

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**A Cross Layer Opportunistic Routing Protocol for  
Wireless Sensor Network: Analysis, Modelling and  
Quality of Service Support**

A thesis presented in partial fulfilment of the requirements for the degree of

**Doctor of Philosophy**

**In**

**Communication and Network Engineering**

at Massey University, Manawatu,  
New Zealand.

MOHD EZANEE RUSLI

2013



## Abstract

A wireless sensor network (WSN) provides a platform for embedded sensing and ubiquitous computing. For ad hoc WSNs, multi-hop routing has been adopted in order to save communication power consumption. By acknowledging the lossy characteristics of radio channels on low-power WSNs, the Opportunistic Routing (OR) protocol provides an efficient method for exploiting the spatial and temporal characteristics of these wireless networks by considering multiple forwarding relays for each transmission. The main contribution of this thesis is to provide analysis and modelling for variants of the OR protocol for WSNs.

Firstly, based on the basic concepts that underpin OR, we propose a new variant of OR that can be used in WSNs. It is known that communication in WSN is the most power consuming operation; hence, we propose a variant of OR that specifically reduces the total number of transmissions required during the coordination step used in OR. We investigate the effectiveness of this approach and compare it with OR that adopts existing and common candidate coordination schemes. In addition, we also propose a retransmission scheme based on provisional reliability constraints for local loss recovery that can be used in this new variant of OR.

Secondly, we propose a comprehensive new analytical framework that is based on Markov Chain and Queueing theories that takes into account the key component strategies of OR (prioritization, selection and coordination) as well as the communication components of WSN. The proposed framework can be used to model the end-to-end *reliability* and *delay* performances of WSNs using OR.

Thirdly, taking into account the potential deficiencies of OR due to its static coordination scheme, we introduce a variant of OR that is aware of the *online* quality of its selected forwarding relays that we have named as the Adaptive Coordination Opportunistic Routing (ACOR) protocol. We propose a new local metric to be known as the Opportunistic Quality Score for ACOR to improve the performance of WSNs and, in particular, to support Quality of Service delivery of messages in these networks. In addition, we provide an analytical framework for ACOR that incorporates the adaptive coordination scheme that has been developed.

## **Acknowledgements:**

Praise to the Almighty the most gracious and the most merciful for His blessing and guidance, and for giving me the strength to enable me to successfully complete this study.

I would like to express my sincere appreciation and gratitude to Prof Richard Harris for his constant and continuous support and supervision, which through his invaluable guidance, advice as well as constructive criticisms and opinions during this period has helped me to complete this research.

My sincere thanks also go to my co-supervisor Dr Gardiyawasam Amal Darshana Punchihewa for sharing his ideas as well as providing me with guidance and support during my research.

I am also especially grateful to Universiti Tenaga Nasional, Malaysia (UNITEN) for their financial support and assistance for me and my family during this PhD study in New Zealand.

Special appreciation goes to my friends in the School of Engineering and Advanced Technology at Massey and to my Malaysian friends for the motivation and friendship.

Last, but not least, special thanks to my beloved wife Amissa and my beautiful daughters, Aisya Sofea and Aimi Syazwani for all your love, encouragement, support and care in this special journey in our life. Thanks also to my parents and families for their good wishes, understanding, assistance and patience during the years of this study.

# Table of Contents

Abstract.....	i
Acknowledgements: .....	ii
Table of Contents.....	iii
List of Figures .....	viii
List of Tables.....	xii
Abbreviations .....	xiii
Chapter 1.....	1
Introduction .....	1
1.1    WSN Applications .....	1
1.2    Background and Motivation.....	2
1.3    Scope and Assumptions.....	6
1.4    Thesis Contributions .....	6
1.5    Thesis Outline .....	7
Chapter 2.....	9
An Integrated Overview of WSN Systems .....	9
2.1    Radio Channel.....	9
2.2    Media Access Control (MAC).....	12
2.3    Routing Protocols and Routing Metrics in WSN.....	16
2.3.1    Performance Analysis of Routing Protocols of WSN .....	20
2.4    Quality of Service.....	21
2.5    Conclusions.....	23
Chapter 3.....	24

Review of Opportunistic Routing Protocol in Multi-hop Wireless Networks .....	24
3.1 General Overview of OR .....	25
3.1.1 Prioritisation of the Candidate Relay Nodes .....	26
3.1.2 Selection of the Candidate Relay Nodes .....	27
3.1.2.1 Routing Metric .....	27
3.1.2.2 Candidate Relay Nodes Selection Algorithms .....	31
3.1.3 Coordination of the Candidate Relay Nodes .....	31
3.2 OR for WSN .....	33
3.3 Performance Modelling of Opportunistic Routing .....	34
3.4 OR with Quality of Service Support .....	35
3.5 Conclusions .....	35
Chapter 4 .....	36
Opportunistic Routing Protocol for WSNs: Performance Evaluation .....	36
4.1 Variant of Opportunistic Routing Protocol for WSN .....	36
4.1.1 Prioritisation of CRS .....	37
4.1.2 Selection of CRS .....	38
4.1.3 Coordination of CRS .....	40
4.2 Simulations-based Performance Study .....	41
4.2.1 Link Model .....	42
4.2.2 MAC Model .....	43
4.2.3 Energy Model .....	43
4.3 Simulation Settings .....	44
4.3.1 OR Sensitivity Analysis .....	45

