

Flexible-Schedule-Based TDMA Protocols for Supporting Fault-Tolerance, On-Demand TDMA Slot Transfer, and Peer-to-Peer Communication in Wireless Sensor Networks

THIS THESIS IS
PRESENTED TO THE
SCHOOL OF COMPUTER SCIENCE & SOFTWARE ENGINEERING
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
OF
THE UNIVERSITY OF WESTERN AUSTRALIA

By
Winnie Louis Lee
January 2008

© Copyright 2008

by

Winnie Louis Lee

Abstract

This thesis develops a scheduled protocol (time division multiple access, TDMA) called *flexible-schedule-based TDMA Protocol* (FlexiTP), to address the problem of providing *end-to-end guarantees on data delivery*, whilst also respecting severe *resource constraints* of wireless sensor networks. FlexiTP achieves this balance through a distributed, synchronised, and loose slot structure in which sensor nodes can build, modify, or extend their schedules based on their local information. In FlexiTP, it is not necessary to predetermine the number of slots required for a network. FlexiTP's local repair scheme allows nodes to adjust their schedules dynamically and autonomously to recover from node and communication faults. Hence, it maintains a reliable and self-organising multihop network.

Most sensor network protocols designed for data gathering applications implicitly assume a periodic rate of data collection from all nodes in the network to the base station. However, nodes may want to report their data more rapidly or slowly depending on the significance and importance of their data to the end-user. The problem is that traditional TDMA-based protocols are not flexible to changes in traffic patterns because of their rigid slot structure schemes. This thesis aims to solve this problem by developing an *on-demand TDMA slot transfer* method that leverages the flexible-slot structure algorithm of FlexiTP to transfer time slots from one part of the network to another part. Hence, it allows wireless sensor networks to be adaptive to dynamic traffic patterns in the channel. Many wireless sensor networks are designed with a specific communication pattern such as broadcast from the base station to all sensor nodes in a network, or convergecast from

all nodes in a network towards the base station. While these communication patterns are sufficient for monitoring applications, individual sensor nodes may need to send their data to multiple destination nodes across the network in order to execute a distributed cooperative-function based on their local environment. This *peer-to-peer communication pattern* makes sensor networks more reactive to triggers from the environment. This thesis attempts to solve the problem of lack of peer-to-peer communication in the design of a TDMA-driven protocol by extending the idea of on-demand TDMA slot transfer method to allow each sensor node in the network to claim extra time slots to communicate with any other nodes (peers) in the network, without going through the base station.

Nodes in the network may have different priorities of data because of event-triggering sensor readings or various types of sensor readings (e.g., light, temperature, and humidity) they provide. When nodes with high priority packets increase the frequency of their data collections, the network bandwidth may be dominated by these nodes. It is desirable to allow nodes with low priority packets to aggregate their packets and so enabling these nodes to send their data to the base station under the current available network bandwidth. This thesis proposes an *on-demand data aggregation* algorithm that enables sensor nodes to perform an in-network-aggregation based on their current sensing requirements and network capacity constraints.

In summary, this thesis describes the design, implementation, and evaluation of protocols for wireless sensor networks that focus on achieving energy-efficiency, provisioning performance assurances, and supporting reactivity and adaptability in constantly changing environment.

Preface

Recent trends in the pervasive computing community move towards implementing wireless networks of resource-constrained sensor nodes in a whole new range of applications, including telemonitoring of human physiological data, habitat monitoring of wildlife, automated and smart homes video surveillance, traffic monitoring, vehicle tracking and detection for battlefield surveillance, tracking and monitoring doctors and patients inside a hospital, environmental detection of fire and flood, microclimate monitoring for precision agriculture, and vibration-based structural condition monitoring. Sensor nodes gather information by observing the physical world at fine granularity and transmitting information to more powerful hardware that can process it.

This thesis focuses on designing energy-efficient, fault-tolerant, reactive, and adaptive TDMA protocols for wireless sensor networks. The proposed protocols are implemented, using C++ and OTcl, into the network simulator (NS-2). All of the software and protocols implementation developed in this thesis are available online at:

<http://www.csse.uwa.edu.au/~winnie/programs>

The thesis work has been carried out from March 2004 to July 2007 at the School of Computer Science and Software Engineering. This thesis consists of eight chapters. Four chapters contain papers that are accepted by or intended for international journals or proceedings. These chapters cover the report of our proposed scheduling and routing protocol, traffic-adaptive protocol, peer-to-peer-driven protocol, and network management protocol, for wireless sensor networks.

