

# Protocols and Architectures for Wireless Sensor Networks

Holger Karl  
Andreas Willig

 WILEY



# Contents

<b>Preface</b>	<b>xiii</b>
<b>List of abbreviations</b>	<b>xv</b>
<b>A guide to the book</b>	<b>xxiii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 The vision of Ambient Intelligence	1
1.2 Application examples	3
1.3 Types of applications	6
1.4 Challenges for WSNs	7
1.4.1 <i>Characteristic requirements</i>	7
1.4.2 <i>Required mechanisms</i>	9
1.5 Why are sensor networks different?	10
1.5.1 <i>Mobile ad hoc networks and wireless sensor networks</i>	10
1.5.2 <i>Fieldbuses and wireless sensor networks</i>	12
1.6 Enabling technologies for wireless sensor networks	13
<b>PART I ARCHITECTURES</b>	<b>15</b>
<b>2 Single-node architecture</b>	<b>17</b>
2.1 Hardware components	18
2.1.1 <i>Sensor node hardware overview</i>	18
2.1.2 <i>Controller</i>	19
2.1.3 <i>Memory</i>	21
2.1.4 <i>Communication device</i>	21
2.1.5 <i>Sensors and actuators</i>	31
2.1.6 <i>Power supply of sensor nodes</i>	32
2.2 Energy consumption of sensor nodes	36
2.2.1 <i>Operation states with different power consumption</i>	36
2.2.2 <i>Microcontroller energy consumption</i>	38
2.2.3 <i>Memory</i>	39
2.2.4 <i>Radio transceivers</i>	40

2.2.5	<i>Relationship between computation and communication</i>	44
2.2.6	<i>Power consumption of sensor and actuators</i>	44
2.3	Operating systems and execution environments	45
2.3.1	<i>Embedded operating systems</i>	45
2.3.2	<i>Programming paradigms and application programming interfaces</i>	45
2.3.3	<i>Structure of operating system and protocol stack</i>	47
2.3.4	<i>Dynamic energy and power management</i>	48
2.3.5	<i>Case Study: TinyOS and nesC</i>	50
2.3.6	<i>Other examples</i>	53
2.4	Some examples of sensor nodes	54
2.4.1	<i>The "Mica Mote" family</i>	54
2.4.2	<i>EYES nodes</i>	54
2.4.3	<i>BTnodes</i>	54
2.4.4	<i>Scatterweb</i>	54
2.4.5	<i>Commercial solutions</i>	55
2.5	Conclusion	56
<b>3</b>	<b>Network architecture</b>	<b>59</b>
3.1	Sensor network scenarios	60
3.1.1	<i>Types of sources and sinks</i>	60
3.1.2	<i>Single-hop versus multihop networks</i>	60
3.1.3	<i>Multiple sinks and sources</i>	62
3.1.4	<i>Three types of mobility</i>	62
3.2	Optimization goals and figures of merit	63
3.2.1	<i>Quality of service</i>	64
3.2.2	<i>Energy efficiency</i>	65
3.2.3	<i>Scalability</i>	66
3.2.4	<i>Robustness</i>	67
3.3	Design principles for WSNs	67
3.3.1	<i>Distributed organization</i>	67
3.3.2	<i>In-network processing</i>	67
3.3.3	<i>Adaptive fidelity and accuracy</i>	70
3.3.4	<i>Data centricity</i>	70
3.3.5	<i>Exploit location information</i>	73
3.3.6	<i>Exploit activity patterns</i>	73
3.3.7	<i>Exploit heterogeneity</i>	73
3.3.8	<i>Component-based protocol stacks and cross-layer optimization</i>	74
3.4	Service interfaces of WSNs	74
3.4.1	<i>Structuring application/protocol stack interfaces</i>	74
3.4.2	<i>Expressibility requirements for WSN service interfaces</i>	76
3.4.3	<i>Discussion</i>	77
3.5	Gateway concepts	78
3.5.1	<i>The need for gateways</i>	78
3.5.2	<i>WSN to Internet communication</i>	79
3.5.3	<i>Internet to WSN communication</i>	80
3.5.4	<i>WSN tunneling</i>	81
3.6	Conclusion	81

