UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

ENERGY EFFICIENT COMMUNICATION MODELS IN WIRELESS SENSOR AND ACTOR NETWORKS

by

Suvendi Chinnappen Rimer

Submitted in partial fulfilment of the requirements for the degree
Philosophiae Doctor (Computer Engineering)
in the
Faculty of Engineering, Built Environment and Information Technology,
Department of Electrical, Electronic and Computer Engineering
UNIVERSITY OF PRETORIA

August 2011

SUMMARY

ENERGY EFFICIENT COMMUNICATION MODELS IN WIRELESS SENSOR AND ACTOR NETWORKS

by

Suvendi Chinnappen Rimer

Supervisor: Prof. G.P. Hancke

Co-supervisor: Dr. G.P. Hancke

Department: Electrical, Electronic and Computer Engineering

University: University of Pretoria

Degree: PhD (Computer Engineering)

Keywords: Wireless sensor networks, routing, small world networks, node longevity, network lifetime, energy efficiency, mobile nodes, wireless sensor actor networks, info-gap decision theory, uncertainty, robustness, mobile sink path.

Sensor nodes in a wireless sensor network (WSN) have a small, non-rechargeable power supply. Each message transmission or reception depletes a sensor node's energy. Many WSN applications are ad-hoc deployments where a sensor node is only aware of its immediate neighbours. The lack of a predefined route path and the need to restrict the amount of communication that occurs within the application area impose constraints on WSNs not prevalent in other types of networks.

An area of active research has been how to notify the central sink (or monitoring hub) about an event in real-time by utilising the minimum number of messages to route a message from a source node to the destination sink node. In this thesis, strategies to limit communication within a WSN application area, while ensuring that events are reported on and responded to in real-time, is presented.

A solution based on modelling a WSN as a small world network and then transmitting an initialisation message (IM) on network start-up to create multiple route paths from any sensor node to one or more sinks is proposed. The reason for modelling a WSN as a small

world network is to reduce the number of nodes required to re-transmit a message from a source sensor node to a sink. The purpose of sending an IM at network start-up is to ensure that communication within the WSN is minimised.

When routing a message to a static sink, the nodes closest to the static sink receive a disproportionate number of messages, resulting in their energy being consumed earlier. The use of mobile sinks has been proposed but to our knowledge no studies have been undertaken on the paths these mobile sinks should follow. An algorithm to determine the optimum path for mobile sinks to follow in a WSN application area is described. The purpose of an optimum path is to allow more equitable usage of all nodes to transfer an event message to a mobile sink.

The idea of using multiple static sinks placed at specific points in the small world model is broadened to include using multiple mobile sinks called actors to move within a WSN application area and respond to an event in real-time. Current coordination solutions to determine which actor(s) must respond to the event result in excessive message communication and limit the real-time response to an event. An info gap decision theory (IGDT) model to coordinate which actor or set of actors should respond to the event is described.

A comparison of the small world routing (SWR) model against routing using flooding and gossiping shows that the SWR model significantly reduces the number of messages transmitted within the network. An analysis of the number of IMs transmitted and received at individual node level shows that prudent selection of the hop count (number of additional nodes required to route a message to sink) to a sink node will result in a reduced number of messages transmitted and received per node within the network. The use of the IGDT model results in a robust decision on the actor(s) chosen to respond to an event even when uncertainty about the location and available energy of other actor(s) exists.

OPSOMMING

ENERGIE-DOELTREFFENDE KOMMUNIKASIE-MODELLE IN DRAADLOSE SENSOR- EN AKTUEERDER-NETWERKE

deur

Suvendi Chinnappen Rimer

Studieleier: Prof. G.P. Hancke

Mede-studieleier: Dr. G.P. Hancke

Departement: Elektriese, Elektroniese en Rekenaar-Ingenieurswese

Universiteit: Universiteit van Pretoria

Graad: PhD (Rekenaaringenieurswese)

Sleutelwoorde: Draadlose sensornetwerke, roetering, kleinwêreld-netwerke, noduslanglewendheid, netwerkleeftyd, energiedoeltreffendheid, mobiele nodusse, draadlosesensor-rolspelernetwerke, informasiegapingbeslissingsteorie, onsekerheid, robuustheid, mobiele sinkputroete

Sensornodusse in 'n draadlose sensornetwerk (DSN) het 'n klein nie-herlaaibare energievoorraad. Elke boodskapoorsending of -aanvaarding verminder 'n sensornodus se energie. Baie draadlose sensornetwerktoepassings is onvoorbereide ontplooings waar sensornodusse net bewus is van sy naaste bure. Die gebrek aan 'n voorbepaalde roete en die behoefte om die hoeveelheid boodskappe in die toepassingsgebied te beperk skep beperkings op draadlose sensornetwerke wat nie oorwegend in ander netwerke is nie.

