

Contents

Abstract	III
Kurzfassung	V
1 Wireless Localization: An Introduction	1
1.1 Introduction	1
1.2 Exemplary Areas of Application	3
1.2.1 Massively Scalable Localization for Industry 4.0	4
1.2.2 Highly Reliable Networked Robotics	5
1.3 Problem Statement: Resource Limitations of Wireless Localization	7
1.4 Research Challenges, Methodology, and Contributions of this Thesis	10
1.5 Outline	11
1.6 Summary	12
2 Selected Technical Basics and Related Work	13
2.1 Introduction	13
2.2 Selected Features of the Ultra-Wideband Physical Layer	14
2.2.1 The IEEE 802.15.4a-2015 UWB PHY Frame	14
2.2.2 Implications of the PHY on the Robustness and Range	15
2.2.3 Ultra-wideband Medium Access Control as defined in the IEEE 802.15.4	19
2.3 Topologies for TOA-based Localization	20
2.3.1 Two-Way Ranging (TWR)	20
2.3.2 Time Difference of Arrival (TDOA)	25
2.3.3 Hybrid and Other Approaches	28
2.4 Location Estimation Methods	29
2.4.1 Tri- and Multilateration	29
2.4.2 Extended Kalman Filter (EKF)	30
2.4.3 Particle Filter	31
2.5 State of the Art in Resource Efficiency for Wireless Localization	32
2.5.1 Accuracy Improvement	32
2.5.2 Energy Efficiency	35
2.5.3 Multi-User Scalability and Real-Time Capabilities	35
2.6 Summary	39
3 ATLAS: Augmented Terrestrial Localization for Autonomous Systems	41
3.1 Introduction	41
3.2 Integrated Hardware and System Architecture ATLAS	42

3.3	Proposed Localization-Specific Channel Access Scheme FaST . . .	45
3.3.1	Structuring the Channel Access	45
3.3.2	FaST Association Procedure	46
3.3.3	Distributed Wireless Clock Synchronization	50
3.4	Proposed Location Estimation Scheme	52
3.4.1	Integrated Inertial Sensor based Data Fusion	52
3.4.2	Proposed Signal Quality Assessment	54
3.5	Key Performance Indicators (KPIs)	57
3.6	Summary	58
4	Scalability of Wireless Localization	59
4.1	Introduction	59
4.2	An Analytical Multi-User Interference Model	60
4.3	Topology-Specific Available Location Throughput	62
4.4	Experimental Validation of Random Access Throughput	66
4.5	Real-Time Capabilities and Availability	71
4.5.1	Experimental Evaluation of Achievable Update Rates . . .	72
4.5.2	ATLAS FaST Re-Association Reliability	73
4.5.3	Massive Initial Association Stability	75
4.6	Summary	76
5	Energy Efficiency and Constraints	77
5.1	Introduction	77
5.2	Energy Characteristics of the Ultra-Wideband Physical Layer . . .	78
5.3	Implications for Practical System Implementations	82
5.3.1	Battery Types and Battery Modelling	82
5.3.2	Time-Keeping in Low Power Mode	85
5.4	Evaluation of the Topology Specific Energy Efficiency	87
5.4.1	Energy Tradeoff for the Scheduled FaST-based Access . . .	87
5.4.2	Energy Utilization of Existing Topologies	89
5.5	Summary	92
6	Reliability and Achievable Accuracy	93
6.1	Introduction and Reference Scenarios	93
6.2	Experimental Evaluation of Achievable Accuracy	95
6.2.1	Experimental Setup	95
6.2.2	Inertial Sensor Fusion Orientation Accuracy	96
6.2.3	Best Case Evaluation without Obstruction	98
6.2.4	Evaluation with Strong Obstruction	100
6.3	Antenna Characteristics and Channel Response Processing	102
6.3.1	Experimental Evaluation of Controlled Rotational Movement	103
6.3.2	Machine Learning on Channel Response Data	107

6.4	Control-Grade Localization for Unmanned Aerial Vehicles	109
6.4.1	System Implementation and Experimental Testbed	111
6.4.2	Evaluation of UAV-Specific Controller	113
6.4.3	Multi-UAV Flight in Constrained Environment	117
6.4.4	Enhanced Indoor Navigation through SLAM-Augmented Flight	119
6.5	Competitive System Accuracy Evaluation	130
6.5.1	Participating in the EvAAL Competition 2016: Indoor Mo- bile Robot Positioning	131
6.5.2	Participating in the Microsoft Indoor Localization Compe- tition 2018: Heterogeneous 3D Systems	135
6.6	Summary	141
7	Conclusion and Outlook	145
7.1	Conclusion	145
7.2	Outlook and Future Work	147
7.2.1	IEEE 802.15.4z based Real-Time Locating Systems (RTLs)	148
7.2.2	Hybrid Low-Power Localization Solutions	148
7.2.3	Towards Ubiquitous Localization through 5G-NR and Beyond	149
A	Parameters of the Experimental Evaluation	151
A.1	Inertial Sensor Fusion and Signal Quality Assessment	151
A.2	Antenna Characteristics and Channel Response Processing	153
A.3	Control-Grade Localization for Unmanned Aerial Vehicles	154
A.4	Competitive System Accuracy Evaluation	156
B	Parameters of the Energy Models	161
	List of Acronyms	163
	List of Symbols	167
	Bibliography	173
	Scientific Activity Report	200