**PART II COMMUNICATION PROTOCOLS****83**

<b>4</b>	<b>Physical layer</b>	<b>85</b>
4.1	Introduction	85
4.2	Wireless channel and communication fundamentals	86
	4.2.1 <i>Frequency allocation</i>	86
	4.2.2 <i>Modulation and demodulation</i>	88
	4.2.3 <i>Wave propagation effects and noise</i>	90
	4.2.4 <i>Channel models</i>	96
	4.2.5 <i>Spread-spectrum communications</i>	98
	4.2.6 <i>Packet transmission and synchronization</i>	100
	4.2.7 <i>Quality of wireless channels and measures for improvement</i>	102
4.3	Physical layer and transceiver design considerations in WSNs	103
	4.3.1 <i>Energy usage profile</i>	103
	4.3.2 <i>Choice of modulation scheme</i>	104
	4.3.3 <i>Dynamic modulation scaling</i>	108
	4.3.4 <i>Antenna considerations</i>	108
4.4	Further reading	109
<b>5</b>	<b>MAC protocols</b>	<b>111</b>
5.1	Fundamentals of (wireless) MAC protocols	112
	5.1.1 <i>Requirements and design constraints for wireless MAC protocols</i>	112
	5.1.2 <i>Important classes of MAC protocols</i>	114
	5.1.3 <i>MAC protocols for wireless sensor networks</i>	119
5.2	Low duty cycle protocols and wakeup concepts	120
	5.2.1 <i>Sparse topology and energy management (STEM)</i>	121
	5.2.2 <i>S-MAC</i>	123
	5.2.3 <i>The mediation device protocol</i>	126
	5.2.4 <i>Wakeup radio concepts</i>	127
	5.2.5 <i>Further reading</i>	128
5.3	Contention-based protocols	129
	5.3.1 <i>CSMA protocols</i>	129
	5.3.2 <i>PAMAS</i>	131
	5.3.3 <i>Further solutions</i>	132
5.4	Schedule-based protocols	133
	5.4.1 <i>LEACH</i>	133
	5.4.2 <i>SMACS</i>	135
	5.4.3 <i>Traffic-adaptive medium access protocol (TRAMA)</i>	137
	5.4.4 <i>Further solutions</i>	139
5.5	The IEEE 802.15.4 MAC protocol	139
	5.5.1 <i>Network architecture and types/roles of nodes</i>	140
	5.5.2 <i>Superframe structure</i>	141
	5.5.3 <i>GTS management</i>	141
	5.5.4 <i>Data transfer procedures</i>	142
	5.5.5 <i>Slotted CSMA-CA protocol</i>	142
	5.5.6 <i>Nonbeaconed mode</i>	144
	5.5.7 <i>Further reading</i>	145
5.6	How about IEEE 802.11 and bluetooth?	145
5.7	Further reading	146
5.8	Conclusion	148

<b>6</b>	<b>Link-layer protocols</b>	<b>149</b>
6.1	Fundamentals: tasks and requirements	150
6.2	Error control	151
6.2.1	<i>Causes and characteristics of transmission errors</i>	151
6.2.2	<i>ARQ techniques</i>	152
6.2.3	<i>FEC techniques</i>	158
6.2.4	<i>Hybrid schemes</i>	163
6.2.5	<i>Power control</i>	165
6.2.6	<i>Further mechanisms to combat errors</i>	166
6.2.7	<i>Error control: summary</i>	167
6.3	Framing	167
6.3.1	<i>Adaptive schemes</i>	170
6.3.2	<i>Intermediate checksum schemes</i>	172
6.3.3	<i>Combining packet-size optimization and FEC</i>	173
6.3.4	<i>Treatment of frame headers</i>	174
6.3.5	<i>Framing: summary</i>	174
6.4	Link management	174
6.4.1	<i>Link-quality characteristics</i>	175
6.4.2	<i>Link-quality estimation</i>	177
6.5	Summary	179
<b>7</b>	<b>Naming and addressing</b>	<b>181</b>
7.1	Fundamentals	182
7.1.1	<i>Use of addresses and names in (sensor) networks</i>	182
7.1.2	<i>Address management tasks</i>	183
7.1.3	<i>Uniqueness of addresses</i>	184
7.1.4	<i>Address allocation and assignment</i>	184
7.1.5	<i>Addressing overhead</i>	185
7.2	Address and name management in wireless sensor networks	186
7.3	Assignment of MAC addresses	186
7.3.1	<i>Distributed assignment of networkwide addresses</i>	187
7.4	Distributed assignment of locally unique addresses	189
7.4.1	<i>Address assignment algorithm</i>	189
7.4.2	<i>Address selection and representation</i>	191
7.4.3	<i>Further schemes</i>	194
7.5	Content-based and geographic addressing	194
7.5.1	<i>Content-based addressing</i>	194
7.5.2	<i>Geographic addressing</i>	198
7.6	Summary	198
<b>8</b>	<b>Time synchronization</b>	<b>201</b>
8.1	Introduction to the time synchronization problem	201
8.1.1	<i>The need for time synchronization in wireless sensor networks</i>	202
8.1.2	<i>Node clocks and the problem of accuracy</i>	203
8.1.3	<i>Properties and structure of time synchronization algorithms</i>	204
8.1.4	<i>Time synchronization in wireless sensor networks</i>	206
8.2	Protocols based on sender/receiver synchronization	207
8.2.1	<i>Lightweight time synchronization protocol (LTS)</i>	207

