

Data Gathering Using Mobile Elements In Wireless
Sensors Networks (WSNs)

((جمع البيانات عن طريق العناصر المتحركة في شبكات الاستشعار
اللاسلكية))

By

Khaled Mohammed AL-hasanat

401320022

Supervisor

Dr. Maamoun Khalid Ahmad

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Middle East University

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Authorization

I am Khaled Mohammed AL-hasanat, authorize **Middle East University (MEU)** to provide copies of my dissertation to the concerned libraries, organizations, and institutes upon request.

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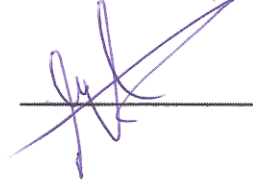
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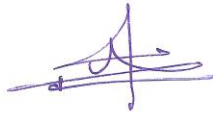
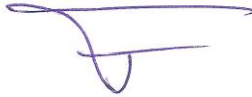


الاسم : خالد محمد سليمان الحسنات

التاريخ: 10/1/16

التوقيع: 

Thesis Committee Decision

This Thesis “Data Gathering Using Mobile Elements in Wireless Sensors Networks (WSNs)” was discussed and certified on 10-01-2016

Thesis Committee	Signature
Dr. Abdelrahman Abuarqoub	
Dr. Ahmad Kayed	
Dr. Mohammed alzamel	
Dr. Maamoun Khalid Ahmad (Supervisor)	

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Dedication

To my kindhearted Father

To spirit of my mother

To my wonderful wife ...Alaa

To my future daughter: Sara

To my brothers and my sisters

I dedicate this work.

Khaled

Table of Contents

Title	i
Authorization	ii
Thesis Committee Decision	iii
Acknowledgments	iv
Dedication	v
Table of Contents	vi
Abbreviations	ix
List of Figures	xi
List of Tables	xii
Abstract in English	xiv
Abstract in Arabic	xvi
Chapter One. Introduction	1
1.1. Overview	1
1.2. Low Energy Adaptive Clustering Hierarchy	3
1.3. Data Gathering in WSN without Using Mobile Element	3
1.4. Data Gathering in WSN Using Mobile Element	5
1.5. Problem Definition	6
1.6. Objectives	7
1.7. Motivation	7

1.8. Limitations	7
1.9. Contributions	8
1.10. Thesis Structure	8
Chapter Two. Literature Review and Related Works.....	9
2.1. Literature Review	9
2.1.1. Classify Mobility	9
2.1.2. Mobility Types of Mobile Sinks	11
2.1.2.1. Random Mobility	11
2.1.2. 2. Controlled Mobility	11
2.1.2.3. Predefined Mobility	11
2.2. Related Works	12
2.2.1. Rendezvous-Based Approach	12
2.2.2. Trajectory Mobile Element	14
2.2.3. Communication Model	16
2.2.4. Redundant Sensor Nodes	17
2.4.5. Multiple Mobile Elements	19
Chapter Three. The Proposed Methods	23
3.1. Overview	23
3.2. Section One: Single Mobile Element of Data Gathering.....	24
3.2.1. Genetic Algorithm	25
3.2.2. Problem Formulation	25

3.2.3. Proposed Algorithm	28
3.2.3.1. Path Refinement	31
3.3. Section Two: Multiple Mobile Elements of Data Gathering.....	32
3.3.1. Problem Formulation	34
3.3.2. Proposed Algorithm	35
Chapter Four. Results and Discussions	39
4.1. Simulation Tool	42
4.2. Section One: The Performance Evaluation of IPCR Algorithm	42
4.2.1. Simulation Scenario	43
4.2.2. Path Length of Mobile Element	44
4.2.3. The Number of Collection Points	46
4.2.4. Data Gathering Latency	49
4.2.5. Network Throughput	49
4.3. Section Two: The Performance Evaluation of CDCA Algorithm ...	50
4.3.1. Simulation Scenario	50
4.3.2. CDCA and ASA Comparison	53
4.3.2.1. Number of Mobile Elements	52
4.3.2.2. Load Balance on Mobile Element	53
4.3.2.3. Network Latency	54
Chapter Five. Conclusions and Future Works	59
References	61
Appendix	68