'n Gebied van aktiewe navorsing is hoe om die sentrale sinkput (of moniteringsmiddelpunt) intyds in kennis te stel van 'n gebeurtenis, deur die minimum hoeveelheid energie van die sensornodusse te gebruik. In hierdie proefskrif is strategieë voorgestel om kommunikasie in draadlose sensornetwerke te beperk terwyl gebeurtenisse onmiddelik rapporteur en op gereageer is.

'n Oplossing vir die roeteringsprobleem in DSN is aangebied, gebaseer op die modellering van 'n DSN as 'n kleinwêreld-netwerk en die stuur van 'n aanvangsboodskap (AB) by netwerkaanvang om veelvoudige roetes van enige sensornodus na een of meer sinkputte te

vorm. Die rede hoekom 'n DSN as 'n kleinwêreld-netwerk gemodelleer is en van die AB gebruik gemaak word is om die aantal boodskappe in die toepassingsarea te verminder.

Wanneer 'n boodskap na 'n stilstaande sinkput geroeteer word, ontvang die nodusse naaste aan die stilstaande sinkput 'n buitensporige getal boodskappe, wat veroorsaak dat hul energie vroeër opgebruik word. Die gebruik van mobiele sinkputte is reeds aangebied maar studies oor die paaie wat hierdie mobiele sinkputte moet volg is nie gedoen nie. 'n Algoritme om die optimal roete vir mobiele sinkputte te vind is voorgestel. Die rede hoekom 'n optimale roete nodig is is om toe te laat vir die gelyke gebruik van alle nodusse om 'n gebeurtenisboodskap oor te dra en toe te laat dat 'n gebeurtenis intyds gerapporteer word.

Die idee om veelvoudige sinkputte op spesifieke punte in die kleinwêreld-model te plaas is uitgebrei deur voor te stel dat mobiele sinkputte, wat rolspelers genoem word, gebruik word om in 'n DSN-gebied te beweeg en op 'n gebeurtenis te reageer. Huidige gekoördineerde oplossings om te bepaal watter rolspeler moet reageer op 'n gebeurtenis maak gebruik van baie boodskappe en bepaal die intydse reaksie van 'n rolspeler. 'n Informasiegaping-beslissingsmodel (IGBM) is voorgestel om te koördineer watter rolspeler of stel rolspelers op die gebeurtenis moet reageer.

Die kleinwêreld-roeteringsmodel is vergelyk met roetering wat van oorstroming en skindery gebruik maak en wys dat die plasing van sinkputte op spesifieke punte in die toepassingsarea die aantal boodskappe wat binne die netwerk oorgedra word, aansienlik verminder. Die aantal AB boodskappe wat gestuur en ontvang word, is ontleed op die vlak van die individuele nodusse en wys dat versigtige keuses van die hoptelling (aantal bykomende nodusse wat nodig is om 'n boodskap na 'n sinkput te lei) na 'n sinkputnodus sal lei tot 'n beperkte aantal boodskappe wat gestuur en ontvang word per nodus in die netwerk tydens die aanvangsfase. Die gebruik van IGBM lei tot 'n sterk besluit op watter rolspelers moet reageer op 'n gebeurtenis, selfs as daar onsekerheid oor die ligging en beskikbare krag van die ander rolspelers is. Die berekening van 'n optimaleroete-algoritme verseker die gelyke gebruik van alle nodusse om 'n gebeurtenisboodskap na 'n mobiele sinkput toe oor te dra.

Dedication

To my family,

Raphael, Roja and Rachamim

Acknowledgements

I would like to thank Prof. Gerhard Hancke for his courage in accepting me as a PhD candidate. He knows I have young children and live and work in another city, and it would have been easier and perfectly justifiable to dismiss my attempts to undertake a research PhD as a waste of his time. However, he decided to accept me as a PhD student and gave me the freedom and time to structure my studies around my work and family.

