductance Models . . . 37
3.1.5. Resistive Loss Mechanisms . . . 39

3.2. Circuit Theoretic System Description . . . 41
3.2.1. Load Modulation . . . 41
3.2.2. SISO Communication Model . . . 42
3.2.3. Communication in the Presence of Secondary Nodes . . . 47
3.3. Descriptive Limitations and Approximations . . . 49
3.3.1. Valid Frequency Range for MQS Approximation . . . 49
3.3.2. Phase Relation of Inductively Coupled Antennas . . . 52
3.4. Scaling Behavior of Miniaturized Inductively Coupled Networks . . . 53
3.4.1. Self- and Mutual Inductance . . . 54
3.4.2. Loss Resistance . . . 54
3.4.3. Communication Performance . . . 55

II. Cooperative Communications in Inductively Coupled Networks 59

4. Range Extension by Relaying 61
4.1. Classical Relaying . . . 62
4.2. Relaying in Inductively Coupled Networks . . . 63
4.2.1. Active Relaying . . . 63
4.2.2. Passive Relaying . . . 65
4.3. Range Extension Using Passive Relays . . . 67
4.3.1. Quasiperiodic Relay Configurations . . . 70
4.4. Position and Load Optimization of Passive Relays . . . 74
4.4.1. Random Relay Configurations . . . 76
4.4.2. Verification by Experiment . . . 77
4.5. Conclusions . . . 78

5. Wireless Artificial Neural Networks 81
5.1. The Paradigm of Wireless Artificial Neural Networks . . . 81
5.2. System Model of Wireless Artificial Neural Networks . . . 82
5.2.1. The Multilayer Perceptron ANN . . . 83
5.2.2. Wireless Implementation of ANNs on the Physical Layer . . . 85
5.2.3. Channel Shaping by Cooperative Relaying . . . 86
5.3. Wireless ANN Behavior in Additive Noise . . . 89
5.3.1. Comparison of Ideal and Wireless ANNs . . . 89
5.3.2. Impact of Noise Amplification . . . 91
5.4. Iterative Gain Allocation with Reduced Feedback . . . 94

5.5. Application of Wireless ANNs to Inductively Coupled Sensor Networks 97
5.5.1. Node Failure 99
5.5.2. Phase Synchronization Errors 100
5.6. Conclusions 102

III. Localization in Inductively Coupled Networks 103

6. Circuit Based Localization Using Multiple Anchors 105
6.1. Wireless Localization Systems 106
6.1.1. Geometric Localization Methods 106
6.1.2. Fingerprinting Based Localization Methods 107
6.1.3. Localization in Near-Field Systems 108
6.2. Principles of Circuit Based Localization 109
6.2.1. Network Topology 110
6.2.2. Circuit Model Representation 110
6.2.3. Optimization Process 114
6.2.4. Performance Bound 116
6.3. Numerical Performance Evaluation 118
6.3.1. Evaluation of Ranging Performance 118
6.3.2. Impact of Initial Position 119
6.3.3. Reduction of Grid Search Complexity 120
6.3.4. Optimized Choice of Anchor Topology 123
6.3.5. Impact of Network Density on Localization Performance 125
6.3.6. Scalability Considerations 126
6.4. Suboptimal Localization in 3D Space 128
6.4.1. Bounding of Anchor-Agent Distance 129
6.4.2. Impact of Noise on Distance Bounding 130
6.4.3. Location Estimation from Distance Bounding Property 134
6.5. Conclusions 134

7. Single-Port Localization Systems 137
7.1. System Model for Single-Port Localization 138
7.2. Single-Port Localization Using Passive Anchors 141
7.2.1. Reduction of Localization Ambiguities 142
7.2.2. Range Estimation Assisted by Passive Anchors 144
7.2.3. Simulative Evaluation of Localization Performance 148

7.3. Joint Decoding and Localization . . . 152
7.3.1. Numerical Performance Analysis . . . 156
7.3.2. Reliability of Decoded Bits . . . 162
7.4. Conclusions . . . 166

8. Practical Verification of Localization in Imperfect Environments 167
8.1. Anchor and Agent Node Design . . . 167
8.2. Measurement System . . . 171
8.2.1. Localization Based on Virtual Anchors . . . 173
8.3. Circuit Calibration . . . 174
8.4. Drift Autocalibration . . . 177
8.4.1. Open-Circuit Autocalibration . . . 180
8.5. Measurement Results . . . 181
8.5.1. Experimental Ranging Performance . . . 184
8.5.2. Experimental Localization Performance . . . 184
8.6. Conclusions . . . 188

IV. Outlook and Conclusions 189

9. Summary and Conclusions 191

A. Derivation of Cramér-Rao Lower Bound for Single-Port Localization 193

Acronyms 197

Notation 199

Bibliography 205