UNIVERSITI PUTRA MALAYSIA

MOBILE DATA GATHERING ALGORITHMS FOR WIRELESS SENSOR NETWORKS

MUKHTAR MAHMOUD YAHYA GHALEB

FSKTM 2014 23

MOBILE DATA GATHERING ALGORITHMS FOR WIRELESS SENSOR NETWORKS

MUKHTAR MAHMOUD YAHYA GHALEB

DOCTOR OF PHILOSOPHY
UNIVERSITI PUTRA MALAYSIA

2014

MOBILE DATA GATHERING ALGORITHMS FOR WIRELESS SENSOR NETWORKS

By

MUKHTAR MAHMOUD YAHYA GHALEB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

November 2014

COPYRIGHT

DEDICATIONS

To whom I owe them the prosperity of my life, who exert their precious effort to make my life successful:
My late grandmother Fatimah Al-hakami, my father, my mother, my brothers, my sisters, my lovely wife, and my wonderful daughters Tasnim and Tarnim.
Finally, To All whom I love and To All those who supported me.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

MOBILE DATA GATHERING ALGORITHMS FOR WIRELESS SENSOR NETWORKS

By

MUKHTAR MAHMOUD YAHYA GHALEB

November 2014

Chairman: Assoc. Prof. Shamala Subramaniam, PhD
Faculty: Computer Science and Information Technology

Data gathering is among the issues constantly acquiring attention in the area of Wireless Sensor Networks (WSNs) due to its impact and ability to transform many areas associated with the human life. There is a consistent increase in the research directed on the gains of applying mobile elements to collect data from sensors, especially those oriented to power issues as compared to multi-hop technique. There are two prevailing strategies used to collect data in sensor networks. The first approach requires data packets to be serviced via multi-hop relay to reach the respective Base Station (BS). The second strategy encompasses a mobile element which serves as the core element for the searching of data. These mobile elements will go to each transmission range of each respective sensor to upload its data.

In this research, a Mobile Data Gathering based Network Layout (MDG-NL) algorithm is proposed. This algorithm enables shortened tour length for the respective mobile element. In addition, a certain number of nodes work as a temporary BS by aggregating the data packets from affiliated sensors via multi-hop. Furthermore, strategically divisioning the area of data collection, the optimization of the mobile element can be elevated. These derived areas are centric on determining the common configuration ranges strategically placing the collection point. Thus, within each of these areas, the multi-hop collection is deployed. This research presents a Zonal Data Gathering based Multi-hop and Mobile Element (ZDG-MME) algorithm to enhance the network lifetime. ZDG-MME algorithm is able to segment the deployment field into two divisions and forward the tailored data to the BS. First, the inner division which is the closest to the BS reports the sensed data directly through multi-hop. Second, the outer division reports the data to certain nodes selected as polling nodes. ZDG-MME algorithm is designed to ensure minimizing both the energy consumption and the data gathering latency whilst avoiding the hotspot area. The third proposed algorithm achieves an adaptive data gathering strategy. In this algorithm, the user has to tune an appropriate variable which directly affects the power consumption and the data gathering latency. This variable is a trade-off parameter that balances between the energy consumption and data gathering latency. The selection of this parameter is based on the application requirements. Minimal Constrained Rendezvous Node (MCRN) algorithm is designed to ensure that the number of pause locations for the mobile element is minimized. In MCRN, the selecting of rendezvous nodes is based on three factors: 1) bounded relay hop 2) number of affiliation nodes 3) distance of the respective rendezvous node to the BS. The algorithm is proven to minimize the number of rendezvous nodes which ensure that the tour length and the data gathering latency are both minimized. The performance evaluation of the proposed data gathering algorithms has been done through a detailed and extensive discrete-event-simulation analysis. The acquired results show that the MDG-NL scheme significantly improves the performance over SPT-DGA up to 12.5%. The results obtained by the ZDG-MME shows an enhancement on the performance up to 15.21%. The results have proven the enhancements achieved by the proposed algorithms through the performance metrics of tour length, data gathering latency and total energy consumed.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ALGORITMA PENGUMPULAN DATA MUDAH ALIH UNTUK RANGKAIAN WAYARLES SENSOR

Oleh

MUKHTAR MAHMOUD YAHYA GHALEB

November 2014

Pengerusi: Assoc. Prof. Shamala Subramaniam, PhD
Fakulti: Sains Komputer dan Teknolologi Maklumat

Pengumpulan data adalah antara isu yang sentiasa mendapat perhatian dalam bidang Pengesanan Rangkaian Tanpa Wayar (Wireless Sensor Networks /WSN). Ini adalah kerana bidang tersebut banyak memberi kebaikan dan impak kualiti rangkaian kepada pengguna rangkaian tanpa wayar. Terdapat peningkatan yang konsisten dalam penyelidikan yang diarahkan ke atas keuntungan daripada menggunakan unsur-unsur mudah alih untuk mengumpul data dari pengesan rangkaian, terutamanya yang berorientasikan kepada isu-isu kuasa berbanding dengan teknik berbilang gelang. Terdapat dua strategi yang lazim digunakan untuk mengumpul data dalam bidang pengesanan rangkaian. Pertama strategi memerlukan data paket diservis melalui teknik relai berbilang-gelang untuk tiba di Stesen Pangkalan (BS) masing-masing. Strategi kedua merangkumi unsur mudah alih yang berfungsi sebagai elemen teras dalam pencarian data paket. Unsur-unsur mudah alih ini akan merentasi setiap julat penghantar di setiap pengesan untuk memuatnaik data paket tersebut.

Dalam kajian ini, satu algoritma pengumpulan data mudah alih berasaskan rekaletak rangkaian atau ringkasannya MDG-NL telah dicadangkan. Algoritma ini membolehkan jarak penjelajahan untuk setiap unsur mudah alih dipendekkan. Di samping itu, melalui teknik berbilang gelang, dengan menjumlahkan data paket daripada pengesan rangkaian yang bergabung dapat menjadikan beberapa nod berfungsi sebagai stesen sementara. Tambahan pula, dengan membahagikan kawasan pengumpulan data secara strategik, pengoptimuman unsur mudah alih boleh dipertingkatkan. Pembahagian ini dapat membantu dalam menentukan julat konfigurasi umum titik pengumpulan data secara strategik. Seterusnya, teknik berbilang gelung untuk pengumpulan data ini dilaksanakan dalam ruang lingkup kawasan tersebut. Kajian ini juga memperkenalkan algoritma zon pengumpulan data yang berasaskan berbilang gelang dan unsur bergerak atau secara ringkasnya ZDG-MME. Objektif pertama algoritma adalah bertujuan untuk meningkatkan jangka hayat rangkaian. Menerusi algoritma ZDG-MME, ia mampu untuk membahagikan kawasan liputan rangkaian kepada dua segmen. Seterusnya, data yang telah disesuaikan dengan BS akan dikemukakan. Langkah untuk melaksanakannya adalah seperti berikut ; pertama, melalui teknik rangkaian berbilang gelung, kawasan liputan yang paling dekat dengan BS, akan mengesan data secara terus. Seterusnya langkah kedua, kawasan luar liputan pula akan melaporkan data kepada nod tertentu yang telah dipilih sebagai nod pengundian. Algoritma ZDG-MME ini, juga direkabentuk untuk memastikan penggunaan tenaga dan perlengahan pengumpulan data diminimumkan di samping dapat mengelak daripada kawasan hotspot. Objektif ketiga algoritma ini adalah untuk mencapai ciri mudah suai kepada strategi pengumpulan data. Menerusi algoritma ini, pengguna perlu membuat menala pembolehubah yang sesuai. Seterusnya,pembolehubah ini secara langsung memberi impak kepada penggunaan kuasa dan kependaman pengumpulan data. Pembolehubah tersebut adalah satu parameter keseimbangan yang mengimbangkan penggunaan tenaga dan perlengahan pengumpulan data. Pemilihan parameter ini adalah berdasarkan kepada permohonan keperluan aplikasi dalam rangkaian. Algoritma Minimal Kekangan Nod Rendezvous (MCRN) direka untuk memastikan bilangan lokasi jeda untuk unsur mudah alih dapat dikurangkan. Dalam MCRN, pemilihan nod pertemuan adalah berdasarkan kepada tiga faktor laitu 1) hophad gegelang relai, 2) bilangan nod gabungan, dan 3) jarak antara setiap nod pertemuan kepada dengan BS. Algoritma ini terbukti dapat meminimakan bilangan nod pertemuan yang seterusnya mengurangkan jarak penjelajahan dan perlengahan. Untuk menilai prestasi algoritma yang telah dicadangkan, simulasi acara-diskret telah dilaksanakan. Hasil simulasi telah dikumpul, dianalisis dan dibuat perbandingan dengan algoritma lain. Simulasi ini menggunakan jarak penjelajahan, perlengahan pengumpulan data dan jumlah penggunaan tenaga sebagai paramater penilaian metrik. Hasil simulasi menunjukkan bahawa skim MDG-NL telah meningkatkan prestasi lebih tinggi sehingga 12.5% berbanding dengan skim SPT-DGA. Hasil simulasi skim ZDG-MME juga telah menunjukkan peningkatan prestasi sehingga 15.21%. Ini telah membuktikan bahawa algoritma algoritma yang telah dicadangkan berjaya meningkatkan prestasi pengesanan dalam rangkaian mudah-alih.