I would like to thank my co-supervisor, Dr. Gerhard Hancke for his guidance and insight, which helped strengthen and improve my research. I valued our discussions and felt motivated to improve on certain aspects of my research that he had mentioned needed more attention.

A PhD is not done in isolation. I thank my work colleagues, especially Dr. Khmaies Ouahada, Prof. Bheki Twala, Prof. Hendrick Ferreira and Mrs. Reolyn Heymann for their support and valuable and helpful comments on my work. Ek wil ook Dr. Theo Swart bedank vir sy hulp met die vertaling van die opsomming in hierdie proefskrif.

I thank my maid Nomvula Vundla, who usually arrives at a messy house in the morning and leaves behind a neat, organised home in the afternoon. By taking care of the domestic chores, she freed up my time to pursue my research studies.

I would not be at this place in my life if it were not for my parents, whose hard work and personal sacrifice enabled me to obtain a university education. I am eternally grateful to my parents, Jagathusen and Salachee Chinnappen.

Finally I thank my husband, Rafi, for his unswerving patience and support, without which this thesis could not have been completed, as well as my daughter, Roja and my son, Rami, for letting me skip reading bedtime stories so I could work on this thesis.

List of Abbreviations

GPS	Global Positioning System
IGDT	Info-Gap Decision Theory
IM	Initialisation Message
ISM	Industrial, Scientific, and Medical (band)
LEACH	Low Energy Adaptive Clustering Hierarchy
MAC	Media Access Control
MACD	Multi-Actor Centralised Decision
MADD	Multi-Actor Distributed Decision
NS	Network Simulator
PEA	Perimeter Echo Algorithm
SACD	Single-Actor Centralised Decision
SADD	Single-Actor Distributed Decision
SNR	Signal-to-Noise Ratio
SPIN	Sensor Protocol for Information via Negotiation
SWN	Small World Network
SWR	Small World Routing
WSN	Wireless Sensor Network
WSAN	Wireless Sensor Actor Network

Table of Contents

CHAPTER 1 RESEARCH OVERVIEW 1
1.1 Introduction 1
1.2 Wireless Sensor Network Applications 5
1.2.1 Application design space and design challenges 6
1.2.2 Examples of WSN applications 10
1.3 Relevance of Wireless Sensor Networks 10
1.3.1 Multiple connected sensors versus a large single sensor 10
1.3.2 Wired versus wireless 12
1.4 Scope 13
1.5 Problem Statement 14
1.6 Research Objective 16
1.7 Research Contribution 17
1.8 Outline of the thesis 18
1.9 Flow Chart: Thesis' Themes and Publications 20
CHAPTER 2 OVERVIEW OF WIRELESS SENSOR NETWORKS 21
2.1 Introduction 21
2.2 Routing in WSNs 21
2.2.1 Classical routing techniques 22
2.2.2 Current routing techniques 23
2.3 Routing Design Challenges 25
2.4 LocaliSation 28
2.5 Wireless Sensor Actor Networks 31
2.6 Mobile Sinks and Mobile Relays 32
2.7 Standards 34

2.7.1 IEEE 802.15.4 standard 34
2.7.2 6loWPAN 35
2.7.3 ZigBee 36
CHAPTER 3 ARCHITECTURE: SINK PLACEMENT 37
3.1 Introduction 37
3.2 Small World Networks 38
3.2.1 Watts-Strogatz model 38
3.2.2 Kleinberg model 38
3.2.3 Similarities between small world networks and WSNs 39
3.3 Algorithm Design 39
3.3.1 Definitions 40
3.3.2 Assumptions 40
3.3.3 Calculation of number of sensor nodes 40
3.3.4 Calculation of number of sinks (long edges) 40
3.3.5 Placement of sink and sensor nodes 41
3.4 Examples of the use of small world networks in wireless sensor networks 43
3.5 Results and Analysis 44
3.6 Conclusion 49
3.7 Declaration 50
CHAPTER 4 ENERGY-EFFICIENT MESSAGE ROUTING 51
4.1 Introduction 51
4.2 Algorithm Design 53
4.2.1 Creating route table algorithm 53
4.2.2 Routing algorithm 55
4.3 Examples of relevant routing algorithms 58
4.4 Experimental Simulation 60
4.5 Results and Analysis 61

