Contents

1 Introduction 1
1.1 Application Scenario 1
1.2 Problem Exposition 8
1.3 Solution Approach 10
1.4 Structure of the Thesis 12

2 Related Work and Background 13
2.1 Communication in Industrial Automation 13
2.1.1 Real-time Ethernet 13
2.1.2 Engineering Aspects and Flexibility 18
2.2 Industrial Wireless Communication 18
2.2.1 Systems Based on IEEE 802.15.1 19
2.2.2 Systems Based on IEEE 802.15.4 21
2.3 IEEE 802.11 23
2.3.1 Physical Layer 23
2.3.2 Medium Access Control 24
2.3.3 Admission Control and Scheduling 27
2.3.4 Relevant Amendments 28
2.3.5 Industrial Extensions 30
2.3.6 Existing Limitations of IEEE 802.11 30
2.4 Wireless Network Topologies 32
2.5 Analysis and Classification 33

3 Industrial Environment Characterisation 35
3.1 Industrial Traffic Characteristics and Requirements 35
3.1.1 Quality-of-Service Requirements for Common Multimedia Services 36
3.1.2 Analysis and Measurement Methodology 37
3.1.3 Manufacturing System for Terminal Blocks 37
3.1.4 Robot Cell 42
3.2 Industrial Wireless Channel 44

3.2.1 Weaknesses of Existing Channel Characterisation Approaches 45
3.2.2 Approach to Wireless Channel Characterisation 46
3.2.3 Channel Characterisation 48

4 Isochronous Wireless Network for Industrial Automation 53
4.1 System Model 53
4.1.1 Network Model 53
4.1.2 QoS Parameter for Control Applications 55
4.1.3 Fault Model 59
4.2 Isochronous Wireless Network 60
4.2.1 Deterministic Medium Access Control 61
4.2.2 Resource Allocation 62
4.2.3 Global Time Base 63
4.3 Integration Aspects 64
4.3.1 Mapping Concepts 64
4.3.2 Hybrid System Implications 65

5 Deterministic Medium Access Control 69
5.1 Coordinated Medium Access Control 69
5.1.1 Related Work 69
5.1.2 Protocol Description using UML 72
5.2 Isochronous Medium Access Control 72
5.2.1 Network Topology 73
5.2.2 Coordinated Channel Access 74
5.2.3 Schedule Distribution and Restricted Phase 77
5.3 Frame Error Recovery 78
5.3.1 Recovery Phase 78
5.3.2 Beacon Recovery 79
5.4 Analysis of the Isochronous MAC 80
5.4.1 Upper Bounds of the IsoMAC Approach 81
5.4.2 Efficiency of IsoMAC 84
5.4.3 Temporal Characteristics 86
5.5 Concluding Remarks 90

6 Resource Allocation 91
6.1 Admission Control and Scheduling in TDMA-based Wireless Networks 91
6.1.1 Related Work 91
6.1.2 Industrial Traffic Types 93
6.2 Admission Control 94
6.2.1 Retransmission Behaviour in Industrial Environments 95
6.2.2 Cross-layer Traffic Inspection 97
6.2.3 Resource Reservation and Admission Control 98
6.3 Scheduler 99
6.3.1 Scheduling and Admission Control of Periodic Flows 99
6.3.2 Scheduling and Admission Control of Aperiodic Flows 100

6.4 Dynamic Scheduling of Retransmissions 101
6.4.1 Application Layer Considerations 102
6.4.2 Adaptive Retransmission Policies 103
6.4.3 Analysis of the Dynamic Resource Allocation 104

7 Provision of a Global Time Base 107
7.1 Clock Synchronization in Hybrid Networks 107
7.1.1 Problems and Requirements 107
7.1.2 Related Work 108
7.1.3 Precision Time Protocol 110
7.2 Wireless Synchronization Concept 111
7.2.1 Precision Time Protocol over Wireless 113
7.2.2 Clock Synchronization Using Beacon Frames 114
7.2.3 Path-delay Asymmetry Compensation 115
7.3 Challenges for Time Stamping 116
7.3.1 Packet Reception Time 116
7.3.2 Interrupt Notification 117
7.3.3 Interrupt Handling Delay 117
7.3.4 Timestamping Delay 118
7.4 Accuracy and Precision Analysis 119
7.4.1 Testbed Setup 119
7.4.2 Bandwidth Utilization 120
7.4.3 Accuracy and Precision 121
7.5 Concluding Remarks 124

8 Evaluation 125
8.1 Overview and Structure 125
8.2 Prototypical Implementation 127
8.2.1 Implementation Architecture 127
8.2.2 Isochronous Wireless Network (IWN) Access Point 129
8.2.3 IWN Node 130
8.3 Simulation Modeling 130
8.3.1 Conceptual Simulation Model 130
8.3.2 Wireless Channel Model 132
8.3.3 Model Validation 136
8.4 Case Study 1: Reconfigurable Manufacturing 141
8.4.1 Approach and Implementation of the Experiments 141
8.4.2 Results of the First Experiment 143
8.4.3 Results of the Second Experiment 144
8.4.4 Summary of Case Study 1 145
8.5 Case Study 2: Wind Energy Automation 146
8.5.1 Approach and Implementation of the Experiments 146
8.5.2 Results of the First Experiment 148
8.5.3 Results of the Second Experiment 150
8.5.4 Summary of Case Study 2 153
8.6 Concluding remarks 153

9 Conclusion and Future Research Directions 155
9.1 Conclusion 155
9.2 Future Research Directions 156

References 159