ACKNOWLEDGEMENTS

First and foremost, praise is for *Allah Subhanahu Wa Taala* for giving me the strength, guidance and patience to complete this thesis. May blessing and peace be upon Prophet Muhammad *Sallalahu Alaihi Wasallam*, who was sent for mercy to the world.

I would like to express my sincere gratitude to my supervisor Associated Prof. Dr. Shamala Subramaniam for the continuous support of my study and research, for her patience, motivation, enthusiasm, and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better supervisor and mentor for my PhD study.

I would like to thank the supervisory committee members, Prof. Dr. Mohamed Othman and Associated Prof. Dr. Zuriati Ahmad Zukarnain for their encouragement and insightful comments.

I am very grateful to the Faculty of Computer Science and Information Technology and the staff of Postgraduate office, Library and Universiti Putra Malaysia, for providing the research environment. Thanks to every person who has supported me to produce my thesis.

I am very grateful to my family: my late grandmother, Fatima, my father, Mahmoud my mother, Badrah, my brothers and my sisters for their unflagging love and support throughout my life. I have no suitable words that can fully describe my everlasting love to them except, I love you all.

Words fail me to express my appreciation to my lovely wife Marwah whose dedication, love and persistent confidence in me, has taken the load off my shoulder. I owe her for being unselfishly let her intelligence, passions, and ambitions collide with mine.

Special thanks goes to my kids Tasnim and Tarnim, you are my joy and guiding lights. Thanks for giving me your valuable time through all this long process. I promise I will never let you alone any more.

Last but by no means least, it gives me immense pleasure to express my deepest gratitude to my friends Anwar, Mohammed and Ammar for their constant support and encouragement.

Finally, I would like to thank everybody who was important to the successful realization of thesis, as well as expressing my apology that I could not mention personally one by one.

APPROVAL

I certify that a Thesis Examination Committee has met on 17/11/2014 to conduct the final examination of MUKHTAR MAHMOUD YAHYA GHALEB on his thesis entitled "MOBILE DATA GATHERING ALGORITHMS FOR WIRELESS SENSOR NETWORKS" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Rusli bin Hj Abdullah, PhD
Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Chairman)

Hamidah bt Ibrahim, PhD
Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Internal Examiner)

Nor Kamariah bt Noordin, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

External Examiner name, PhD
Professor
Clayton School of Information Technology
Monash University
(External Examiner)

NORITAH OMAR, PhD
Associated Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Shamala a/p K subramaniam, PhD
Associate Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Chairman)

Mohamed b Othman, PhD
Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Member)

Zuriati bt ahmad Zukarnain, PhD
Associate Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ____________________ Date: ____________________

Name and Matric No.: ______________________________

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________
Name of Chairman of Supervisory Committee: ______________________

Signature: ______________________
Name of Member of Supervisory Committee: ______________________

Signature: ______________________
Name of Member of Supervisory Committee: ______________________

Signature: ______________________
Name of Member of Supervisory Committee: ______________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ATA	Adjusting Tree Algorithm
BS	Base Station
CH	Cluster Head
CTPs	Common Turning Points
DAC	Data Aggregation enhanced Convergecast
DCs	Data Collectors
DES	Discrete Event Simulator
ETX	Expected Transmission Count
GBMES	Grid-Based Mobile Elements Scheduling
GloMoSim	Global Mobile System Simulator
GN	Grid Node
GPS	Global Positioning System
GUI	Graphical User Interface
HEED	Hybrid Energy-Efficient Distributed
ILP	Integer Linear Program
LEACH	Low-Energy Adaptive Clustering Hierarchy
LP-RDA	Load Priority based RN Determination Algorithm
MAC	Medium Access Control
MCRN	Minimal Constraint Rendezvous Node
MDCs	Mobile Data Collectors
MDG-BRH	Mobile Data Gathering based Bounded Relay Hop
MDG-NL	Mobile Data Gathering based Network Layout
MEs	Mobile Elements
MEST	Minimum Expected Spanning Tree
MPE	Max-min Path Energy
MST	Minimum Spanning Tree
MTCP	Multiple Target Coverage Problem
MULEs	Mobile Ubiquitous LAN Extensions
NN	Nearest Neighbor
NS-2	Network Simulator-2
NS-3	Network Simulator-3
OOP	Object Oriented Programming
OPNET	Optimized Network Engineering Tool
PEACH	Power-Efficient and Adaptive Clustering Hierarchy
PEGASIS	Power-Efficient GAthering in Sensor Information

	Systems
PPs	Polling Points
RP	Rendezvous Point
SPPs	Sub Polling Points
SPT	Shortest Path spanning Tree
SPT-DGA	Shortest Path Tree based Data Gathering Algorithm
TDMA	Time Division Multiple Access
TEDAS	Tree-based Energy and Delay Aware Scheme
TSP	Travel Salesman Problem
VV&T	Validation, Verification and Testing
WPE	Weighted Path Energy
WSNs	Wireless Sensor Networks
ZDG-MME	Zonal Data Gathering algorithm based on Multi-hop and Mobile Element

CHAPTER 1

INTRODUCTION

Wireless Sensor Networks (WSNs) have gained substantial and critical attention over the last few years due to their impact and ability to transform many areas associated with the human life such as vital sign monitoring (Chang et al., 2012), long-term surveillance of elderly patients, and postoperative and intensive care (Alemdar and Ersoy, 2010; Huang et al., 2009). WSNs have positioned itself within the revolutionary network technologies as a credible member. This is mainly due to the enormous benefits on WSNs in multitudes of fields such as disaster relief operations (Chen et al., 2013), biodiversity mapping (Garcia-Sanchez et al., 2010), intelligent buildings or bridges (Yeh et al., 2009), precision agriculture (Sutar, 2012), earthquake early warning (Wang and Ni, 2012), medicine and health care, logistics (Becker et al., 2010), and so on. It is becoming increasingly difficult to ignore the successful usage of WSNs in different areas that affects human civilization.

WSNs consist of hundreds or even thousands of sensors which are tiny, low powered and have limited storage and transmission. These sensors are used to acquire data which generally pose a challenge or threat to the element of human accessibility and safety. Once the sensors are deployed they are indeed unreachable (Mahajan and Mahotra, 2011; Wang et al., 2010) due to their placement in hazardous environments such as in a volcano or unreachable terrains or due to the issue of inaccessibility of a dense forest. In addition, these sensors which are powered by battery implies a clear finite energy sources. Thus, factors such as inaccessibility and constrained power supply have made energy consumption one of the primary issues in sensor networks.

Data transmissions and aggregation constitute a major portion of sensor energy consumption (Zhao and Yang, 2012). There is a rich and a heterogeneous spectrum of solutions to maximize the network lifetime. The related strategies are discussed in Chapter 2. The power of WSNs lies in three factors, 1) the ability to deploy large numbers of tiny nodes that assemble and configure themselves after deployment, 2) the deployment cost would be minimal unlike the traditional wired network, and 3) the ability to adapt dynamically to changing environments (Buratti et al., 2009).