4.5.1 Scenario 1 62
4.5.2 Scenario 2 64
4.6 Conclusion 67
4.7 Declaration 67
CHAPTER 5 EFFECT OF SMALL WORLD ROUTING ON NODE LONGEVITY 68
5.1 Introduction 68
5.2 Algorithm Design 69
5.2.1 Node lifetime model 69
5.2.2 Minimising message re-transmissions 71
5.3 Alternative Approaches to improving network lifetime 71
5.4 Results and Analysis 73
5.4.1 Total messages vs. number of hops 73
5.4.2 Total messages per node vs. number of hops 75
5.4.3 Multiple Sinks 84
5.4.4 Managing message routes 87
5.5 Conclusion 88
CHAPTER 6 LOCALISATION IN A WSN 90
6.1 Introduction 90
6.2 Algorithm Design 91
6.3 Related Work 96
6.4 Experimental Simulation 97
6.4.1 Scenario 1 98
6.4.2 Scenario 2 98
6.5 Results and Analysis 98
6.5.1 Scenario 1 98
6.5.2 Scenario 2 100
6.6 Conclusion 102

6.7 Declaration 103

CHAPTER 7 ACTOR-ACTOR COORDINATION IN A WSN 104

7.1 Introduction 104

7.2 Background: Info-gap Decision Theory 106

7.3 Algorithm Design 107

7.3.1 Sensor-sensor and sensor-actor coordination 108

7.3.2 Actor-actor coordination using IGDT 109

7.4 Related Work 115

7.5 Experimental Simulation 117

7.6 Results and Analysis 119

7.6.1 The info-gap model 119

7.6.2 The nearest neighbour info-gap model 125

7.6.3 The info-gap model and the cluster model 126

7.6.4 Robustness, uncertainty and 95% confidence interval 134

7.7 Conclusion 141

7.8 Declaration 141

CHAPTER 8 OPTIMUM PATHS FOR MOBILE SINKS/ACTORS 142

8.1 Introduction 142

8.2 Algorithm Design 143

8.2.1 Calculation of optimum path for one or more mobile sinks 143

8.2.2 Calculation of distance between each “hello” broadcast message from mobile sink 149

8.2.3 Time for a mobile sink to complete one loop around the path 149

8.2.4 Calculation of total time it takes a sink to complete one loop across the mobile path 150

8.3 Related Work 152

8.4 Experimental Simulation 155

8.5 Results and Analysis 156

8.6 Conclusion 158

CHAPTER 9 FINAL CONCLUSIONS AND FUTURE WORK 160

REFERENCES 164

Table of Figures

Figure 1.1: Wireless sensor node architecture 2
Figure 1.2: Single sink interfaces to external manager (Akyildiz et al., 2002) 3
Figure 1.3: Multiple sink/actor interfaces to external manager (Akyildiz et al., 2002) 3
Figure 1.4: Factors to consider when designing WSN applications 9
Figure 1.5: Main energy consuming activities in a WSN (TRADS) 15
Figure 1.6: Thesis flow chart 20
Figure 2.1: Current routing categories 23
Figure 2.2: Categories of localisation measurement techniques in WSNs 29
Figure 3.1: Sink node placement calculations 42
Figure 3.2: Node range is 10m 45
Figure 3.3: Node range is 20m 45
Figure 3.4: Node range is 30m for small application areas 46
Figure 3.5: Node range is 30m for large application areas 46
Figure 3.6: Node range is 50m for small application areas 47
Figure 3.7: Node range is 50m for large application areas 47
Figure 3.8: Sinks vs. hops (range=10m) 48
Figure 3.9: Sinks vs. hops (range=30m) 49
Figure 4.1: Creating route paths with an initialisation message 54
Figure 4.2: Message routing via the nearest neighbour table 57
Figure 4.3: Possible routes from sensor to sink 61
Figure 4.4: Messages vs. time (Nodes [1,5,20,24] to [0]) 63
Figure 4.5: Messages vs. energy (Nodes [1,5,20,24] to [0]) 64
Figure 4.6: Messages vs. time (Node[1]to[24]) 65
Figure 4.7: SWR without IM vs. gossiping 65
Figure 4.8: Energy usage to send message (Node[1] to [24]) 66
Figure 5.1: Total number of IMs versus number of hops/sinks 75
Figure 5.2: Application area 100mx100m 76
Figure 5.3: Application area 200mx200 76
Figure 5.4: Application area 300mx300m 77
Figure 5.5: IMs per node [area 100mx100m] 78
Figure 5.6: IMs per node [area 200mx200m] 79
Figure 5.7: IMs per node [area 300mx300m] 80

