Contents

1 Motivation and Contributions **1**

1.1 Wireless Sensors: Technological Situation 1

1.2 Magnetic Induction for Wireless Sensors 3

1.3 State of the Art, Open Issues, Contributions 5

1.4 Acknowledgments and Joint Work 14

2 Essential Physics for Electrically Small Coils **17**

2.1 Mutual Impedance Between Wire Loops 17

2.2 Coil Self-Impedance 32

2.3 Coil Interaction 36

3 General Modeling and Analysis of Magneto-Inductive Links **41**

3.1 Signal Propagation and Transmit Power 41

3.2 Noise Statistics 46

3.3 Useful Equivalent Models 48

3.4 Power Transfer Efficiency 49

3.5 Achievable Rates 50

3.6 Matching Strategies 54

3.7 Channel Structure and Special Cases 59

3.8 Spatial Degrees of Freedom 63

3.9 Limits of Cooperative Load Modulation 67

4 The Channel Between Randomly Oriented Coils in Free Space **71**

4.1 SISO Channel Statistics 75

4.2 SISO Channel: Performance and Outage 84

4.3 Spatial Diversity Schemes 88

4.4 Further Stochastic Results 94

5 Randomly Placed Passive Relays: Effects and Utilization **97**

5.1 Effects and General Properties 99

5.2 One Passive Relay Near the Receiver 104

5.3 Random Relay Swarm Near the Receiver 108

5.4 Utilizing Spectral Fluctuations 114

6 A Study of Magnetic Induction for Small-Scale Medical Sensors 119
6.1 Biomedical Setup and Link Design 120
6.2 Wireless Powering Downlink 124
6.3 Data Uplink 127
6.4 Cooperative Data Uplink 134

7 Position and Orientation Estimation of an Active Coil in 3D 139
7.1 Problem Formulation and Channel Modeling 141
7.2 Position-Related Information in Measured Channel Coefficients 146
7.3 CRLB-Based Study of Accuracy Regimes 153
7.4 Localization Algorithm Design 156
7.5 Indoor Localization System Implementation 168
7.6 Investigation of Practical Performance Limits 171

8 Distance Estimation from UWB Channels to Observer Nodes 177
8.1 Distance Estimates from Delay Differences 180
8.2 Performance Evaluation 187
8.3 Technological Comparison and Opportunities 193

9 Summary 195

APPENDICES 199

A Fields Generated by a Circular Loop: Vector Formula 199

B Coupling Formulae Correspondences and Propagation Modes 203

C Maximum PTE over a Two-Port Network: Z-Parameter Formula 207

D Resonant SISO Channels: Power Allocation and Capacity 211

E The Role of Transients in Load Modulation Receive Processing 217