8.2.2	<i>How to increase accuracy and estimate drift</i>	212
8.2.3	<i>Timing-sync protocol for sensor networks (TPSN)</i>	214
8.3	Protocols based on receiver/receiver synchronization	217
8.3.1	<i>Reference broadcast synchronization (RBS)</i>	217
8.3.2	<i>Hierarchy referencing time synchronization (HRTS)</i>	223
8.4	Further reading	226
<b>9</b>	<b>Localization and positioning</b>	<b>231</b>
9.1	Properties of localization and positioning procedures	232
9.2	Possible approaches	233
9.2.1	<i>Proximity</i>	233
9.2.2	<i>Trilateration and triangulation</i>	234
9.2.3	<i>Scene analysis</i>	237
9.3	Mathematical basics for the lateration problem	237
9.3.1	<i>Solution with three anchors and correct distance values</i>	238
9.3.2	<i>Solving with distance errors</i>	238
9.4	Single-hop localization	240
9.4.1	<i>Active Badge</i>	240
9.4.2	<i>Active office</i>	240
9.4.3	<i>RADAR</i>	240
9.4.4	<i>Cricket</i>	241
9.4.5	<i>Overlapping connectivity</i>	241
9.4.6	<i>Approximate point in triangle</i>	242
9.4.7	<i>Using angle of arrival information</i>	243
9.5	Positioning in multihop environments	243
9.5.1	<i>Connectivity in a multihop network</i>	244
9.5.2	<i>Multihop range estimation</i>	244
9.5.3	<i>Iterative and collaborative multilateration</i>	245
9.5.4	<i>Probabilistic positioning description and propagation</i>	247
9.6	Impact of anchor placement	247
9.7	Further reading	248
9.8	Conclusion	249
<b>10</b>	<b>Topology control</b>	<b>251</b>
10.1	Motivation and basic ideas	251
10.1.1	<i>Options for topology control</i>	252
10.1.2	<i>Aspects of topology-control algorithms</i>	254
10.2	Controlling topology in flat networks – Power control	256
10.2.1	<i>Some complexity results</i>	256
10.2.2	<i>Are there magic numbers? – bounds on critical parameters</i>	257
10.2.3	<i>Some example constructions and protocols</i>	259
10.2.4	<i>Further reading on flat topology control</i>	265
10.3	Hierarchical networks by dominating sets	266
10.3.1	<i>Motivation and definition</i>	266
10.3.2	<i>A hardness result</i>	266
10.3.3	<i>Some ideas from centralized algorithms</i>	267
10.3.4	<i>Some distributed approximations</i>	270
10.3.5	<i>Further reading</i>	273
10.4	Hierarchical networks by clustering	274

10.4.1	<i>Definition of clusters</i>	274
10.4.2	<i>A basic idea to construct independent sets</i>	277
10.4.3	<i>A generalization and some performance insights</i>	278
10.4.4	<i>Connecting clusters</i>	278
10.4.5	<i>Rotating clusterheads</i>	279
10.4.6	<i>Some more algorithm examples</i>	280
10.4.7	<i>Multihop clusters</i>	281
10.4.8	<i>Multiple layers of clustering</i>	283
10.4.9	<i>Passive clustering</i>	284
10.4.10	<i>Further reading</i>	284
10.5	<i>Combining hierarchical topologies and power control</i>	285
10.5.1	<i>Pilot-based power control</i>	285
10.5.2	<i>Ad hoc Network Design Algorithm (ANDA)</i>	285
10.5.3	<i>CLUSTERPOW</i>	286
10.6	<i>Adaptive node activity</i>	286
10.6.1	<i>Geographic Adaptive Fidelity (GAF)</i>	286
10.6.2	<i>Adaptive Self-Configuring sEmsor Networks' Topologies (ASCENT)</i>	287
10.6.3	<i>Turning off nodes on the basis of sensing coverage</i>	288
10.7	<i>Conclusions</i>	288
<b>11</b>	<b>Routing protocols</b>	<b>289</b>
11.1	<i>The many faces of forwarding and routing</i>	289
11.2	<i>Gossiping and agent-based unicast forwarding</i>	292
11.2.1	<i>Basic idea</i>	292
11.2.2	<i>Randomized forwarding</i>	292
11.2.3	<i>Random walks</i>	293
11.2.4	<i>Further reading</i>	294
11.3	<i>Energy-efficient unicast</i>	295
11.3.1	<i>Overview</i>	295
11.3.2	<i>Some example unicast protocols</i>	297
11.3.3	<i>Further reading</i>	301
11.3.4	<i>Multipath unicast routing</i>	301
11.3.5	<i>Further reading</i>	304
11.4	<i>Broadcast and multicast</i>	305
11.4.1	<i>Overview</i>	305
11.4.2	<i>Source-based tree protocols</i>	308
11.4.3	<i>Shared, core-based tree protocols</i>	314
11.4.4	<i>Mesh-based protocols</i>	314
11.4.5	<i>Further reading on broadcast and multicast</i>	315
11.5	<i>Geographic routing</i>	316
11.5.1	<i>Basics of position-based routing</i>	316
11.5.2	<i>Geocasting</i>	323
11.5.3	<i>Further reading on geographic routing</i>	326
11.6	<i>Mobile nodes</i>	328
11.6.1	<i>Mobile sinks</i>	328
11.6.2	<i>Mobile data collectors</i>	328
11.6.3	<i>Mobile regions</i>	329
11.7	<i>Conclusions</i>	329