List of Abbreviations

ASA	Area Splitting Algorithm
BS	Base Station
CBDC	Connectivity Based Data Collection
CDCA	Collaborative Data Collection Algorithm
CH	Cluster Head
DCA	Direct Communication Area
FCM	Full Coverage Mobility
GA	Genetic Algorithm
HiCoDG	Hierarchical and Cooperative Data-Gathering
IGMM	Improved Gauss Markov Mobility
IPCR	Intersection Points of Communication Range
LEACH	Low Energy Adaptive Clustering Hierarchy
MASP	Maximum Amount Shortest Path
MBS	Mobile Base Station
MCA	Multi-hop Communication Area
MC	Mobile Collector
MCSC	Minimum Connected Sensor Cover
MDC	Mobile Data Collector
ME	Mobile Element
MILP	Mixed Integer Linear Programming
MIMO	Multiple Input Multiple Output
MPP	Multi-Path Planning

MR	Mobile Relay
PBS	Partitioning-Based Scheduling
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
RP s	Rendezvous Points
RSS	Received Signal Strength
SCD	Stop to Collected Data
SHM	Structural Health Monitoring
SISO	Single Input Single Output
SPT	Shortest Path Tree
TDMA	Time Division Multiple Access
TSP	Travel Sales-Man Problem
VC	Variation Coefficient
WSNs	Wireless Sensor Networks

List of Figures

Figure 1	Basic Structure of WSNs	4
Figure 2	Basic Structure of WSNs use Mobile Element,.....	5
Figure 3	ME-based data collection.....	13
Figure 4	An example of path-constrained mobile WSNs	15
Figure 5	An example of faulty node replacement by redundant node.....	18
Figure 6	Examples on Collection Points Determination	29
Figure 7	Flowchart of IPCR Algorithm.....	30
Figure 8	Examples on Sensor nodes distribution.....	32
Figure 9	Horizontal Division of the Network Area.....	37
Figure 10	Horizontal and Vertical Division of the Network Area	38
Figure 11	Startup Times of Mobile Elements.....	39
Figure 12	Flowchart of CDCA Algorithm.....	39
Figure 13	Path Lengths of Mobile element, (a) Increasing Number of Sensor Nodes, and (b) Increasing RSS Values.....	48
Figure 14	Number of Collection to IPCR, CBDC and TSP Algorithms,(a) Increasing the Number of Sensor Nodes, and (b) Increasing RSS Values.....	48
Figure 15	Data Gathering Latency of the IPCR, CBDC and TSP Algorithms, (a) Increasing the Number of Sensor Nodes, and (b) Increasing RSS Values.....	49
Figure 16	Network Throughput of the IPCR, CBDC and Algorithms, (a) Increasing the Number of Sensor Nodes, and (b) Increasing RSS Values.....	49
Figure 17	Path Constraints versus the Number of Mobile Elements for 20m, 40m, and 60m Communication Ranges of Mobile Elements.....	52

Figure 18	Path Constraints versus the Number of Mobile Elements for 100x100m ² , 500x500m ² and 1000x1000m ² Network Areas.	52
Figure 19	Path Constraint and Number of Mobile Elements Based on τ values.....	52
Figure 20	The Number of Mobile Elements as a Function of (a) Increasing Network Areas, and (b) Increasing Path Constraints of the Mobile Elements....	55
Figure 21	Variation Coefficient (VC), (a) Increasing Network Area, (b) Increasing Number of Sensor Nodes, (c) Increasing Path Constraints.....	57
Figure 22	Network Latency, (a) Increasing Network Area, (b) Increasing Number of Sensor Nodes, and (c) Increasing the Path Constraint.....	57

List of Tables

Table 1	Comparison of Mobility-Based Communication.....	10
Table 2	The Notations of IPCR.....	26
Table 3	The Notations of CDCA.....	35
Table 4	Simulation Parameters of IPCR	43
Table 5	Typical RSS Sensitivity Values (RSS_{th}), (D_{th}) and the Connectivity.....	45
Table 6	Simulation Parameters of CDCA.....	51

Data Gathering Using Mobile Elements In Wireless Sensors Networks (WSNs)

Prepared by khaled Mohammed AL-hasanat

Supervised by Dr. Maamoun Khalid Ahmad

Abstract

Wireless Sensor Networks (WSNs) have been emerged in many important aspects in the real world, such as industry, agriculture, and military applications. Since the main challenge that WSNs facing is the energy consumption, it is necessary to investigate the suitability of using mobile elements for data collection in these networks.

