UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

ACCURATE AND EFFICIENT LOCALISATION IN WIRELESS SENSOR NETWORKS USING A BEST-REFERENCE SELECTION

by

Adnan Mohammed Abu-Mahfouz

Submitted in partial fulfilment of the requirements for the degree

Philosophae Doctor (Computer Engineering)

in the

Faculty of Engineering, the Built Environment and Information Technology

Department of Electrical, Electronic and Computer Engineering

UNIVERSITY OF PRETORIA

April 2011

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

SUMMARY

ACCURATE AND EFFICIENT LOCALISATION IN WIRELESS SENSOR NETWORKS USING A BEST-REFERENCE SELECTION

by

Adnan M. Abu-Mahfouz

Supervisor: Dr G. P. Hancke

Co-Supervisor: Prof. G. P. Hancke

Department: Electrical, Electronic and Computer Engineering

University: University of Pretoria

Degree: Philosophae Doctor (Computer Engineering)

Keywords: ALWadHA, design objectives, distance bounding, information-fusion, localisation systems, localised algorithm, location estimation, position determination, smart references selection, wireless sensor networks.

Many wireless sensor network (WSN) applications depend on knowing the position of nodes within the network if they are to function efficiently. Location information is used, for example, in item tracking, routing protocols and controlling node density. Configuring each node with its position manually is cumbersome, and not feasible in networks with mobile nodes or dynamic topologies. WSNs, therefore, rely on localisation algorithms for the sensor nodes to determine their own physical location.

The basis of several localisation algorithms is the theory that the higher the number of reference nodes (called "references") used, the greater the accuracy of the estimated position. However, this approach makes computation more complex and increases the likelihood that the location estimation may be inaccurate. Such inaccuracy in estimation could be due to including data from nodes with a large measurement error, or from nodes that intentionally aim to undermine the localisation process. This approach also has limited success in networks with sparse references, or where data cannot always be collected from

many references (due for example to communication obstructions or bandwidth limitations). These situations require a method for achieving reliable and accurate localisation using a limited number of references.

Designing a localisation algorithm that could estimate node position with high accuracy using a low number of references is not a trivial problem. As the number of references decreases, more statistical weight is attached to each reference's location estimate. The overall localisation accuracy therefore greatly depends on the robustness of the selection method that is used to eliminate inaccurate references. Various localisation algorithms and their performance in WSNs were studied. Information-fusion theory was also investigated and a new technique, rooted in information-fusion theory, was proposed for defining the best criteria for the selection of references. The researcher chose selection criteria to identify only those references that would increase the overall localisation accuracy. Using these criteria also minimises the number of iterations needed to refine the accuracy of the estimated position. This reduces bandwidth requirements and the time required for a position estimation after any topology change (or even after initial network deployment). The resultant algorithm achieved two main goals simultaneously: accurate location discovery and information fusion. Moreover, the algorithm fulfils several secondary design objectives: self-organising nature, simplicity, robustness, localised processing and security.

The proposed method was implemented and evaluated using a commercial network simulator. This evaluation of the proposed algorithm's performance demonstrated that it is superior to other localisation algorithms evaluated; using fewer references, the algorithm performed better in terms of accuracy, robustness, security and energy efficiency.

These results confirm that the proposed selection method and associated localisation algorithm allow for reliable and accurate location information to be gathered using a minimum number of references. This decreases the computational burden of gathering and analysing location data from the high number of references previously believed to be necessary.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

OPSOMMING

AKKURATE EN DOELTREFFENDE LOKALISERING IN DRAADLOSE SENSORNETWERKE DEUR DIE KEUSE VAN DIE BESTE VERWYSINGS

deur

Adnan M. Abu-Mahfouz

Studieleier:	Dr G. P. Hancke
Mede-studieleier:	Prof. G. P. Hancke
Departement:	Elektriese, Elektroniese en Rekenaar-ingenieurswese
Universiteit:	Universiteit van Pretoria
Graad:	Philosophae Doctor (Rekenaar-Ingenieurswese)
Sleutelwoorde:	ALWadHA, ontwerpdoelwitte, afstandsbegrensing, informasiefusie, lokaliseringsisteme, gelokaliseerde algoritme, liggingskatting, posisiebepaling, slim verwysingkeusemaatstaf, draadlose sensornetwerke.

Baie toepassings van draadlose sensornetwerke (DSN) maak gebruik van kennis van die ligging van nodusse in die netwerk om doeltreffend te funksioneer. Lokaliseringinligting kan gebruik word as 'n basis om onder andere nasporing van items, hulp met roeteringsprotokolle en beheer oor nodusdigtheid moontlik te maak. Konfigurasie van die ligging van nodusse per hand is lomp en nie lewensvatbaar in netwerke met mobiele nodusse of dinamiese topologieë nie. DSN berus dus op lokaliseringalgoritmes wat op hoogte kan bly van al hulle nodusse se fisiese ligging.