---

<b>12</b>	<b>Data-centric and content-based networking</b>	<b>331</b>
12.1	Introduction	331
12.1.1	<i>The publish/subscribe interaction paradigm</i>	331
12.1.2	<i>Addressing data</i>	332
12.1.3	<i>Implementation options</i>	333
12.1.4	<i>Distribution versus gathering of data – In-network processing</i>	334
12.2	Data-centric routing	335
12.2.1	<i>One-shot interactions</i>	335
12.2.2	<i>Repeated interactions</i>	337
12.2.3	<i>Further reading</i>	340
12.3	Data aggregation	341
12.3.1	<i>Overview</i>	341
12.3.2	<i>A database interface to describe aggregation operations</i>	342
12.3.3	<i>Categories of aggregation operations</i>	343
12.3.4	<i>Placement of aggregation points</i>	345
12.3.5	<i>When to stop waiting for more data</i>	345
12.3.6	<i>Aggregation as an optimization problem</i>	347
12.3.7	<i>Broadcasting an aggregated value</i>	347
12.3.8	<i>Information-directed routing and aggregation</i>	350
12.3.9	<i>Some further examples</i>	352
12.3.10	<i>Further reading on data aggregation</i>	355
12.4	Data-centric storage	355
12.5	Conclusions	357
<b>13</b>	<b>Transport layer and quality of service</b>	<b>359</b>
13.1	The transport layer and QoS in wireless sensor networks	359
13.1.1	<i>Quality of service/reliability</i>	360
13.1.2	<i>Transport protocols</i>	361
13.2	Coverage and deployment	362
13.2.1	<i>Sensing models</i>	362
13.2.2	<i>Coverage measures</i>	364
13.2.3	<i>Uniform random deployments: Poisson point processes</i>	365
13.2.4	<i>Coverage of random deployments: Boolean sensing model</i>	366
13.2.5	<i>Coverage of random deployments: general sensing model</i>	368
13.2.6	<i>Coverage determination</i>	369
13.2.7	<i>Coverage of grid deployments</i>	374
13.2.8	<i>Further reading</i>	375
13.3	Reliable data transport	376
13.3.1	<i>Reliability requirements in sensor networks</i>	377
13.4	Single packet delivery	378
13.4.1	<i>Using a single path</i>	379
13.4.2	<i>Using multiple paths</i>	384
13.4.3	<i>Multiple receivers</i>	388
13.4.4	<i>Summary</i>	389
13.5	Block delivery	389
13.5.1	<i>PSFQ: block delivery in the sink-to-sensors case</i>	389
13.5.2	<i>RMST: block delivery in the sensors-to-sink case</i>	395
13.5.3	<i>What about TCP?</i>	397
13.5.4	<i>Further reading</i>	399

---

13.6	Congestion control and rate control	400
13.6.1	<i>Congestion situations in sensor networks</i>	400
13.6.2	<i>Mechanisms for congestion detection and handling</i>	402
13.6.3	<i>Protocols with rate control</i>	403
13.6.4	<i>The CODA congestion-control framework</i>	408
13.6.5	<i>Further reading</i>	411
<b>14</b>	<b>Advanced application support</b>	<b>413</b>
14.1	Advanced in-network processing	413
14.1.1	<i>Going beyond mere aggregation of data</i>	413
14.1.2	<i>Distributed signal processing</i>	414
14.1.3	<i>Distributed source coding</i>	416
14.1.4	<i>Network coding</i>	420
14.1.5	<i>Further issues</i>	421
14.2	Security	422
14.2.1	<i>Fundamentals</i>	422
14.2.2	<i>Security considerations in wireless sensor networks</i>	423
14.2.3	<i>Denial-of-service attacks</i>	423
14.2.4	<i>Further reading</i>	425
14.3	Application-specific support	425
14.3.1	<i>Target detection and tracking</i>	426
14.3.2	<i>Contour/edge detection</i>	429
14.3.3	<i>Field sampling</i>	432
	<b>Bibliography</b>	<b>437</b>
	<b>Index</b>	<b>481</b>