Acknowledgements

I found joy not only in finishing my doctoral work but also in doing it. This thesis is the result of three and half years of work whereby I have been accompanied and supported by many people. It is a pleasure to express my gratitude to all of them.

It is difficult to overstate my gratitude to my PhD supervisors. Associate Professor Amitava Datta has greatly inspired me, encouraged me to develop research skills, taught me how to be an independent researcher, and given me a lot of research directions. I would have been lost without him. I am deeply indebted to Associate Professor Rachel Cardell-Oliver for her encouragement, steadfast support, valuable advice, and all the interesting discussions throughout the course of my PhD programme.

I am deeply grateful to anonymous referees whose comments helped me improve my research papers that in turns improve my thesis chapters.

I wish to thank student colleagues: Babak Pazand (The University of Western Australia), Valance Phua (The University of Western Australia), and Ajit Warriar (North Carolina State University) for fruitful discussions on NS-2, it was great to collaborate with you all.

I am grateful to the researchers, computer systems administrators, and secretaries in the school of computer science and software engineering, for assisting me in many different ways. Dr David Glance, Dr Chris McDonald, Jing Bo Sun, Ashley Chew, Laurie McKeaig, and Sam Sein Muan Tie, deserve special mention.

My research has been partially supported and funded by Australian Postgraduate Award,

a scholarship from the School of Computer Science & Software engineering at the University of Western Australia, ARC Linkage Grant, the contributions from both my supervisors, the substantial travel grant from the Council of Convocation (the University Graduates Association), and the travel grant from the Postgraduate Student Association.

I wish to thank my sister, Berlina Louis Lee, and also my dear friends for providing a fun, supportive, and loving environment for me.

I wish to thank my fiance, Hans William Sendjaja, for helping me get through the difficult times and for his continuous emotional support.

Lastly, and most importantly, I wish to thank my parents, Benny Louis Lee and Deasy Louis Lee. They raised me, supported me, and loved me. To them I dedicate this thesis.

Publications

International Journal Publication (*Fully Refereed*)

[1] Winnie Louis Lee, Amitava Datta, and Rachel Cardell-Oliver, “FlexiTP: a flexible-schedule-based TDMA protocol for fault-tolerant and energy-efficient wireless sensor networks”, accepted to appear in *IEEE Transactions on Parallel and Distributed Systems*.

The paper forms Chapter 4 of this thesis.

[2] Winnie Louis Lee, Amitava Datta, and Rachel Cardell-Oliver, “On-demand TDMA slot transfer for supporting adaptive sensing in wireless sensor networks”, submitted to *ACM Transactions on Sensor Networks*.

The paper forms Chapter 5 of this thesis.

[3] Winnie Louis Lee, Amitava Datta, and Rachel Cardell-Oliver, “Peer-to-peer multicasting overlay over TDMA schedule for reactive wireless sensor networks”, submitted to *Elsevier Ad Hoc Networks*.

The paper forms Chapter 6 of this thesis.

Book Chapter Publication (*Fully Refereed*)

[4] Winnie Louis Lee, Amitava Datta, and Rachel Cardell-Oliver, “Network management in wireless sensor networks”, accepted to appear in *Handbook of Mobile Ad Hoc and*

Pervasive Communications, edited by Mieso K. Denko and Laurence. T. Yang, published by American Scientific Publishers.

The comprehensive literature review presented in this paper contributed towards Chapter 7 of this thesis.

International Conference Publications (*Fully Refereed*)

[5] Winnie Louis Lee, Amitava Datta, and Rachel Cardell-Oliver, “FlexiMAC: a flexible TDMA-based MAC protocol for fault-tolerant and energy-efficient wireless sensor networks”, in *Proceedings of the 14th IEEE International Conference on Networks (ICON’06)*, volume 2, pages 1-6, September 2006.

The preliminary ideas of this paper were refined and extended to contribute towards [1].

[6] Winnie Louis Lee, Amitava Datta, and Rachel Cardell-Oliver, “A novel systematic resource transfer method for wireless sensor networks”, in *Proceedings of the 49th IEEE Global Telecommunications Conference (GLOBECOM’06)*, pages 1-6, December 2006.

The preliminary ideas and results of this paper were refined and extended to contribute towards [2].

International Conference Publications (*Refereed on the Basis of Abstract*)

[7] Winnie Louis Lee, Amitava Datta, and Rachel Cardell-Oliver, “Peer-to-peer multicasting overlay over TDMA schedule for reactive wireless sensor networks”, submitted to the fifth ACM Conference on Embedded Networked Sensor Systems (SenSys’07).