Figure 5.8: SWR and flooding (flooding restricted to same hop count as SWR) 81
Figure 5.9: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction) 82
Figure 5.10: SWR and flooding (flooding restricted to same hop count as SWN) 82
Figure 5.11: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction) 83
Figure 5.12: SWR and flooding (flooding restricted to same hop count as SWR) 83
Figure 5.13: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction) 84
Figure 5.14: Number of messages per node for four sinks and five hops. 85
Figure 5.15: Number of messages per node for three sinks and six hops. 85
Figure 5.16: Number of messages per node for two sinks and seven hops. 86
Figure 6.1: Overview of the Perimeter Echo Algorithm 94
Figure 6.2: Location of node using trilateration 95
Figure 6.3: Calculating node location 96
Figure 6.4: Number of beacon initialisation messages re-transmitted in WSN 99
Figure 6.5: Time difference from start to end for each node to receive three beacon messages 100
Figure 6.6: Number of hops for a specific number of beacons as application area size varies 101
Figure 6.7: Number of hops from 3 closest beacons as application area size varies..... 102
Figure 7.1: Event equidistant..... 119
Figure 7.2: Event close to one actor 119
Figure 7.3: Robustness for uncertainty in actor *energy* to reach event location and react to event. 120
Figure 7.4: Robustness for uncertainty in actor *time* to reach event location. 120
Figure 7.5: Robustness for uncertainty in actor *distance* to event 121
Figure 7.6: Uncertainty of actor time of arrival in number of actors chosen in optimum set 122
Figure 7.7: Uncertainty of actor energy in number of actors chosen in optimum set 122
Figure 7.8: Uncertainty of actor distance to an equidistant event. 124
Figure 7.9: Uncertainty of actor distance to an event close to a specific actor 125
Figure 7.10: Hybrid nearest neighbour model..... 126

Figure 7.11: IGDT chooses correct cluster actor 127
Figure 7.12: Cluster actor best placed to react 128
Figure 7.13: IGDT chooses correct actor for an event in cluster corner when uncertainty about the actor's location is significant. 128
Figure 7.14: Event almost equidistant for all actors 129
Figure 7.15: IGDT chooses correct actor for event equidistant from actors for only a small amount of uncertainty about the actor's location 129
Figure 7.16: Event furthest from cluster actor 130
Figure 7.17: IGDT chooses correct nearest actor when event at centre and actor in cluster corner 130
Figure 7.18: Robustness of IGDT decision 132
Figure 7.19: Localised nodes assist actor choice 133
Figure 7.20: 95% confidence interval for an equidistant event for uncertainty in actor energy 135
Figure 7.21: 95% confidence interval for an event close to a specific actor for uncertainty in actor energy 135
Figure 7.22: 95% confidence interval for an equidistant event for uncertainty in actor time of arrival 136
Figure 7.23: 95% confidence interval for an event close to a specific actor for uncertainty in actor time of arrival 137
Figure 7.24: 95% confidence interval for an equidistant event for uncertainty in actor location 138
Figure 7.25: 95% confidence interval for an event close to a specific actor for uncertainty in actor location 138
Figure 7.26: 95% confidence interval for an event in cluster corner 139
Figure 7.27: 95% confidence interval for an event almost equidistant from all actors 140
Figure 7.28: 95% confidence interval for an event in centre of application area when cluster actor farthest away 140
Figure 8.1: Path for a mobile node to follow in a 300mx300m application area. 146
Figure 8.2: Four mobile sinks and each sinks path in a 300mx300m application area. 148
Figure 8.3: Moving corner nodes within communication range of mobile sink path 149
Figure 8.4: Number of messages received by nodes neighbouring mobile node's path 157

Figure 8.5: Number of messages per node when event message sent to node on mobile nodes perimeter..... 158

Table of Tables

Table 4.1: Advantages and disadvantages of SPIN family of routing protocols..... 58

Table 5.1: Description of variables used in node longevity calculations 69

Table 8.1: Definitions of variables used in calculations of mobile sink path..... 144