1.1 WSNs Overview

WSNs generated an increasing interest in multitude type of fields. A WSN can be generally described as a network which encompasses number of distributed nodes that sense the environment and enabling interaction between the end users/computers and the surrounding environment. In this section, an overview of WSNs is presented

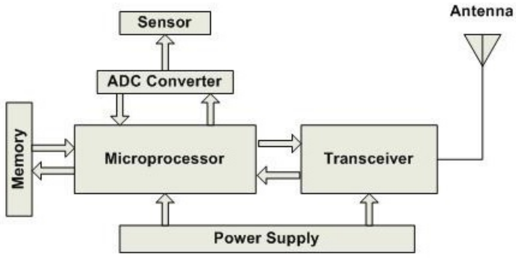

Figure 1.1: Architecture of a Sensor Node

encompasses a sensor node architecture, applications and tasks, and limitations of WSNs.

1.1.1 Node Architecture

A sensor node in WSNs is a node that is capable of performing some tasks such as sensing environment, gathering data and communicate with other nodes within its range. This node is composed of multiple layers, each one performing a specific function of the node. The layers encompasses sensing, power supply, processing and communication (i.e., transceiver). In addition, it consists of one or more sensors that detect any change in the surrounding environment. Analog-to-Digital Converter (ADC) used to convert the detection analog event to digital and sent it to the embedded microprocessor. The required energy for sensing, processing and data communication is supplied by the power supply unit. Figure 1.1 illustrates the architecture of a sensor node.

1.1.2 Applications and Tasks

WSNs have existed for decades and used for diverse applications ranging from medical care to military battlefield, and from home to industry. This emerging is aimed to show the increasing of numbers of society who depend upon reliable sensor networks. Possible applications of sensor networks are of interest in the most diverse field. The following applications are only some examples of WSNs.

- Disaster relief operations such as wildfire detection (Bouabdellah et al., 2013; Manolakos et al., 2010).
- Biodiversity mapping which gain an understanding about plants and animals (Mainwaring et al., 2002; Szewczyk et al., 2004).

- Intelligent buildings, bridges, and industry which focus on measurements about temperature, energy wastage, monitoring of mechanical stress level, and earthquake (Akhondi et al., 2010; Kurata et al., 2005; Petersen et al., 2007).
- Precision agriculture which includes precise irrigation and fertilising of fields and temperature and brightness monitoring (Bencini et al., 2010; Shah et al., 2009).

The main tasks which are performed in a generic WSN application can be described as follows.

- The first step to be performed is the node deployment either manually or randomly such as thrown from an aircraft.
- The second step is network initialization to set up the whole network such as self localization and node clustering.
- The third step is the main step which is sampling the monitoring environment and process their data.
- The final step is to deliver the data to the final destination in cooperate with other nodes to be available to the end users through internet as example. It includes multiple sending and receiving packets during the transmission period.

1.1.3 WSNs Limitations

WSNs have positioned itself within the revolutionary network technologies as a credible member. This is due to the enormous benefit on WSNs in multitudes of fields that affect human life. In addition, WSNs consist of a large number of sensor nodes which are tiny and low-cost and are distributed randomly over a specified area. These sensors typically used for sampling the surrounding environment, processing and may temporally storing the collected data and transmit the data to the specific point such as the sink or the Base Station (BS) (Akyildiz et al., 2002). Several limitations and challenges are emerged in the area of WSNs. These limitations are as follows:

- Sensor node is a tiny device with limited storage, bandwidth, processing, and communication range.
- The criticalness of power management as each sensor node is powered by low-energy batteries (Hoang et al., 2010).
- The design of sensor networks are influenced by many factors such as, energy consumption, cost, security issues, data aggregation, topology, communication paradigm, and data delivery to the BS.

1.1.4 Data Gathering in WSNs

Data gathering is among the issues constantly acquiring attention in the area of WSNs. Gauging the various research area to sensing the environment and temporarily store the sensed data, the energy consumption for passes the data from each sensor to the BS is a more the pertinent issue in WSNs (Rooshenas et al., 2010; Shebli et al., 2007; Zhao and Yang, 2012). This is because the data must be transmitted via multiple nodes before reaching the BS for subsequent processing. This process is called the data gathering process. In this process, each sensor node is responsible to gather the raw data from their surrounding environment. Subsequently the data is stored temporarily before being forwarded to the BS. Based on the type of method applied and the carrier for data gathering in WSNs, there are three predominant strategies used to gather data in WSNs namely, static multi-hop, mobile, and hybrid (i.e., static and mobile).

1.1.4.1 Multi-Hop Data Gathering

The first strategy requires data packets to be delivered to the respective BS via multi-hop relay (Farooq et al., 2010; Jiang et al., 2010; Sun et al., 2010; Yan et al., 2008; Yi et al., 2007). Thus, nodes will send their packets through other intermediate nodes. However, this strategy has proven to consume high and a substantial amount of energy due to the dependency on other nodes for transmission. It is also not preferred to send data packets directly between nodes and the BS as it costs nodes faster energy depletion. This is due to the correlation between distance and the energy consumption. In this correlation, increasing the transmission distance (i.e., long-range communication) leads to increase the energy consumption and vice versa (Teixeira et al., 2004). Thus, sensors are preferred to send their data to the BS through other sensors within their ranges and in the way to the BS. Figure 1.2 illustrates one of the multi-hop technique used to deliver the data to the BS based on constructing spanning tree to the BS as root. In this figure, shortest path is ensured based on the minimum hop distance between each node and the BS.

1.1.4.2 Mobile Data Gathering

The second strategy encompasses a Mobile Element (ME) which serves as a temporary BS. The ME will traverse each transmission range of each respective sensor to upload its data. The ME then returns to the respective BS after the completion of data gathering tour. This strategy has proven to reduce the energy consumption substantially as compared to the previous strategy (i.e., multi-hop). However, it has a trade-off which is the increase of delay incurred and is constrained by the speed

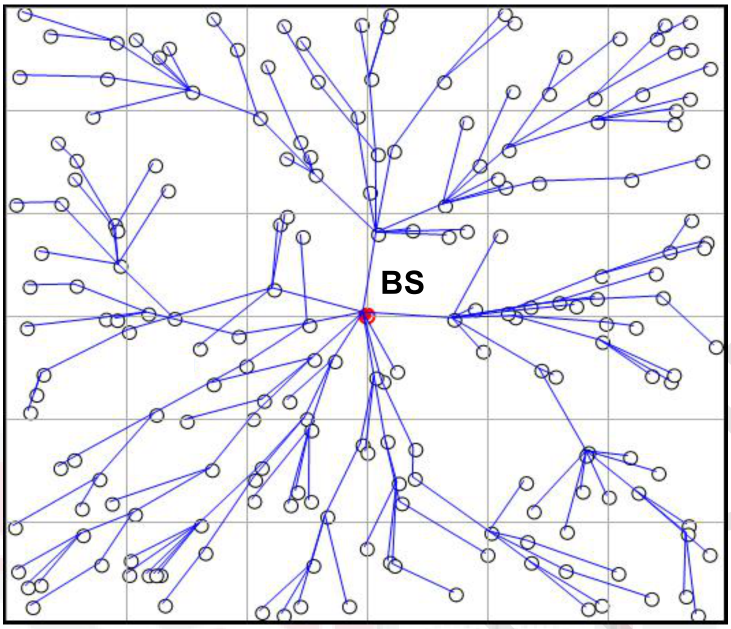

Figure 1.2: Multi-hop Data Gathering

of the respective ME. In addition, some sensor may lose their data due to overflow while waiting for the ME. In the last few years, many researchers have employed ME to gather data via short range communications in WSNs (Almi'ani et al., 2010; Kumar and Sivalingam, 2010; Ma et al., 2013; Shah et al., 2003; Wang and Ma, 2011; Zhao et al., 2011). These MEs will be responsible for gathering data packets directly from sensors which minimizes/eliminates traversing packets among nodes. Figure 1.3 illustrates the tour path of ME which roams to reach every sensor node in the deployment area as an extreme case of mobile data gathering. The tour path of ME starts from the BS in the center of the deployed field, then consequently visits each sensor node before eventually returns to the BS. In addition, as an advantage of adopting ME in data gathering process, sparse networks are no longer considered as a problem due to covering the whole network by the respective ME.