The preliminary ideas and results of this poster abstract were refined and extended to contribute towards [3].

Contribution of Candidate to Published Papers

My contribution in all the papers was 85%. I developed and implemented the protocols, performed the simulations and wrote the papers. My supervisors, Associate Professor Amitava Datta and Associate Professor Rachel Cardell-Oliver, reviewed the papers and provided useful feedback for improvement.

Contents

Abstract	iv
Preface	vi
Acknowledgements	vii
Publications	ix
Contribution of Candidate to Published Papers	xi
1 Introduction	1
1.1 Motivation and Objectives	4
1.1.1 Protocol Design Criteria for Sensor Networks	4
1.1.2 Medium Access Control	5
1.2 Challenges	7
1.3 Solutions	8
1.3.1 FlexiTP	8
1.3.2 On-Demand TDMA Slot Transfer Method	10
1.4 Contributions of this Thesis	12
1.5 Thesis Overview	13

2	Literature Review	15
2.1	MAC Protocols for Sensor Networks	15
2.1.1	Contention-based MAC Protocols	16
2.1.2	Scheduled-based MAC Protocols	19
2.1.3	Two-Radio-Based MAC Protocols	31
2.1.4	Discussion	32
2.2	Cross Layer Design Optimisations in Sensor Networks	37
3	Research Methodology	39
3.1	Wireless Sensor Network Model	39
3.2	Simulation Framework	40
3.2.1	WirelessPhy Module	40
3.2.2	MAC802.11 Module	41
3.2.3	Propagation Module	42
3.2.4	Energy Module	43
3.2.5	Network Topology Model	45
3.3	Performance Metrics	45
4	Flexible-Schedule-Based TDMA Protocol for Fault-Tolerant and Energy-Efficient Wireless Sensor Networks	47
4.1	Introduction	48
4.2	FlexiTP Description	49
4.2.1	Protocol Overview	49
4.2.2	Data Gathering Tree Construction	52
4.2.3	Time Slot Assignment	54

4.2.4	Time Synchronisation Scheme	59
4.2.5	Fault Tolerance	60
4.3	Performance Evaluation	64
4.3.1	Energy Efficiency	65
4.3.2	End-to-End Guarantees on Data Delivery	70
4.3.3	Protocol Comparison	73
4.3.4	Fault Tolerance	76
4.4	Conclusion	80
5	On-Demand TDMA Slot Transfer for Supporting Adaptive Sensing in Wire-	
	less Sensor Networks	82
5.1	Introduction	83
5.2	OST Description	85
5.2.1	Local OST Algorithm	87
5.2.2	Central OST Algorithm	91
5.3	Performance Evaluation	97
5.3.1	Simulation Setup	98
5.3.2	OST Slot Allocation	99
5.3.3	Network Performance	100
5.3.4	Energy Efficiency	104
5.4	Conclusion	105
6	Peer-to-Peer Multicasting Overlay over TDMA Schedule for Reactive Wire-	
	less Sensor Networks	107
6.1	Introduction	107
6.2	Related Work	112

6.3	WiseP2P Description	114
6.3.1	P2P Group Assignment	115
6.3.2	Multicast Tree Assignment	116
6.3.3	P2P Virtual Path Activation	117
6.3.4	Local P2P Virtual Path Activation	119
6.3.5	Central P2P Virtual Path Activation	121
6.3.6	P2P Virtual Path Repair	125
6.4	Performance Evaluation	128
6.4.1	Simulation Setup	128
6.4.2	Network Performance	130
6.4.3	Energy Efficiency	136
6.5	Conclusion	138
7	Network Management in Wireless Sensor Networks	140
7.1	Introduction	140
7.2	Related Work	143
7.3	WinMS Description	147
7.3.1	Sensor Network Models	148
7.3.2	Management Functionalities	148
7.3.3	Management Services	150
7.4	On-Demand Aggregation Algorithm	154
7.4.1	Related Work	155
7.4.2	Algorithm Description	156
7.4.3	Algorithm Formulation	159
7.4.4	TDMA-Slot Blockage Aggregation Scheme	160

7.4.5	Imposed Aggregation Schemes	161
7.5	Performance Evaluation	164
7.5.1	TDMA-Slot Blockage Aggregation Evaluation	165
7.5.2	Imposed Aggregation Evaluation	166
7.6	Conclusion	167
8	Conclusion and Future Work	169
8.1	Summary of Contributions	169
8.2	Limitations	173
8.3	Future Work	174
8.4	Concluding Remarks	176
	Bibliography	176