A data collection is the process of collecting data from sensor nodes and transmitting these data to the sink node or base station. One of the effective approaches is the gathering of data in clustering node as cluster head and sends it to the base station. This approach accomplished utilization of the available power resources.

In fact, using mobile elements to gathering data in WSN leads to extend the life time of the network through reducing energy consumption.

In this thesis, we introduce two algorithms in order to address the power consumption and network latency problem of data gathering in WSNs. The first algorithm, a new algorithm, called Intersection Point in Communication Ranges (IPCR) is proposed. IPCR uses communication range for each sensor node to identify the location of collection points (CP) and then applying the genetic algorithm of these points to identify the shortest

path. This method attempts to obtain the best path of the mobile element such that the data gathering latency is minimized.

The second algorithm called Collaborative Data Collection Algorithm (CDCA) is proposed. In this Algorithm, multiple mobile elements used to collect data from sensor nodes through predetermined path. A considerable reduction of the network latency and the number of mobile elements is achieved using CDCA as compared to other related Algorithm.

Keywords: Mobile Elements, Intersection Point, Energy Consumption, Collaborative Algorithm.

جمع البيانات عن طريق العناصر المتحركة في شبكات الاستشعار اللاسلكية

إعداد الطالب خالد محمد سليمان الحسنات

إشراف الدكتور مأمون خالد أحمد

ملخص

قد ظهرت شبكات الاستشعار اللاسلكية في العديد من الجوانب الهامة في العالم الحقيقي، مثل الصناعة، والزراعة، والتطبيقات العسكرية. كما أن التحدي الرئيسي الذي تواجهه هو استهلاك الطاقة، فمن الضروري معرفة مدى ملائمة استخدام العناصر المتنقلة في جمع البيانات في هذا النوع من الشبكات.

جمع البيانات هي عملية جمع البيانات من العقد استشعار ونقل هذه البيانات إلى المحطة الأساسية. واحد الطرق الفعالة، جمع البيانات في نقطة تجميع رئيسية ثم إرسالها إلى المحطة الأساسية، ومع هذه الطريقة كان هنالك استفاضة من موارد الطاقة المتاحة.

ايضا إضافة عناصر متنقلة لجمع البيانات يؤدي إلى تمديد تشغيل الشبكة من خلال الحد من استهلاك الطاقة.

في هذه الأطروحة، قدمنا طريقتين لجمع البيانات من أجل معالجة استهلاك الطاقة ومشكلة تاخر وصول المعلومات الى المحطة الاساسية , وتسمى الاولى نقاط التقاط لنطاق الاتصال , حيث تستخدم نطاق الاتصالات لتحديد نقاط تجميع ثم تطبيق الخوارزمية الجينية .يحاول هذا الأسلوب للحصول على أفضل مسار للعنصر المحمول بحيث اقل وقت لوصل المعلومات للمحطات الاساسية.

يسمى المقترح الثاني الخوارزمية التعاونية لجمع البيانات, وهذه التقنية تعتمد على اكثر من عنصر متحرك يستخدم لجمع البيانات من أجهزة الاستشعار من خلال التحرك في مسار محدد مسبقا. ويتحقق من هذه التقنية خفض كبير لوقت تاخر وصل البيانات الى المحطات الاساسية وايضا خفض عدد العناصر المستخدمة مقارنة مع التقنيات الأخرى ذات العلاقة.

الكلمات المفتاحية: العناصر المتحركة, نقاط التقاطع, استهلاك الطاقة, الخوارزمية التعاونية.

CHAPTER ONE

Introduction

1.1. Overview

Recent technologies in wireless communication and embedded systems have led to develop least-power consumption, less cost and several different uses sensor nodes referred to as Wireless Sensor Networks (WSN). For the purpose of identification of physical situation, communication and manipulation, a sensor node will be used which is an electronic device. The networks of sensor comprise of vast amount of sensor nodes, i.e. it is responsible for processing of data's, sensing the networks in addition to communication between each other (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002).