1.1.4.3 Hybrid Data Gathering

The third strategy is combining the multi-hop forwarding approach with the use of mobile data gathering in order to ensure a balance between energy consumption and latency of data gathering which is called a hybrid approach. In this approach, a trade-off between latency of data gathering and energy consumption are presented by select some sensor nodes as caching points (i.e., Sub Polling Points (SPPs)) (Jea et al., 2005; Ma and Yang, 2007; Sheu et al., 2010; Vupputuri et al., 2010; Xing et al., 2012; Zhao and Yang, 2012). These nodes are responsible for gathering the

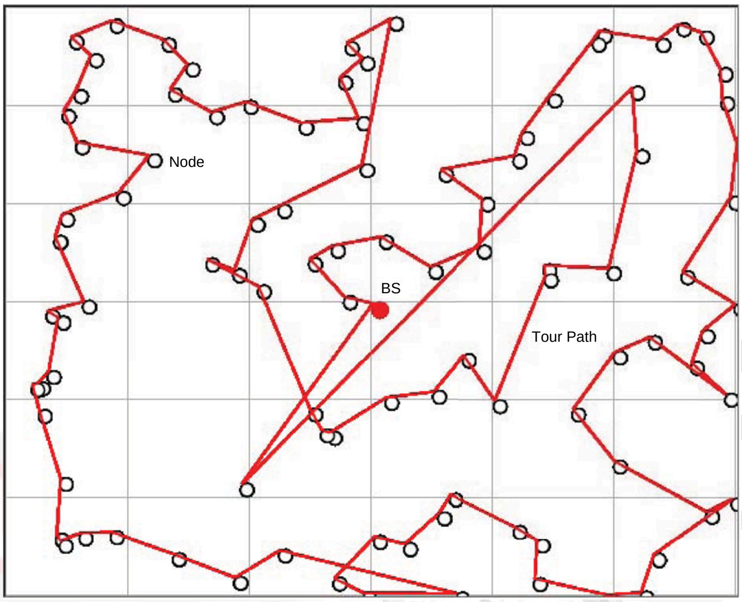

Figure 1.3: Mobile Data Gathering Tour Path

data from other nodes via multi-hop fashion and communicate directly with mobile data collector when reaching their transmission range. Figure 1.4 illustrates the tour path of mobilc data collector and the SPPs including the BS. Each SPP gathers the data from affiliated sensors via multi-hop.

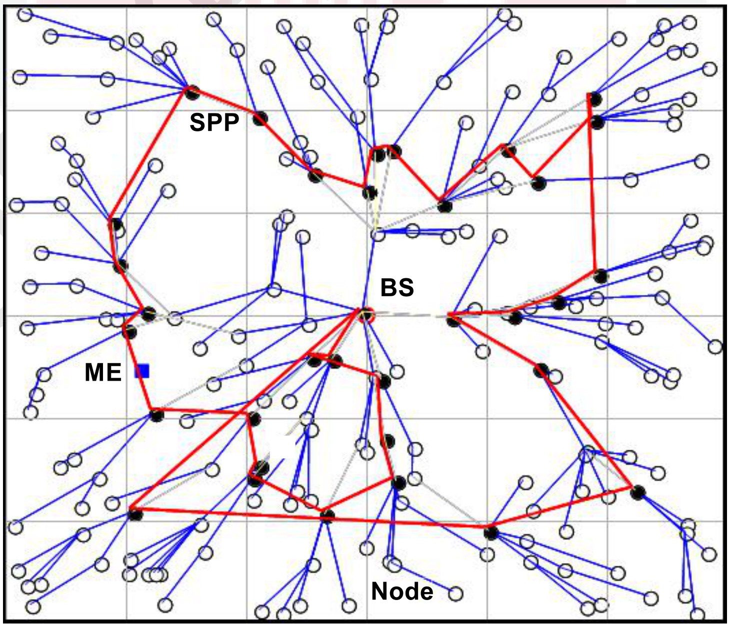

Figure 1.4: Hybrid Data Gathering

1.2 WSNs Challenges and Research Issues

WSNs consist of hundreds or even thousands of sensors. These sensors are tiny, low powered and have limited storage and transmission (Bhattacharyya et al., 2010). In addition, these sensors are used to acquire data which generally pose a challenge or threat to the element of human accessibility and safety. Once the sensors are deployed they are indeed unreachable and cannot be easily recharged (Wang et al., 2010). This is due to their placement in hazardous environments such as the Volcano or due to the issue of inaccessibility of a dense forest. The sensors are powered by battery have a finite energy. Thus, factors such as inaccessibility and constrained power have made energy consumption a primary issue in sensor networks. In addition, data transmissions and aggregation constitute a major portion of sensor energy consumption (Rooshenas et al., 2010; Shebli et al., 2007; Zhao and Yang, 2012) and is rich in its heterogeneity of solutions which includes the maximization of the network lifetime. The related strategies which are classified based on the type of data carrier are divided into two approaches, which are either static multi-hop or mobile.

The static approach focuses on routing using cooperative static sensor nodes. In this approach, data packets are forwarded to the data sink via multi-hop relay among sensors. The deployment of the shortest path solution, has not been able to prolong the network lifetime (Zhao and Yang, 2012). This is because some sensors may serve many paths due to their unique position which causes the depletion of their energy faster as compared to others and further causes non uniform energy consumption. Thus, this static approach causes emerging the hotspot areas near the BS due to unbalanced energy consumption. Nodes which are physically located closer to the BS impose a higher burden.

Migrating towards more innovative solutions and diversifying the nodes (or subset of nodes) design is becoming a prevailing strategy to ensure effectiveness. This trend has also impacted mobile data gathering as a revolutionary solution. This strategy applies one or more mobile data collectors that are elements which are equipped with powerful transceivers and batteries.

A generic scenario in this context will involve a ME traverses the deployment field and uploading the data from all sensors via short range communications whilst moving or pauses at some selected points. This approach has led to the remarkable reduction of the energy consumption inquired due to data gathering. This reduction is due to the mobility of the ME which enable shortened the transmission range and may eliminating the need and burden of relay hop for sending packets to the BS. Obviously, to have an ultimate energy saving, a ME should visit each sensor node to upload their data via short range communication. However, a constraint of this mobile approach will lead to higher data gathering latency resulting from the limited velocity of the ME which constraints the mobility pattern. Thus, this is not a preferred solution in some applications that are sensitive to latency.

Thus, there are two conclusions which can be drawn. First, power consumption increases dramatically when the multi-hop data gathering approach is applied. Second, latency increases when the mobile data gathering approach is applied via a single hop. However, remarkable energy is saved when an appropriate data gathering approach is applied. Thus, increasing the number of nodes that are visited by the ME causes a long tour path which implies increasing latency. It is, thus, obvious that there is an intrinsic trade-off between energy consumption and latency in correlation to the properties of the mobile collector.

1.3 Problem Statement

In analysing the various discussion deliberated in the previous section, the following pertinent problems have been identified for this research. They are as follows:

- Mobile data gathering incurs high latency during data gathering process. The ME fails to increase the throughput of data delivery to the BS due to its limited velocity. In addition, some nodes may lose their data due to buffer overflow while waiting for the ME. Thus, the shortened of ME tour path is better to increase the data gathering throughput and minimize the data gathering latency. However, the power consumption should be minimized to a certain level.
- Multi-hop data gathering incurs high power consumption due to multiple forwarded packets among nodes. The nodes near the BS deplete their energy faster than the other due to serving other nodes located far away from the BS. Thus, emerging the hotspot area near the BS is high which leads to disconnected network. However, latency to deliver data to the BS is minimized due to fast forwarding data packets among nodes.
- The applications of sensor networks are of interest of the most diverse field. The diversity leads to vastly varying requirements and characteristics. As a consequence, it is becoming increasingly difficult to have an identical requirements for all applications. For example, delay intolerant applications would prefer to minimize the latency to the lowest level. In contrast, delay tolerant applications would prefer to minimize the power consumption to the lowest level.