4.3.2	OR with Implicit Acknowledgement Scheme.....	52
4.4	Soft-QoS: Provisional Reliability .....	57
4.4.1	Sensitivity Analysis .....	60
4.5	Conclusions.....	62
Chapter 5.....		63
Analytical Framework for the Opportunistic Routing Protocol .....		63
5.1	System Model .....	65
5.1.1	Network Model.....	65
5.1.2	Channel Model.....	66
5.1.3	Media Access Control (MAC) Model.....	69
5.1.3.1	Collision Probability.....	70
5.1.3.2	Channel Access Probability .....	75
5.1.3.3	Interference Probability.....	76
5.1.4	Successful Transmission Probability.....	78
5.2	Opportunistic Routing Protocol Model .....	78
5.2.1	Multi-hop Network .....	78
5.3	Analytical Framework of Opportunistic Routing in WSN .....	79
5.3.1	The Absorbing Markov Chain Model .....	79
5.3.2	Queueing Model .....	82
5.4	Illustration of the usage of the analytical framework of OR.....	85
5.5	Numerical Results .....	90
5.5.1	Simulation Setup.....	90
5.6	Conclusions.....	100



Chapter 6 .....	101
An Adaptive Coordination Scheme for the Opportunistic Routing Protocol – A Quality of Service Perspective .....	101
6.1 Problem Formulation and System Model .....	103
6.2 Adaptive Coordination Scheme.....	104
6.2.1 The Opportunistic Quality Score (OQS).....	105
6.3 Adaptive Coordination Opportunistic Routing Protocol (ACOR).....	107
6.3.1 Estimation of OQS .....	110
6.4 Performance Evaluation .....	110
6.4.1 Simulation Setup.....	110
6.4.2 Simulation Results and Analysis.....	112
6.4.3 Sensitivity Analysis .....	115
6.5 Conclusions .....	118
Chapter 7 .....	119
An Enhanced Analytical Framework For OR with Quality of Service Support.....	119
7.1 Modelling of the adaptive OR protocol .....	119
7.1.1 ACOR Absorbing Markov Chain .....	119
7.1.2 Queueing Model.....	122
7.2 Numerical Results.....	123
7.3 Conclusions .....	127
Chapter 8 .....	128
Conclusions and Future Work .....	128
8.1 Summary .....	128

8.2 Future Work .....	130
References.....	131
APPENDIX: Publications .....	144

## List of Figures

Figure 2-1: The differences in analytical packet success rates (PRRs) between wireless communication involving sensor nodes and WIFI wireless networks. The PRR for Mica2 is determined based on the model developed in [40] while the PRR for typical WiFi is determined based on model proposed in [23].....	10
Figure 2-2: The packet reception rate of 100 samples for fixed separation distance (x-axis) between 2 nodes based on Mica2 (Non-coherent FSK, NRZ radio, Transmission power=6 dBm, Path loss exponent=3.5, Shadowing standard deviation=3.8). Regions (A), (B) and (C) represent connected, transitional and disconnected regions respectively. Two vertical lines correspond to starting ( $d_s$ ) and ending ( $d_e$ ) of the transitional region.....	11
Figure 2-3: Flow chart of non-persistent CSMA/CA implementation of IEEE.802.15.4 MAC. NB=Number of back-offs, BE=Back-off exponent. ....	14
Figure 2-4: Flow chart for a persistent CSMA/CA implementation of B-MAC.....	15
Figure 3-1: Example of simple network topology.....	25
Figure 3-2: Example of two-hop WSN.....	27
Figure 3-3: Coordination with Slotted Explicit Acknowledgement Mechanism. ....	32
Figure 4-1: Example of OR operation in WSN. The solid lines show the communication between node A and all its priority ordered candidate relays. The labels indicate the link qualities (PRR) between nodes. The dashed lines show communication among the candidate relays during coordination.....	37
Figure4-2: Overlapping area that represents the forwarding region.....	38
Figure 4-3: Coordination with Slotted Implicit Acknowledgement.....	40
Figure 4-4: The end-to-end delay of OR with different minimum <i>Initial_Backoff</i> interval of MAC layer.....	47
Figure 4-5: Total number of transmissions of OR with different minimum <i>Initial_Backoff</i> interval of MAC layer .....	48
Figure 4-6: Total number of packet duplications of OR with different minimum <i>Initial_Backoff</i> interval of MAC layer.....	49
Figure 4-7: The packet success rate OR with different minimum <i>Initial_Backoff</i> interval of MAC layer.....	49
Figure 4-8: Energy Efficiency versus Minimum <i>Initial_Backoff</i> interval for the MAC layer	51
Figure 4-9: Total communication energy utilisation of OR with different minimum <i>Initial_Backoff</i> interval .....	51