List of Tables

1	Mica2 Mote energy consumption models.	44
2	Mica2 Mote property.	44
3	Z-MAC simulation parameters in NS-2.	74
4	FlexiTP versus Z-MAC: performance evaluation	75
5	Simulation parameters for evaluating traffic-adaptive protocols.	98
6	Simulation parameters for evaluating the performance of P2P-enabled protocols.	128
7	WiseP2P versus CSMA: energy consumption per packet versus network density, with P2P-requestors from distinct P2P-groups.	138

List of Figures

1	The UC Berkeley mote evolution.	1
2	A wireless sensor network example.	2
3	S-MAC frame format and slot structure.	18
4	T-MAC frame format and slot structure.	18
5	EMACS frame format and slot structure.	21
6	LMAC frame format and slot structure.	22
7	TRAMA frame format.	25
8	Z-MAC frame format and slot structure.	27
9	PMAC frame format.	29
10	Crankshaft frame format.	30
11	FlexiTP simulation framework in NS-2.	41
12	FlexiTP phases.	49
13	FlexiTP node schedule structure.	50
14	A data gathering tree.	52
15	FlexiTP schedule lookup table.	58
16	FlexiTP: initial network setup cost per node versus network density.	66
17	FlexiTP: initial network setup duration versus network density.	67
18	FlexiTP: energy consumption per node versus network density.	68

19	FlexiTP: energy consumption per packet versus network density.	68
20	FlexiTP: network lifetime versus network density.	69
21	FlexiTP: percentage of sleep time versus network density.	69
22	FlexiTP: packet latency versus network density.	70
23	FlexiTP: network throughput versus network density.	72
24	FlexiTP: error rate versus network density.	73
25	FlexiTP: network connectivity re-establishment.	77
26	FlexiTP: local repair energy expenditure per node.	78
27	FlexiTP: local repair latency for node failures.	79
28	FlexiTP: local repair latency for node additions.	79
29	A local on-demand TDMA slot transfer example.	88
30	A central on-demand TDMA slot transfer example: demand < supply. . .	92
31	A central on-demand TDMA slot transfer example: demand > supply. . .	94
32	OST: percentage of demand allocation versus total percentage of nodes in the network with demand.	99
33	FlexiTP-OST versus Z-MAC versus CSMA: network throughput versus total slot-requestors.	100
34	FlexiTP-OST versus Z-MAC versus CSMA: percentage of slot-requestor throughput versus total slot-requestors.	101
35	FlexiTP-OST versus Z-MAC versus CSMA: total explicit congestion no- tification packets versus total slot-requestors.	102
36	FlexiTP-OST versus Z-MAC versus CSMA: network packet latency ver- sus total slot-requestors.	103
37	FlexiTP-OST versus Z-MAC versus CSMA: slot-requestor packet la- tency versus total slot-requestors.	104

38	FlexiTP-OST versus Z-MAC versus CSMA: energy consumption per packet versus total slot-requestors.	105
39	A smart-office application.	108
40	A network with a P2P-group.	116
41	A WiseP2P multicast tree.	118
42	A P2P virtual path repair example.	127
43	WiseP2P versus CSMA: network throughput versus total P2P-requestors, with P2P-requestors from the same P2P-group.	132
44	WiseP2P versus CSMA: network throughput versus network density, with P2P-requestors from distinct P2P-groups.	132
45	WiseP2P versus CSMA: P2P-requestor throughput versus total P2P-requestors, with P2P-requestors from the same P2P-group.	133
46	WiseP2P versus CSMA: P2P-requestor throughput versus network density, with P2P-requestors from distinct P2P-groups.	133
47	WiseP2P versus CSMA: P2P-requestor packet latency versus total P2P-requestors, with P2P-requestors from the same P2P-group.	135
48	WiseP2P versus CSMA: P2P-requestor packet latency versus network density, with P2P-requestors from distinct P2P-groups.	135
49	WiseP2P versus CSMA: energy consumption per node versus total P2P-requestors, with P2P-requestors from the same P2P-group.	137
50	WiseP2P versus CSMA: energy consumption per node versus network density, with P2P-requestors from distinct P2P-groups.	137
51	WiseP2P versus CSMA: energy consumption per packet versus total P2P-requestors, with P2P-requestors from the same P2P-group.	138
52	WinMS architecture.	147
53	An environmental monitoring application.	157

54 OST-ODA: percentage of demand allocation versus total percentage of nodes in the network with demand. 166

55 ODA: percentage of energy saving per node versus network density. . . . 167