1.4 Research Objectives

The main objectives of this research is to propose and develop an enhancement data gathering approach with minimizing the tour length of mobile collector, minimizing the energy consumption, minimizing the data gathering latency, minimizing the pause location for the ME, and eliminating the hotspot area near the BS. Below are the details of our objectives:

- To propose and design an enhanced data gathering path algorithm that shortened the tour length of ME to a certain level by visiting some selected sensors and avoiding visiting each one separately. This predetermined path of mobile data gathering in WSNs based on network layout minimizes the data gathering latency and maintains the energy consumption at certain level.
- To propose and develop an algorithm which will be able to provide intelligent data collections capturing the unique nature of nodes. The algorithm should be able to segment the deployment field and forward tailored collection to the BS with respect to, shortens the tour length of ME, minimizing both the data gathering latency and energy consumption, and eliminating the hotspot area near the BS.
- To develop an adaptive algorithm which provides a solution based on the application requirements which ensure a trade-off between mobile data gathering latency and the power consumption during data gathering process.
- To propose and develop minimal constraint rendezvous node algorithm. The algorithm is able to select some certain node as rendezvous node for the ME. The selection is based on the location of rendezvous node, number of affiliation nodes, and relay hop bound. Thus, minimizes the number of pause location for the ME is ensured which implies a shortened tour length.

1.5 Research Scope

This research focuses on the data gathering techniques as a main task in WSNs. It concentrates on two types of data gathering, the multi-hop data gathering and the mobile data gathering. More focus is given to minimize the tour length of mobile data collector which implies the minimization of data gathering latency. In addition, the power consumption at each sensor node during the forwarding data packets to the BS due to the communication process is studied too. Thus, minimizing tour length, enhancing the power consumption, and reducing the data gathering latency are the targets of this work.

Applying an appropriate data gathering scheme result in enhancing the network lifetime (Zhao and Yang, 2012). Thus, the use of ME as a data collector traverses the deployment field gathering the sensed data leads to minimize the power consumption. In addition, due to low mobile velocity the local data aggregation based multi-hop minimize the data gathering latency by avoiding visiting each sensor node separately. The proposed schemes based on mobile and multi-hop data gathering are tested under the various environments of WSNs. These schemes enhance the data gathering process by balancing the power consumption and data gathering latency.

1.6 Research Contributions

The use of mobile element of gathering data proves to be an enhanced method that could save more energy at each sensor node due to short communication range. On the other hand, multi-hop data gathering proves to be a faster way to deliver the data to the BS. However, even with minimized latency the power consumption at each sensor node drain faster due to serving other nodes during a data transmission stage. In this research, mobile element and multi-hop data gathering are jointly considered. Four algorithms are proposed to enhance data gathering in terms of tour length, latency and energy consumptions. The significance of this work stems from the challenge of design a data gathering scheme that minimize the energy consumption, minimize the tour length of mobile element, and minimize the data gathering latency.

1.7 Thesis Organization

This thesis consists of eight chapters. Chapter two presents and discusses in details the related work of mobile data gathering as well as the multi-hop data gathering. Chapter three discusses and presents the details of research methodology which encompasses the performance analysis tool in the area of WSNs, the developed Discrete Event Simulator (DES) and its related components. A detailed discussion on Mobile Data Gathering based Network Layout (MDG-NL) algorithm to minimize the latency of ME is presented in Chapter four. Chapter five presents Zonal Data Gathering based Multi-hop and Mobile Element (ZDG-MME) algorithm. It shows and discusses the ability to segment the deployment field into two divisions and assign appropriate data gathering scheme to each division which enhance the power consumption. Chapter six presents the adaptive segmentation of the deployment area which based on the application requirements. Chapter seven presents the minimal constrained rendezvous node algorithm. The algorithm is searched the minimum pause locations for the ME. Chapter eight concludes the work and state the recommendation of promising directions for the future research.

REFERENCES

Abbasi, A. and Younis, M. (2007), 'A survey on clustering algorithms for wireless sensor networks', *Computer communications* **30**(14), 2826–2841.

Akhondi, M. R., Talevski, A., Carlsen, S. and Petersen, S. (2010), Applications of wireless sensor networks in the oil, gas and resources industries, *in* '24th IEEE International Conference on Advanced Information Networking and Applications (AINA), '10', pp. 941–948.

Akshay, N., Kumar, M., Harish, B. and Dhanorkar, S. (2010), An efficient approach for sensor deployments in wireless sensor network, *in* 'International Conference on Emerging Trends in Robotics and Communication Technologies (INTERACT)', pp. 350–355.

Akyildiz, I., Su, W., Sankarasubramaniam, Y. and Cayirci, E. (2002), 'Wireless sensor networks: a survey', *Computer networks* **38**(4), 393–422.

Alemdar, H. and Ersoy, C. (2010), 'Wireless sensor networks for healthcare: A survey', *Computer Networks* **54**(15), 2688 – 2710.

Almi'ani, K., Viglas, A. and Libman, L. (2010), Mobile element path planning for time-constrained data gathering in wireless sensor networks, *in* '24th IEEE International Conference on Advanced Information Networking and Applications (AINA), '10', pp. 843 –850.

Anastasi, G., Conti, M., Di Francesco, M. and Passarella, A. (2006), An adaptive and low-latency power management protocol for wireless sensor networks, *in* 'Proceedings of the 4th ACM international workshop on Mobility management and wireless access', pp. 67–74.

Balci, O. (1994), 'Validation, verification, and testing techniques throughout the life cycle of a simulation study', *Annals of Operations Research* **53**(1), 121–173.

Balci, O. (1995), Principles and techniques of simulation validation, verification, and testing, *in* 'Simulation Conference Proceedings, '95. Winter', pp. 147–154.

Bandyopadhyay, S., Tian, Q. and Coyle, E. (2005), 'Spatio-temporal sampling rates and energy efficiency in wireless sensor networks', *IEEE/ACM Transactions on Networking* **13**(6), 1339 – 1352.

Becker, M., Wenning, B.-L., Görg, C., Jedermann, R. and Timm-Giel, A. (2010), Logistic applications with wireless sensor networks, *in* 'Proceedings of the 6th Workshop on Hot Topics in Embedded Networked Sensors', p. 6.

Bencini, L., Di Palma, D., Collodi, G., Manes, A. and Manes, G. (2010), 'Wireless sensor networks for on-field agricultural management process', *Wireless Sensor Networks: Application-Centric Design Book, INTECH Open Access Publisher* pp. 1–18.

Bhattacharyya, D., Kim, T.-h. and Pal, S. (2010), 'A comparative study of wireless sensor networks and their routing protocols', *Sensors* **10**(12), 10506–10523.

Bi, Y., Li, N. and Sun, L. (2007), 'Dar: An energy-balanced data-gathering scheme for wireless sensor networks', *Computer Communications* **30**(14), 2812 – 2825.

Bi, Y., Niu, J., Sun, L., Huangfu, W. and Sun, Y. (2007), Moving schemes for mobile sinks in wireless sensor networks, *in* 'IEEE International Performance, Computing, and Communications Conference, IPCCC '07', pp. 101–108.

Bista, R., Kim, Y.-K., Choi, Y.-H. and Chang, J.-W. (2009), A new energy-balanced data aggregation scheme in wireless sensor networks, *in* 'International Conference on Computational Science and Engineering, CSE '09', Vol. 2, pp. 558 –563.

Bormann, I. (2012), 'Digitizeit version 1.5. 8b'.
URL: *http://www.digitizeit.de/, Accessed 12 Nov 2012*

Bouabdellah, K., Noureddine, H. and Larbi, S. (2013), 'Using wireless sensor networks for reliable forest fires detection', *Procedia Computer Science* **19**, 794–801.

Boukerche, A. and Pazzi, R. (2007), Lightweight mobile data gathering strategy for wireless sensor networks, *in* '9th IFIP International Conference on Mobile Wireless Communications Networks', pp. 151–155.

Boyinbode, O., Le, H., Mbogho, A., Takizawa, M. and Poliah, R. (2010), A survey on clustering algorithms for wireless sensor networks, *in* '13th International Conference on Network-Based Information Systems (NBiS)', pp. 358–364.

