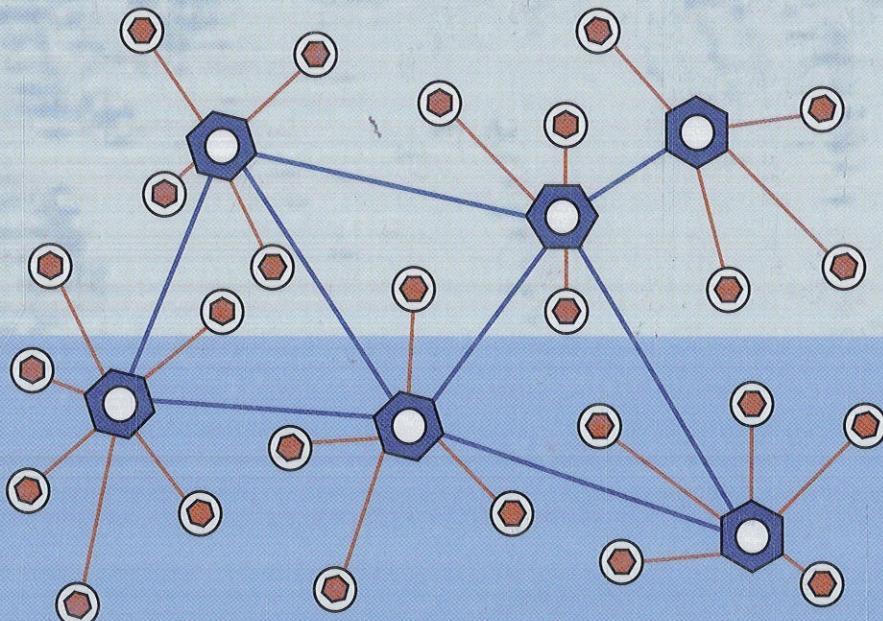


# Synchronization in Wireless Sensor Networks

Parameter Estimation,  
Performance Benchmarks,  
and Protocols



Erchin Serpedin and Qasim M. Chaudhari

CAMBRIDGE

# CONTENTS

PREFACE · *page xi*

1 INTRODUCTION · *page 1*

§1.1 Wireless Sensor Networks · 1

§1.2 Time Synchronization · 2

§1.3 Importance of Time Synchronization · 3

§1.4 History of Clock Synchronization · 4

§1.5 Outline · 6

2 SIGNAL MODELS FOR TIME SYNCHRONIZATION · *page 10*

§2.1 Definition of Clock · 10

§2.2 Design Considerations · 11

§2.3 Delay Components in Timing Message Delivery · 13

3 TIME SYNCHRONIZATION PROTOCOLS · *page 15*

§3.1 Pairwise Synchronization · 16

§3.1.1 Timing-Sync Protocol for Sensor Networks (TPSN) · 16

§3.1.2 Tiny-Sync and Mini-Sync · 18

§3.1.3 Reference Broadcast Synchronization (RBS) · 19

§3.1.4 Flooding Time Synchronization Protocol (FTSP) · 21

§3.2 Network-Wide Synchronization · 21

§3.2.1 Extension of TPSN · 22

§3.2.2 Lightweight Time Synchronization (LTS) · 22

§3.2.3 Extension of RBS · 23

§3.2.4 Extension of FTSP · 23

§3.2.5 Pairwise Broadcast Synchronization (PBS) · 24

§3.2.6 Time Diffusion Protocol (TDP) · 24

§3.2.7 Synchronous and Asynchronous Diffusion Algorithms · 26

§3.2.8	Protocols Based on Pulse Transmissions · 27
§3.3	Adaptive Time Synchronization · 28
§3.3.1	Rate-Adaptive Time Synchronization (RATS) · 28
§3.3.2	RBS-based Adaptive Clock Synchronization · 29
§3.3.3	Adaptive Multi-Hop Time Synchronization (AMTS) · 30
4	FUNDAMENTAL APPROACHES TO TIME SYNCHRONIZATION · <i>page 32</i>
§4.1	Sender–Receiver Synchronization (SRS) · 33
§4.2	Receiver-Only Synchronization (ROS) · 36
§4.3	Receiver–Receiver Synchronization (RRS) · 39
§4.4	Comparisons · 41
5	MINIMUM VARIANCE UNBIASED ESTIMATION (MVUE) OF CLOCK OFFSET · <i>page 42</i>
§5.1	The System Architecture · 43
§5.2	Best Linear Unbiased Estimation Using Order Statistics (BLUE-OS) · 45
§5.2.1	Symmetric Link Delays · 47
§5.2.2	Asymmetric Link Delays · 48
§5.3	Minimum Variance Unbiased Estimation (MVUE) · 51
§5.3.1	Asymmetric Link Delays · 51
§5.3.2	Symmetric Link Delays · 55
§5.4	Explanatory Remarks · 57
6	CLOCK OFFSET AND SKEW ESTIMATION · <i>page 62</i>
§6.1	Gaussian Delay Model · 63
§6.1.1	Maximum Likelihood (ML) Clock Offset Estimation · 63
§6.1.2	Cramer–Rao Lower Bound (CRLB) for Clock Offset · 64
§6.1.3	Joint Maximum Likelihood Estimation (JMLE) of Clock Offset and Skew · 64
§6.1.4	Cramer–Rao Lower Bound (CRLB) for Clock Offset and Skew · 67
§6.2	Exponential Delay Model · 69
§6.2.1	Cramer–Rao Lower Bound (CRLB) for Clock Offset · 70
§6.2.2	Joint Maximum Likelihood Estimation (JMLE) of Clock Offset and Skew · 73