Verskeie lokaliseringalgoritmes ondersteun die idee dat om die akkuraatheid van posisieskatting te ondersteun, 'n groot aantal verwysings gebruik moet word. Hierdie benadering het egter verskeie nadele. Die insluiting van 'n groot aantal verwysings verhoog die kompleksiteit van lokalisering sowel as die moontlikheid dat die lokaliseringskatting

onakkuraat mag wees, hetsy as gevolg van die insluiting van data afkomsig van nodes met 'n groot metingsfout, of van nodusse wat bewustelik probeer om die lokaliseringproses te ondermyn. Hierdie benadering het ook beperkte sukses in netwerktopologieë met min verwysings, of waar datakommunikasie beperk is en data nie deurlopend van 'n groot aantal nodusse versamel kan word nie. In sodanige gevalle word 'n metode om betroubare en akkurate lokalisering met 'n beperkte aantal verwysings te bereik, vereis.

Dit is nie maklik om 'n lokaliseringalgoritme wat hoogs akkuraat is, maar 'n beperkte aantal verwysings gebruik, te ontwerp nie. Soos die aantal verwysings toeneem, word meer statistiese gewig toegeken aan die lokalisering van elke verwysingskatting en die oorhoofse lokaliseringakkuraatheid is dus in 'n groot mate afhanklik van die robuustheid van die onderliggende seleksiekriteria om sodoende onakkurate verwysing uit te skakel. Verskeie lokaliseringalgoritmes en hulle werkverrigting in DSN is bestudeer. Informasiefusieteorie is ook ondersoek. Vervolgens is 'n nuwe tegniek, gegrond op informasiefusieteorie, voorgestel om die beste keuse van verwysings te doen. Kriteria om 'n verwysing in te sluit, is versigtig saamgestel om slegs die verwysings te identifiseer wat die oorhoofse lokaliseringsakkuraatheid sou verbeter. Hierdie seleksiekriteria minimeer ook die aantal verfyningsiterasies en verminder sodoende die vereistes vir datakommunikasiekapasiteit, en minimeer die tyd wat dit neem voordat akkurate lokaliseringsinligting beskikbaar gestel word na 'n netwerkontplooiing of 'n verandering in topologie. Die gevolglike lokaliseringsalgoritme het gelyktydig twee hoofdoelwitte bereik: akkurate posisie-bepaling en informasiefusie. Daarbenewens voldoen die algoritme aan verskeie sekondêre ontwerpdoelwitte: self-organiserende aard, eenvoud, robuustheid, gelokaliseerde prosessering en sekuriteit.

Die voorgestelde metode is geïmplementeer en geëvalueer deur die gebruik van 'n kommersiële simulator. Hierdie evaluasie van die werkverrigting van die voorgestelde algoritme het die doeltreffendheid daarvan teenoor dié van bestaande lokaliseringsalgoritmes bewys. Deur die gebruik van minder verwysings het die algoritme beduidende verbetering getoon wat betref akkuraatheid, robuustheid, sekuriteit en energiedoeltreffendheid. Hierdie resultate bevestig dat die voorgestelde seleksiekriteria en lokalisasie-algoritme dit moontlik maak om betroubare en akkurate netwerklokaliserings-inligting in te samel en daardeur ook die berekeningslas te verlig van insameling en analise van lokaliseringdata deur die gebruik van 'n groot aantal verwysings, wat voorheen beskou is as noodsaaklik.

ACKNOWLEDGEMENTS

Finally, I have the opportunity to express my deepest gratitude to all of those who selflessly assisted, supported and made a critical contribution to the completion of this work. Without the help, supervision, advice and encouragement of many people this thesis would have never been completed.

First and foremost, thanks to God (ALLAH), the omniscient and the bestower, for granting me abundant grace without measure, patience and ability to complete such a large endeavour.

I would like to thank my supervisors, Dr Gerhard P. Hancke and Prof. Gerhard P. Hancke, for their critical contribution, guidance, support and availability when I needed their advice. They have taken great trouble to ensure the standard of this work. I believe that they are one of the most encouraging supervisors available and that any student would like to work under their supervision. A word of thanks must also go to Dr Ntsibane Ntlatlapa, John Isaac and Johan Eksteen for their encouragement, suggestions and friendship.