Buratti, C., Conti, A., Dardari, D. and Verdone, R. (2009), 'An overview on wireless sensor networks technology and evolution', *Sensors* **9**(9), 6869–6896.

Chang, Y.-J., Chen, C.-H., Lin, L.-F., Han, R.-P., Huang, W.-T. and Lee, G.-C. (2012), 'Wireless sensor networks for vital signs monitoring: Application in a nursing home', *International Journal of Distributed Sensor Networks* **2012**.

Chatterjee, P. and Das, N. (2009), A cross-layer distributed tdma scheduling for data gathering with minimum latency in wireless sensor networks, *in* '1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology, Wireless VITAE '09', pp. 813–817.

Chehri, A. and Mouftah, H. T. (2012), 'Energy efficiency adaptation for multihop routing in wireless sensor networks', *Journal of Computer Networks and Communications* **2012**.

Chen, D., Liu, Z., Wang, L., Dou, M., Chen, J. and Li, H. (2013), 'Natural disaster monitoring with wireless sensor networks: A case study of data-intensive applications upon low-cost scalable systems', *Mobile Networks and Applications* **18**(5), 651–663.

Chowdhury, S. and Giri, C. (2013), Data collection point based mobile data gathering scheme with relay hop constraint, *in* 'International Conference on Advances in Computing, Communications and Informatics (ICACCI)', pp. 282–287.

Cormen, T., Leiserson, C., Rivest, R. and Stein, C. (2001), *Introduction to algorithms*, MIT press.

CPLEX package (2012).
URL: *http://www.ilog.com/products/cplex/, Accessed 12 Nov 2012*

Dantu, K., Rahimi, M., Shah, H., Babel, S., Dhariwal, A. and Sukhatme, G. (2005), Robomote: enabling mobility in sensor networks, *in* 'Fourth International Symposium on Information Processing in Sensor Networks, IPSN '05', pp. 404–409.

Dasgupta, K., Kalpakis, K. and Namjoshi, P. (2003), An efficient clustering-based heuristic for data gathering and aggregation in sensor networks, *in* 'IEEE Wireless Communications and Networking, WCNC '03', Vol. 3, pp. 1948–1953.

Deosarkar, B., Yadav, N. and Yadav, R. (2008), Clusterhead selection in clustering algorithms for wireless sensor networks: A survey, *in* 'International Conference on Computing, Communication and Networking, ICCCn '08', pp. 1–8.

Di Francesco, M., Das, S. K. and Anastasi, G. (2011), 'Data collection in wireless sensor networks with mobile elements: A survey', *ACM Transactions on Sensor Networks (TOSN)* **8**(1), 7.

Díaz, A., Sanchez, P., Sancho, J. and Rico, J. (2013), Wireless sensor network simulation for security and performance analysis, *in* 'Design, Automation & Test in Europe Conference & Exhibition (DATE), '13', pp. 432–435.

Ding, Z. and Yamauchi, N. (2010), An improvement of energy efficient multi-hop time synchronization algorithm in wireless sensor network, *in* 'IEEE International Conference on Wireless Communications, Networking and Information Security (WCNIS '10)', pp. 116 –120.

Egea-Lopez, E., Vales-Alonso, J., Martinez-Sala, A., Pavon-Marino, P. and García-Haro, J. (2005), Simulation tools for wireless sensor networks, *in* 'Proceedings of the International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS '05)', p. 24.

Farooq, M., Dogar, A. and Shah, G. (2010), Mr-leach: multi-hop routing with low energy adaptive clustering hierarchy, *in* 'Fourth International Conference on Sensor Technologies and Applications (SENSORCOMM)', pp. 262–268.

Fasolo, E., Rossi, M., Widmer, J. and Zorzi, M. (2007), 'In-network aggregation techniques for wireless sensor networks: a survey', *IEEE Wireless Communications* **14**(2), 70–87.

Fernandez, M., Wahle, S. and Magedanz, T. (2012), A new approach to ngn evaluation integrating simulation and testbed methodology, *in* 'ICN '12, The Eleventh International Conference on Networks', pp. 22–27.

Gallais, A. and Carle, J. (2007), An adaptive localized algorithm for multiple sensor area coverage, *in* '21st International Conference on Advanced Information Networking and Applications, AINA '07', pp. 525–532.

Garcia-Sanchez, A.-J., Garcia-Sanchez, F., Losilla, F., Kulakowski, P., Garcia-Haro, J., Rodríguez, A., López-Bao, J.-V. and Palomares, F. (2010), 'Wireless sensor network deployment for monitoring wildlife passages', *Sensors* **10**(8), 7236–7262.

Gavish, B. (1983), 'Formulations and algorithms for the capacitated minimal directed tree problem', *J. ACM* **30**(1), 118–132.

Goyeneche, M., Villadangos, J. and Astrain, J. (2011), S-dawin: A self-adapted distributed algorithm for data gathering in wireless sensor networks, *in* 'IEEE Sensors, '11', pp. 1201–1204.

Handy, M., Haase, M. and Timmermann, D. (2002), Low energy adaptive clustering hierarchy with deterministic cluster-head selection, *in* '4th International Workshop on Mobile and Wireless Communications Network', pp. 368–372.

Heinzelman, W., Chandrakasan, A. and Balakrishnan, H. (2000), Energy-efficient communication protocol for wireless microsensor networks, *in* 'Proceedings of the 33rd Annual Hawaii International Conference on System Sciences', pp. 10–pp.

Heinzelman, W., Chandrakasan, A. and Balakrishnan, H. (2002), 'An application-specific protocol architecture for wireless microsensor networks', *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS* **1**(4), 660–670.

Hoang, D., Yadav, P., Kumar, R. and Panda, S. (2010), A robust harmony search algorithm based clustering protocol for wireless sensor networks, *in* 'IEEE International Conference on Communications Workshops (ICC)', pp. 1–5.

Howard, A., Matarić, M. J. and Sukhatme, G. S. (2002), 'An incremental self-deployment algorithm for mobile sensor networks', *Autonomous Robots* **13**(2), 113–126.

Huang, Y.-F., Yang, L.-C. and Lin, J.-Y. (2012), An efficient energy data gathering based on grid-chain for wireless sensor networks, *in* '4th International Conference on Awareness Science and Technology (iCAST), '12', pp. 78–82.

Huang, Y.-M., Hsieh, M.-Y., Chao, H.-C., Hung, S.-H. and Park, J. H. (2009), ‘Pervasive, secure access to a hierarchical sensor-based healthcare monitoring architecture in wireless heterogeneous networks’, *IEEE Journal on Selected Areas in Communications* **27**(4), 400–411.

Hwang, S.-F., Lu, K.-H., Chang, H.-N. and Dow, C.-R. (2007), An efficient grid-based data gathering scheme in wireless sensor networks, *in* ‘Ubiquitous Intelligence and Computing’, pp. 545–556.

Jang, U., Lee, S. and Yoo, S. (2012), ‘Optimal wake-up scheduling of data gathering trees for wireless sensor networks’, *Journal of Parallel and Distributed Computing* **72**(4), 536 – 546.

Jea, D., Somasundara, A. and Srivastava, M. (2005), Multiple controlled mobile elements (data mules) for data collection in sensor networks, *in* ‘Proceedings of the First IEEE international conference on Distributed Computing in Sensor Systems’, DCOSS’05, pp. 244–257.

Jiang, C., Shi, W., TANG, X. et al. (2010), ‘Energy-balanced unequal clustering protocol for wireless sensor networks’, *The Journal of China Universities of Posts and Telecommunications* **17**(4), 94–99.

Jiang, C., Yuan, D. and Zhao, Y. (2009), Towards clustering algorithms in wireless sensor networks-a survey, *in* ‘IEEE Wireless Communications and Networking Conference, WCNC ’09’, pp. 1–6.

Johnson, M., Healy, M., van de Ven, P., Hayes, M., Nelson, J., Newe, T. and Lewis, E. (2009), A comparative review of wireless sensor network mote technologies, *in* ‘IEEE Sensors, ’09’, pp. 1439–1442.

Kleijnen, J. (1995), ‘Verification and validation of simulation models’, *European Journal of Operational Research* **82**(1), 145–162.