Figure 4-10: Examples of network topologies using a random deployment of 50 nodes (A) and 100 nodes (B).....	52
Figure 4-11: End-to-end delay of packets versus network size where $T_{\alpha} = 15 \text{ ms}$ and $T_{BO} = 2.5 \text{ ms}$ (Vertical bars show confidence intervals at 95%).....	53
Figure 4-12: Number of transmissions versus network size where $T_{\alpha} = 15 \text{ ms}$ and $T_{BO} = 2.5 \text{ ms}$ .....	54
Figure 4-13: Number of collisions versus network size where $T_{\alpha} = 15 \text{ ms}$ and $T_{BO} = 2.5 \text{ ms}$ .....	55
Figure 4-14: Energy efficiency versus network size where $T_{\alpha} = 15 \text{ ms}$ and $T_{BO} = 2.5 \text{ ms}$ (Vertical bars show confidence intervals at 95%).....	56
Figure 4-15: Example of communication between node S and its candidate relays (P1, P2 and P3). The labels indicate the priority order for each candidate relay with respect to node S.....	57
Figure 4-16: The PSR versus the retransmission number for different set of nodes and $k$ factor. $k=0$ refers to non-probabilistic retransmission mechanism .....	60
Figure 4-17: Packet success rate versus $k$ -factor for network size of 50 nodes with retransmission attempt (RN) =5 and network size of 100 nodes with retransmission attempt (RN) = 3.....	61
Figure 4-18: Energy efficiency versus $k$ -factor for network size of 50 nodes with retransmission attempt (RN) =5 and network size of 100 nodes with retransmission attempt (RN) = 3.....	62
Figure 5-1: A typical scenario in a randomly populated low power wireless sensor network with source node, S, its neighbours ( $i_1 - i_7$ ) and destination node, D.....	65
Figure 5-2: Packet reception rate as a function of separation distance for different transmission powers where the path loss exponent $\gamma=3.5$ , the standard deviation of fading $\sigma = 3.8$ , frame size (bytes) $f = 50$ and preamble length (bytes) $l = 2$ . The horizontal line at PRR=0.1 is the reception threshold value. In this graph, the values are derived from the adopted radio channel model and the Mica2 module. ....	68
Figure 5-3: Example of a one hop network topology.....	71
Figure 5-4: Example of WSN topology.....	76
Figure 5-5: An example of topology with the hidden terminal problem. In this network, $\Omega_{3\setminus 1} = \Omega_3 - (\Omega_1 \cap \Omega_3) = \{V_4\}$ .....	77

Figure 5-6: Example of a simple WSN topology. The label for each link indicates the priority level of the receiver with respect to the sender. The lower the value the higher the priority level.....83

Figure 5-7: Example of random WSN using OR with 15 nodes in an area of 50m x 50m. The active nodes for a routing flow from source node (1) to destination node (15) are all marked as red circle.....86

Figure 5-8: The connectivity tree from source node to the destination based on OR protocol. In this diagram, the candidate relays for each node are displayed with their associated link quality and priority level.....86

Figure 5-9: Probabilities of success and failure of a packet to reach destination after different number of hops.....89

Figure 5-10: Packet Success Rate versus number of nodes in area of (50m x 50m). The minimum *Initial\_Back-off* time = 1.3 ms, the minimum *Congestion\_Back-off* time = 1.3 ms..92

Figure 5-11: Packet Success Rate versus number of nodes in area of (100m x 100m). The minimum *Initial\_Back-off* time=1.3 ms, the minimum *Congestion\_Back-off* time = 1.3 ms. ..93

Figure 5-12: End-to-end delay vs. number of nodes in an area of 50m x 50m. The minimum *Initial\_Backoff* time=1.3 ms, the minimum *Congestion\_Backoff* time= 1.3 ms.....95

Figure 5-13: End-to-end delay versus number of nodes in an area of 100m x 100m. The minimum *Initial\_Backoff* time = 1.3 ms, the minimum *Congestion\_Backoff* time = 1.3 ms. ...96

Figure 5-14: Ratio of average number of hops of the highest priority node path to the link quality (PRR) along the source to the destination path. (a) ROI=50 x 50 m<sup>2</sup>, (b) ROI=100 x 100 m<sup>2</sup>. .....97