It has been a pleasure to work with the Wireless Africa Research Team. The priceless criticism, suggestions and feedback from the members of this team were very helpful and fruitful. I thank all staff members of the Meraka Institute at the Council for Scientific and Industrial Research (CSIR) for help and support. I would like to acknowledge the Meraka Institute at the CSIR for making this research possible and providing the required funding to complete the work. I would like to thank Mari Ferreira, Maryna Bekker, Heleen Gous and Stefanie Steenberg at the University of Pretoria for their administrative support and friendship. A word of thanks also goes to all of my friends who keep encouraging me to work hard to achieve my goal and complete this work.

Last, but certainly not least, I am grateful to my family for their love and prayers. They really made a great contribution to this work. Special thanks and gratitude to my wife, Leena, who married me in the same month that I started this work and later became the mother of my beautiful little daughter, Leyan. I thank my wife and my daughter for their love, encouragement, patience and for the several weekends they spent alone without me because of my working at my office.

DEDICATION

… …

…

To my family

… … … … …

… … …

…

LIST OF ABBREVIATIONS

ALWadHA	An efficient Localisation algorithm for Wireless ad hoc sensor networks with High Accuracy
AoA	Angle of Arrival
APS	Ad-hoc Positioning System
Asm	Asymmetric cryptography
AT	Avoine and Tchamkerten
BB	Bussard and Bagga
BC	Brands and Chaum
CBH	Capkun, Buttyan and Hubaux
CCD	Current Challenge Dependent
CRLB	Cramer-Rao-Lower-Bound
DB	Distance Bounding
DBPoK	Distance Bounding Proof of Knowledge
DF	Distance Fraud
dwMDS	Distributed weighted-Multidimensional Scaling
ECC	Error-Correcting Codes
ER	Error Resilience
FAR	False Acceptance Rate
GFM	Greedy Filtering by Matrix
HK	Hancke and Kuhn
k-PCD	k-Previous Challenge Dependent
KA	Kim and Avoine
KAKSP	Kim, Avoine, Koeune, Standaert and Pereira
LMS	Least Median Squares
LS	Least Squares
MAC	Media Access Control
MAC	Message Authentication Code
MAD	Mutual Authentication with Distance Bounding
MAP	Mutual Authentication Protocol
Mem	Memory
MF	Mafia Fraud
MLE	Maximum Likelihood Estimation
MMSE	Minimum Mean Square Estimate
MP	Munilla and Peinado
MSC	Meadows, Syverson and Chang
MUSE	MULtiState Enhancement
NAM	Network AniMator
NDBL	Node Distribution-based Localisation

ns	Network Simulator
Otcl	Object-oriented Tool command Language
Perl	Practical Extraction and Report Language
PRF	Pseudo-Random Function
PSH	Protocol Specific Header
RF	Radio Frequency
RFID	Radio Frequency Identification
RLS	Robust Least Square
RN	Random Number
RNTS	Reid, Nieto, Tang and Senadji
RSS	Received Signal Strength
RTT	Round Trip Time
SD	Standard Deviation
SP	Singelée and Preneel
SPA	Success Probability of an Adversary
TclCL	Tool command language with Classes
TCP	Transport Control Protocol
TdoA	Time Difference of Arrival
TF	Terrorist Fraud
TI	Trustability Indicator
TMA	Trujillo, Martin and Avoine
ToA	Time of Arrival
ToF	Time of Flight
TP	Tu and Piramuthu
US	Ultrasound
UWB	Ultra-Wideband
WSN	Wireless Sensor Network

TABLE OF CONTENTS

SUMMARY....................ii
OPSOMMING....................iv
ACKNOWLEDGEMENTS....................vi
LIST OF ABBREVIATIONS....................viii

INTRODUCTION 1

1.1 PROBLEM STATEMENT....................2
1.2 THESIS STATEMENT....................4
1.3 RESEARCH OBJECTIVES....................5
1.4 CHAPTER OVERVIEWS....................7

BACKGROUND 9

2.1 CATEGORISATION OF LOCALISATION ALGORITHMS....................9
2.1.1 Pre-configured coordinates....................10
2.1.2 Location propagation of nodes....................10
2.1.3 Granularity of information....................10
2.1.4 Computational distribution....................11
2.1.5 Number of estimations....................11
2.1.6 The set of references used....................12
2.2 LOCALISATION SYSTEMS....................14
2.2.1 Components of localisation systems....................14
2.2.2 Multilateration method....................16
2.2.3 Assumptions and variables....................18
2.2.4 Localisation errors....................19

2.3 APPROACHES TO SELECTING A SUBSET OF REFERENCES..................21
2.3.1 Nearest references..22
2.3.2 Low-error references..22
2.3.3 Malicious node removal..23
2.3.4 Consistency of references...24
2.3.5 Impact of geometry...24
2.3.6 Noisy distance estimate..25
2.4 COMPARISON OF THE ANALYSED APPROACHES..................................25
2.5 CHAPTER CONCLUSIONS...27