Kumar, A. and Sivalingam, K. (2010), Energy-efficient mobile data collection in wireless sensor networks with delay reduction using wireless communication, *in* ‘Second International Conference on Communication Systems and Networks (COMSNETS), ’10’, pp. 1 –10.

Kumarawadu, P., Dechene, D., Luccini, M. and Sauer, A. (2008), Algorithms for node clustering in wireless sensor networks: A survey, *in* ‘4th International Conference on Information and Automation for Sustainability, ICIAFS ’08’, pp. 295–300.

Kurata, N., Spencer, B. F. and Ruiz-Sandoval, M. (2005), ‘Risk monitoring of buildings with wireless sensor networks’, *Structural Control and Health Monitoring* **12**(3-4), 315–327.

Law, A. (2009), How to build valid and credible simulation models, *in* ‘Proceedings of the ’09 Winter Simulation Conference (WSC),’, pp. 24–33.

Leow, W. L. and Pishro-Nik, H. (2007), Delay and energy tradeoff in multi-state wireless sensor networks, *in* 'IEEE Global Telecommunications Conference, GLOBECOM'07', pp. 1028–1032.

Li, X., Lu, K., Santoro, N., Simplot-Ryl, I., Stojmenovic, I. et al. (2008), Alternative data gathering schemes for wireless sensor networks, *in* 'Proceedings of International Conference on Relations, Orders and Graphs: Interaction with Computer Science (ROGICS)', pp. 577–586.

Lindsey, S. and Raghavendra, C. (2002), Pegasis: Power-efficient gathering in sensor information systems, *in* 'IEEE Aerospace conference proceedings, '02', Vol. 3, pp. 3–1125.

Linping, W., Wu, B., Zhen, C. and Zufeng, W. (2010), Improved algorithm of pegasis protocol introducing double cluster heads in wireless sensor network, *in* 'International Conference on Computer, Mechatronics, Control and Electronic Engineering (CMCE), '10', Vol. 1, pp. 148–151.

Liu, T. and Li, F. (2009), Power-efficient clustering routing protocol based on applications in wireless sensor network, *in* '5th International Conference on Wireless Communications, Networking and Mobile Computing, WiCom '09', pp. 1 –6.

Liu, W., Fan, J., Zhang, S. and Wang, X. (2013), Relay hop constrained rendezvous algorithm for mobile data gathering in wireless sensor networks, *in* 'Network and Parallel Computing', pp. 332–343.

Lotfinezhad, M., Liang, B. and Sousa, E. S. (2008), 'Adaptive cluster-based data collection in sensor networks with direct sink access', *IEEE Transactions on Mobile Computing* **7**(7), 884–897.

Luo, H., Luo, J. and Liu, Y. (2005), Energy efficient routing with adaptive data fusion in sensor networks, *in* 'Proceedings of the 2005 joint workshop on Foundations of mobile computing', pp. 80–88.

Ma, M. and Yang, Y. (2007), 'Sencar: an energy-efficient data gathering mechanism for large-scale multihop sensor networks', *IEEE Transactions on Parallel and Distributed Systems* **18**(10), 1476–1488.

Ma, M. and Yang, Y. (2008), Data gathering in wireless sensor networks with mobile collectors, *in* 'IEEE International Symposium on Parallel and Distributed Processing, IPDPS '08', pp. 1 –9.

Ma, M., Yang, Y. and Zhao, M. (2013), 'Tour planning for mobile data-gathering mechanisms in wireless sensor networks', *IEEE Transactions on Vehicular Technology* **62**(4), 1472–1483.

Madden, S., Franklin, M. J., Hellerstein, J. M. and Hong, W. (2002), 'Tag: A tiny aggregation service for ad-hoc sensor networks', *ACM SIGOPS Operating Systems Review* **36**(SI), 131–146.

Mahajan, S. and Mahotra, J. (2011), 'A novel chain based wireless data sensor network (ecbsn) technique', *International Journal of Computer Science and Telecommunications* **2**(8), 83–97.

Mainwaring, A., Culler, D., Polastre, J., Szewczyk, R. and Anderson, J. (2002), Wireless sensor networks for habitat monitoring, *in* 'Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications', pp. 88–97.

Manolakos, E. S., Logaras, E. and Paschos, F. (2010), Wireless sensor network application for fire hazard detection and monitoring, *in* 'Sensor Applications, Experimentation, and Logistics', pp. 1–15.

Marcelloni, F. and Vecchio, M. (2008), 'A simple algorithm for data compression in wireless sensor networks', *IEEE Communications Letters* **12**(6), 411–413.

Marta, M. and Cardei, M. (2008), Using sink mobility to increase wireless sensor networks lifetime, *in* 'International Symposium on a World of Wireless, Mobile and Multimedia Networks, WoWMoM '08', pp. 1–10.

Marta, M. and Cardei, M. (2009), 'Improved sensor network lifetime with multiple mobile sinks', *Pervasive and Mobile computing* **5**(5), 542–555.

Melli, S. (2011), K-target coverage & connectivity in wireless sensor network considering the angle coverage, *in* '3rd International Conference on Computer Research and Development (ICCRD), '11', Vol. 1, pp. 168–173.

Nouh, S., Abbass, R. A., El Seoud, D. A., Ali, N. A., Daoud, R. M., Amer, H. H. and ElSayed, H. M. (2010), Effect of node distributions on lifetime of wireless sensor networks, *in* 'IEEE International Symposium on Industrial Electronics (ISIE), '10', pp. 434–439.

Oh, Y.-H., Ning, P., Liu, Y. and Reiter, M. K. (2009), Authenticated data compression in delay tolerant wireless sensor networks, *in* 'Sixth International Conference on Networked Sensing Systems (INSS), '09', pp. 1–8.

Pazzi, R. and Boukerche, A. (2008), 'Mobile data collector strategy for delay-sensitive applications over wireless sensor networks', *Computer Communications* **31**(5), 1028–1039.

Petersen, S., Doyle, P., Vatland, S., Aasland, C., Andersen, T. and Sjong, D. (2007), Requirements, drivers and analysis of wireless sensor network solutions for the oil gas industry, *in* 'IEEE Conference on Emerging Technologies and Factory Automation, ETFA '07', pp. 219–226.

Pyun, S.-Y. and Cho, D.-H. (2010), Energy-efficient scheduling for multiple-target coverage in wireless sensor networks, *in* 'IEEE 71st Vehicular Technology Conference (VTC 2010-Spring)', pp. 1–5.

Ranganathan, A. and Berman, K. (2010), Dynamic state-based routing for load balancing and efficient data gathering in wireless sensor networks, *in* 'International Symposium on Collaborative Technologies and Systems (CTS), '10', pp. 103–112.

Rao, J. and Biswas, S. (2012), 'Analyzing multi-hop routing feasibility for sensor data harvesting using mobile sinks', *Journal of Parallel and Distributed Computing* **72**(6), 764–777.

Rastegarnia, A. and Solouk, V. (2011), Performance evaluation of castalia wireless sensor network simulator, *in* '34th International Conference on Telecommunications and Signal Processing (TSP), '11', pp. 111 –115.

Ren, F., Zhang, J., He, T., Lin, C. and Ren, S. (2011), 'Ebrp: Energy-balanced routing protocol for data gathering in wireless sensor networks', *IEEE Transactions on Parallel and Distributed Systems* **22**(12), 2108–2125.

Rooshenas, A., Rabiee, H. R., Movaghar, A. and Naderi, M. Y. (2010), Reducing the data transmission in wireless sensor networks using the principal component analysis, *in* 'Sixth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), '10', pp. 133–138.

Rudnicka, A. R. (2005), 'Essential medical statistics (2nd edn). betty r. kirkwood and jonathan ac sterne, blackwell science, oxford, 2003. no. of pages: 512. price:£ 22.95. isbn 0-86542-871-9', *Statistics in Medicine* **24**(5), 824–824.

Sacaleanu, D., Stoian, R. and Ofrim, D. (2011), An adaptive huffman algorithm for data compression in wireless sensor networks, *in* '10th International Symposium on Signals, Circuits and Systems (ISSCS), '11', pp. 1–4.