Figure 5-15: Average number of hops to reach the destination from the source versus the number of nodes in the WSNs (50 x 50 m<sup>2</sup>). .....98

Figure 5-16: Average number of hops to reach the destination from the source versus the number of nodes in the WSNs (100 x 100 m<sup>2</sup>). .....99

Figure 5-17: Packet Success Rate vs. number of nodes in an area of (50m x 50m). The minimum *Initial\_Backoff* time=2.5ms, the minimum *Congestion\_Backoff* time = 2.5ms.....99

Figure 5-18: End-to-end delay vs. number of nodes in an area of (50m x 50m).The minimum *Initial\_Backoff* time=2.5ms, the minimum *Congestion\_Backoff* time = 2.5ms.....100

Figure 6-1: The simplified frame format for ACOR.....106

Figure 6-2: Example of priority setting based on  $(p \times \overline{Q})$  and  $\gamma$  values. ....107

Figure 6-3: The flow chart for OR with adaptive coordination of CRS on a transmitter. 108

Figure 6-4: Flow chart for OR with Adaptive Coordination of CRS on a receiver where $T_{\alpha}$ is a coordination coefficient delay constant.....	109
Figure 6-5: End-to-end delay for time-critical data packet ( $Msg1$ ). $\gamma=0.5$ , $\alpha=0.9$ . (Vertical bars show confidence intervals at 95%).....	112
Figure 6-6: Packet success rate for time-critical data packet ( $Msg1$ ). $\gamma=0.5$ , $\alpha=0.9$ . (Vertical bars show confidence intervals at 95%).....	113
Figure 6-7: Packet success rate for non-time-critical data packet ( $Msg0$ ). $\gamma=0.5$ , $\alpha=0.9$ . (Vertical bars show confidence intervals at 95%).....	114
Figure 6-8: Energy Efficiency versus the network size. $\gamma=0.5$ , $\alpha=0.9$ .....	115
Figure 6-9: The effect of setting the OQS threshold ( $\gamma$ ) value to the end-to-end delay of packet $Msg1$ of WSNs (Vertical bars show the standard deviation of the simulation analysis).....	116
Figure 6-10: The effect of setting the OQS threshold ( $\gamma$ ) value to the packet success rate of packet $Msg1$ of WSNs .....	117
Figure 6-11: The effect of setting the OQS threshold ( $\gamma$ ) value to the energy efficiency of WSNs.....	118
Figure 7-1: Packet Success Rate versus OQS threshold. Number of nodes = 50. Vertical bar represents 95% confidence limit of simulation results.....	124
Figure 7-2: End-to-end delay versus OQS threshold. Number of nodes = 50. Vertical bar represents 95% confidence limit of simulation results. ....	125
Figure 7-3: Packet Success Rate delay versus OQS threshold. Number of nodes = 100. Vertical bar represents 95% confidence limit of simulation results.....	126
Figure 7-4: End-to-end delay versus OQS threshold. Number of nodes = 100. Vertical bar represents 95% confidence limit of simulation results. ....	127

## List of Tables

Table 3-1: Comparison of routing metrics in variants of OR.....	30
Table 4-1: Mica2 energy model .....	44
Table 4-2: General simulation parameters.....	45
Table 4-3: Contention Window settings .....	46
Table 5-1: Transitional Matrix in canonical form. N1-N15 represents the nodes in the WSN and FS represents state for unsuccessful communication between a particular node and all its candidate relays. ....	87
Table 5-2: Fundamental matrix of the analytical framework.....	88
Table 5-3: The mean sojourn time of every active node for a flow from the source node (1) to the destination node (15).....	88
Table 5-4: PDF and CDF of hop counts.....	89
Table 5-5: The performance results.....	90
Table 5-6: Simulation parameters.....	91
Table 5-7: The observation of the CRS size, mean number of highest priority nodes and mean PRR between these relays. Region of interest area size = $50 \times 50 \text{ m}^2$ .....	96
Table 5-8: The observation of the mean CRS size, mean number of highest priority nodes and mean PRR between these relays. Region of interest area size = $100 \times 100 \text{ m}^2$ . ....	97
Table 6-1: Simulation parameters.....	111

## Abbreviations

ACOR	Adaptive Coordination Opportunistic Routing
ACK	ACKnowledgement
CCA	Clear Channel Assessment
CRC	Cyclic Redundancy Check
CRS	Candidate Relay Set
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear To Send
ETX	Expected Transmission Count
GPS	Global Positioning System
MC	Markov Chain
NTC	Non-Time Critical
OQS	Opportunistic Quality Score
OR	Opportunistic Routing
PRR	Packet Reception Rate
QoS	Quality of Service
RTS	Request To Send
TC	Time Critical
TDMA	Time Division Multiple Access