- 7 COMPUTATIONALLY SIMPLIFIED SCHEMES FOR ESTIMATION OF CLOCK OFFSET AND SKEW · *page* 90
- §7.1 Using the First and the Last Data Sample · 91
- §7.1.1 Gaussian Delay Model · 91
- §7.1.2 Exponential Delay Model · 92
- §7.1.3 Combination of Clock Offset and Skew Estimation · 95
- §7.1.4 Simulation Results · 96
- §7.2 Fitting the Line Between Two Points at Minimum Distance Apart · 99
- §7.2.1 Simulation Results · 101
- §7.2.2 Computational Complexity Comparison · 102
- 8 PAIRWISE BROADCAST SYNCHRONIZATION (PBS) · *page* 104
- §8.1 Synchronization for Single-Cluster Networks · 105
- §8.2 Comparisons and Analysis · 105
- §8.3 Synchronization for Multi-Cluster Networks · 107
- §8.3.1 Network-Wide Pair Selection Algorithm (NPA) · 108
- §8.3.2 Group-Wise Pair Selection Algorithm (GPA) · 110
- §8.4 Comparisons and Analysis · 114
- 9 ENERGY-EFFICIENT ESTIMATION OF CLOCK OFFSET FOR INACTIVE NODES · *page* 118
- §9.1 Problem Formulation · 119
- §9.2 Maximum Likelihood Estimation (MLE) · 121
- §9.3 Cramer–Rao Lower Bound (CRLB) · 132
- §9.3.1 CRLB for the Clock Offset of Inactive Node  $\hat{\phi}_q$  · 133
- §9.3.2 CRLB for the Clock Offset of Active Node  $\hat{\phi}_p$  · 137
- §9.4 Simulation Results · 138
- 10 SOME IMPROVED AND GENERALIZED ESTIMATION SCHEMES FOR CLOCK SYNCHRONIZATION OF INACTIVE NODES · *page* 140
- §10.1 Asymmetric Exponential Link Delays · 141
- §10.1.1 Best Linear Unbiased Estimation Using Order Statistics (BLUE-OS) · 142
- §10.1.2 Minimum Variance Unbiased Estimation (MVUE) · 145
- §10.1.3 Minimum Mean Square Error (MMSE) Estimation · 149
- §10.2 Symmetric Exponential Link Delays · 151
- §10.2.1 Best Linear Unbiased Estimation Using Order Statistics (BLUE-OS) · 151
- §10.2.2 Minimum Variance Unbiased Estimation (MVUE) · 153
- §10.2.3 Minimum Mean Square Error (MMSE) Estimation · 155

11	ADAPTIVE MULTI-HOP TIME SYNCHRONIZATION (AMTS) · <i>page</i> 157
§11.1	Main Ideas · 158
§11.2	Level Discovery Phase · 159
§11.3	Synchronization Phase · 159
§11.4	Network Evaluation Phase · 160
§11.4.1	Synchronization Mode Selection · 160
§11.4.2	Determination of Synchronization Period · 162
§11.4.3	Determination of the Number of Beacons · 164
§11.4.4	Sequential Multi-Hop Synchronization Algorithm (SMA) · 164
§11.5	Simulation Results · 167
12	CLOCK DRIFT ESTIMATION FOR ACHIEVING LONG-TERM SYNCHRONIZATION · <i>page</i> 169
§12.1	Problem Formulation · 170
§12.2	The Estimation Procedure · 171
13	JOINT SYNCHRONIZATION OF CLOCK OFFSET AND SKEW IN A RECEIVER-RECEIVER PROTOCOL · <i>page</i> 177
§13.1	Modeling Assumptions · 177
§13.2	Joint Maximum Likelihood Estimation (JMLE) of the Offset and Skew · 178
§13.3	Application of the Gibbs Sampler · 179
§13.4	Performance Bounds and Simulations · 181
14	ROBUST ESTIMATION OF CLOCK OFFSET · <i>page</i> 185
§14.1	Problem Modeling and Objectives · 187
§14.2	Gaussian Mixture Kalman Particle Filter (GMKPF) · 189
§14.3	Testing the Performance of GMKPF · 192
§14.4	Composite Particle Filtering (CPF) with Bootstrap Sampling (BS) · 196
§14.5	Testing the Performance of CPF and CPF with BS · 204
15	CONCLUSIONS AND FUTURE DIRECTIONS · <i>page</i> 211
	ACRONYMS · <i>page</i> 214
	REFERENCES · <i>page</i> 218
	INDEX · <i>page</i> 227