Sasaki, Y., Nakayama, H., Ansari, N., Nemoto, Y. and Kato, N. (2008), A new data gathering scheme based on set cover algorithm for mobile sinks in wsns, *in* 'IEEE Global Telecommunications Conference, IEEE GLOBECOM '08', pp. 1–5.

Shah, N., Desai, U., Das, I., Merchant, S. and Yadav, S. (2009), 'In-field wireless sensor network(wsn) for estimating evapotranspiration and leaf wetness', *International Agricultural Engineering Journal* **18**(3-4), 43–51.

Shah, R., Roy, S., Jain, S. and Brunette, W. (2003), 'Data mules: Modeling and analysis of a three-tier architecture for sparse sensor networks', *Ad Hoc Networks* **1**(2), 215–233.

Shebli, F., Dayoub, I., Rouvaen, J. et al. (2007), 'Minimizing energy consumption within wireless sensors network', *Ubiquitous Computing and Communication Journal (UBICC), Special Issue on Ubiquitous Sensor Networks* **2**, 19–24.

Shen, Y., Li, Y. and hua Zhu, Y. (2012), Constructing data gathering tree to maximize the lifetime of unreliable wireless sensor network under delay constraint, *in* '8th International Wireless Communications and Mobile Computing Conference (IWCMC), '12', pp. 100–105.

Sheu, J.-P., Sahoo, P. K., Su, C.-H. and Hu, W.-K. (2010), 'Efficient path planning and data gathering protocols for the wireless sensor network', *Computer Communications* **33**(3), 398 – 408.

Soua, R., Saidane, L. and Minet, P. (2010), Sensors deployment enhancement by a mobile robot in wireless sensor networks, *in* '2010 Ninth International Conference on Networks (ICN),', pp. 121–126.

Sreenan, C. J., Nawaz, S., Le, T. D. and Jha, S. (2006), On the sensitivity of sensor network simulations, *in* 'IEEE 63rd Vehicular Technology Conference, VTC '06-Spring', Vol. 3, pp. 1043–1047.

Sugihara, R. and Gupta, R. K. (2009), *Optimizing energy-latency trade-off in sensor networks with controlled mobility*, IEEE INFOCOM '09 proceedings.

Sun, L., Bi, Y. and Ma, J. (2006), A moving strategy for mobile sinks in wireless sensor networks, *in* '2nd IEEE Workshop on Wireless Mesh Networks, WiMesh '06', pp. 151–153.

Sun, Z., Zheng, Z., Chen, S. and Xu, S. (2010), An energy-effective clustering algorithm for multilevel energy heterogeneous wireless sensor networks, *in* '2nd International Conference on Advanced Computer Control (ICACC), '10', Vol. 3, pp. 168–172.

Sutar, S. H. (2012), 'Irrigation and fertilizer control for precision agriculture using wsn: energy efficient approach', *International Journal of Advances in Computing and Information Researches* **1**(1), 25–29.

Szewczyk, R., Osterweil, E., Polastre, J., Hamilton, M., Mainwaring, A. and Estrin, D. (2004), 'Habitat monitoring with sensor networks', *Communications of the ACM* **47**(6), 34–40.

Takruri, M., Rajasegarar, S., Challa, S., Leckie, C. and Palaniswami, M. (2011), 'Spatio-temporal modelling-based drift-aware wireless sensor networks', *IET Wireless Sensor Systems* **1**(2), 110–122.

Tarachand, A., Kumar, V., Raj, A., Kumar, A. and Jana, P. (2012), An energy efficient load balancing algorithm for cluster-based wireless sensor networks, *in* 'Annual IEEE India Conference (INDICON), '12', pp. 1250–1254.

Teixeira, I., De Rezende, J. F. and Pedroza, A. d. C. P. (2004), Wireless sensor network: Improving the network energy consumption, *in* 'XXI Simpósio Brasileiro de Telecomunicações-SBT'.

Upadhyayula, S. and Gupta, S. (2007), 'Spanning tree based algorithms for low latency and energy efficient data aggregation enhanced convergecast (dac) in wireless sensor networks', *Ad Hoc Networks* **5**(5), 626–648.

Vupputuri, S., Rachuri, K. K. and Murthy, C. S. R. (2010), 'Using mobile data collectors to improve network lifetime of wireless sensor networks with reliability constraints', *Journal of Parallel and Distributed Computing* **70**(7), 767 – 778.

Wang, C. and Ma, H. (2011), Data collection in wireless sensor networks by utilizing multiple mobile nodes, *in* 'Seventh International Conference on Mobile Ad-hoc and Sensor Networks (MSN), '11', pp. 83 –90.

Wang, D. and Ni, Y. (2012), Wireless sensor networks for earthquake early warning systems of railway lines, *in* 'Proceedings of the 1st International Workshop on High-Speed and Intercity Railways', pp. 417–426.

Wang, F. and Liu, J. (2011), 'Networked wireless sensor data collection: issues, challenges, and approaches', *IEEE Communications Surveys & Tutorials,* **13**(4), 673–687.

Wang, J., Kim, J.-U., Shu, L., Niu, Y. and Lee, S. (2010), 'A distance-based energy aware routing algorithm for wireless sensor networks', *Sensors* **10**(10), 9493–9511.

Weingartner, E., vom Lehn, H. and Wehrle, K. (2009), A performance comparison of recent network simulators, *in* 'IEEE International Conference on Communications, ICC '09', pp. 1 –5.

Wu, F.-J., Huang, C.-F. and Tseng, Y.-C. (2009), Data gathering by mobile mules in a spatially separated wireless sensor network, *in* 'Proceedings of the 2009 Tenth International Conference on Mobile Data Management: Systems, Services and Middleware', MDM '09, pp. 293–298.

Xing, G., Li, M., Wang, T., Jia, W. and Huang, J. (2012), 'Efficient rendezvous algorithms for mobility-enabled wireless sensor networks', *IEEE Transactions on Mobile Computing* **11**(1), 47 –60.

Xing, G., Wang, T., Xie, Z. and Jia, W. (2007), Rendezvous planning in mobility-assisted wireless sensor networks, *in* '28th IEEE International Real-Time Systems Symposium, RTSS '07', pp. 311–320.

Yan, X., Xi, J., Chicharo, J. and Yu, Y. (2008), An energy-aware multilevel clustering algorithm for wireless sensor networks, *in* 'International Conference on Intelligent Sensors, Sensor Networks and Information Processing, ISSNIP '08', pp. 387–392.

Yeh, L.-W., Wang, Y.-C. and Tseng, Y.-C. (2009), 'ipower: an energy conservation system for intelligent buildings by wireless sensor networks', *International Journal of Sensor Networks* **5**(1), 1–10.

Yi, S., Heo, J., Cho, Y. and Hong, J. (2007), 'Peach: Power-efficient and adaptive clustering hierarchy protocol for wireless sensor networks', *Computer communications* **30**(14), 2842–2852.

Yick, J., Mukherjee, B. and Ghosal, D. (2008), 'Wireless sensor network survey', *Computer Networks* **52**(12), 2292 – 2330.

Younis, O. and Fahmy, S. (2004), 'Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks', *IEEE Transactions on Mobile Computing* **3**(4), 366–379.

Yun, Y. and Xia, Y. (2010), 'Maximizing the lifetime of wireless sensor networks with mobile sink in delay-tolerant applications', *IEEE Transactions on Mobile Computing* **9**(9), 1308–1318.

Zhao, M. (2010), Design and Optimization on Mobile Data Gathering in Wireless Sensor Networks, PhD thesis, Stony Brook University.

Zhao, M., Ma, M. and Yang, Y. (2011), 'Efficient data gathering with mobile collectors and space-division multiple access technique in wireless sensor networks', *IEEE Transactions on Computers* **60**(3), 400 –417.

Zhao, M. and Yang, Y. (2012), 'Bounded relay hop mobile data gathering in wireless sensor networks', *IEEE Transactions on Computers* **61**(2), 265 –277.

Zou, S., Wang, W. and Wang, W. (2013), 'A routing algorithm on delay-tolerant of wireless sensor network based on the node selfishness', *EURASIP Journal on Wireless Communications and Networking* **2013**(1), 1–9.