ACCURATE LOCALISATION SYSTEM 29

3.1 ALWADHA ALGORITHM...29
3.1.1 Initialisation...31
3.1.2 Initial position estimation..33
3.1.3 Refined position estimation...37
3.1.4 Position update...37
3.2 IMPLEMENTATION...38
3.2.1 Network simulator (ns-2) overview...38
3.2.2 The extended ns-2...39
3.2.3 Class hierarchy...42
3.2.4 The structure of the new ns-2...49
3.2.5 Guidelines for running the simulation..51
3.2.6 Manipulate output files..54
3.3 SIMULATION...55
3.3.1 Localisation algorithms...55
3.3.2 Performance comparison...57
3.3.3 Setup and environment..58
3.3.4 Results and comparisons...61
3.4 CHAPTER CONCLUSIONS...73

INFORMATION FUSION PROPERTIES OF THE LOCALISATION SYSTEM 75

4.1 INFORMATION FUSION....75
4.1.1 Information fusion and localisation systems....77
4.2 INFORMATION-FUSION TECHNIQUES FOR LOCATION DISCOVERY 78
4.3 LOCALISED INFORMATION-FUSION ALGORITHMS....81
4.4 THE THREE FILTERS OF ALWADHA....83
4.4.1 Filter one....83
4.4.2 Filter two....83
4.4.3 Filter three....85
4.5 INFORMATION FUSION IN A LEADING ROLE....85
4.6 SIMULATION....86
4.6.1 Localisation error vs number of iterations....87
4.6.2 Number of "location request" packets....88
4.6.3 Number of "location response" packets....89
4.6.4 Remaining energy....89
4.6.5 Performance comparison....90
4.7 TOWARDS MORE ENERGY EFFICIENCY....91
4.7.1 Single-estimation approach....91
4.7.2 Dynamic power control....92
4.7.3 Incremental and exponential requesting rate....93
4.7.4 Performance comparison....94
4.8 CHAPTER CONCLUSION....94

SECURE LOCALISATION SYSTEMS 97

5.1 THE SECURITY OF LOCALISATION SYSTEMS....98
5.1.1 Attacks on localisation systems....98
5.1.2 Secure localisation algorithms....101
5.2 SECURE DISTANCE ESTIMATION....104

5.2.1 Distance bounding as a possible solution for ALWadHA....................106
5.3 DISTANCE-BOUNDING PROTOCOLS....................107
5.3.1 Distance-bounding attacks....................109
5.3.2 Types of distance-bounding protocol....................111
5.3.3 Principles of secure distance bounding....................114
5.4 COMPARISON FRAMEWORK....................115
5.5 SELECTED DISTANCE-BOUNDING PROTOCOLS....................117
5.5.1 Brands and Chaum's distance-bounding protocol....................118
5.5.2 Bussard and Bagga's distance-bounding protocol....................119
5.5.3 Čapkun et al.'s distance-bounding protocol....................119
5.5.4 Hancke and Kuhn's distance-bounding protocol....................120
5.5.5 Reid et al.'s distance-bounding protocol....................121
5.5.6 Tu and Piramuthu's distance-bounding protocol....................121
5.5.7 Munilla and Peinado's distance-bounding protocol....................122
5.5.8 Kim and Avoine's distance-bounding protocol....................122
5.5.9 Kim et al.'s distance-bounding protocol....................122
5.5.10 Meadows et al.'s distance-bounding protocol....................123
5.5.11 Avoine et al.'s technique....................123
5.5.12 Avoine and Tchamkerten's distance-bounding protocol....................124
5.5.13 Trujillo-Rasua et al.'s distance-bounding protocol....................125
5.5.14 Peris-Lopez et al.'s distance-bounding protocol....................125
5.6 COMPARISON OF DISTANCE-BOUNDING PROTOCOLS....................126
5.6.1 Security....................128
5.6.2 Memory and transmitted data....................131
5.6.3 Computation....................133
5.6.4 Choosing a suitable protocol....................134
5.7 ATTACK RESISTANCE OF ALWADHA ALGORITHM....................135
5.8 SIMULATION RESULTS....................137
5.8.1 Dishonest reference nodes....................137
5.8.2 Compromised beacon nodes....................139
5.9 CHAPTER CONCLUSIONS....................140

CONCLUSION 142

6.1 CONCLUSIONS....143
6.2 SUMMARY OF CONTRIBUTIONS....150
6.3 FUTURE WORK....153

References....155