More recently, WSNs are considered for several applications such as War field observation, territory surveillance, traffic supervising and security purpose. However, of sensor nodes with small sizes suffer from problems like restricted processing, capacity of communication and storage. More importantly, such devices suffer from fixed power supply, as they are usually battery-powered, and difficult to recharge or exchange in the test areas that often in remote or inaccessible locations such disaster prevention. Since these nodes consume most of their energy resources when communicating with each other, energy conservative policy represents an essential challenge while designing and maintaining WSNs, which is critical for prolonging network lifetime (Ekici, Gu, & Bozdog, 2006).

By literature survey, several of techniques have been studied in order to achieve this goal. Accordingly, data gathering can be accomplished using either the traditional routing algorithms (Xing, Li, Wang, Jia, & Huang, 2012) (Tang, Wang, Geng, Zheng, & Kim,

2012) or mobile collection techniques (Al-Hasanat, Matrouk, Alasha'ary, & Alqadi, 2014) (Shangguan, Mai, Du, He, & Liu, 2011). With the former approach, multi-hop communication is needed to disseminate data along the path from source to the sink node. With this approach, additional burdens on intermediate nodes are incurred which, as a result, increase the power utilization of these nodes of sensor and therefore limits overall life span of the network. Several methods in this context are also proposed, which depend on hierarchical clustering method; for example. Low Energy Adaptive Clustering Hierarchy (LEACH) (Heinzelman, Chandrakasan & Balakrishnan, 2000). Power Efficient Gathering in Sensor Information Systems (PEGSIS) (Lindsey & Raghavendra, 2002). Although with these methods and protocols the performance of WSN is improved, they still encounter the problem of limited network lifetimes.

Alternatively, using mobile collector for data gathering is reduces the nodes overhead imposed by routing algorithms in addition to increase network lifetime of sensor nodes significantly (Somasundara, Ramamurthy & Srivastava, 2004). Since data gathering using mobile collectors represents a suitable solution for many applications. In fact, using mobile collectors for data gathering experiences two main problems. The first problem is represented by the latency (defined as the time needed until the mobile element completes one collection round) induced by the mobile collector during the data collection phase, since it is required to visit all nodes and gather each sensor data. This is usually restricted by a deadline imposed by the application being considered. The second problem is the path length constraint, which is due to the power recharging cycle of the mobile collector. The second problem could be neglected where using machine to control mobile elements

movement such as vehicular ad hoc network (VANET) (Xing, Li, Wang, Jia, & Huang, 2012).

The network of Wireless sensors comprises of following types of nodes (Ramesh & Somasundaram, 2011).

- Normal Sensor nodes: able to execute some process, collection of information and for the purpose of communication with the neighbor nodes.
- Base Station or Sink: aggregate data that send by sensor nodes and where end user can interact directly or remote.
- Cluster Head: It will gather the data from the group of nodes and transferring to sink node.

1.2. Low Energy Adaptive Clustering Hierarchy

LEACH projected by Heinzelman et al (2000), utilizes hierarchical routing method which is used to enhance a wireless sensor network's lifespan. The wireless network is divided into groups or clusters, where the clusters consist of cluster head. The process of data collection and transferring of data to sink node by multi-hop communication is performed by cluster head. The LEACH is one of the most famous data routing protocol, but do not depends the mobile elements to gathering data from sensor nodes.

1.3. Data Gathering in WSN without Using Mobile Element

The main aim of WSN is collection of sensor node's data and transferring of data to base station in which the destination of user to interact. Whereas, sensor nodes are usually deployed sparsely in the network field, the transmission power must be increased so that sensor nodes may cooperate with another node. Increasing the transmission power of sensor nodes certainly results in an increased shortage in the energy resources, and in turn, reduce

lifetime of sensor nodes (Kaurav & Ghosh, 2012). In order to reduce the transmission power, many sensor nodes can be included in the network, whereas it will lead to the issue of increment in the network cost. Nevertheless, multiple-hop communications among sensor nodes result in a non-uniform energy consumption (Ekici, Gu & Bozdog, 2006), (Somasundara, Ramamoorthy & Srivastava, 2007), (Xing et al, 2012). The network function will fail if the nodes around the sink node are run out of energy. However multiple-hop data transformation is better to saving the energy than increasing power consumed for transmission of nodes of sensors to transfer data for sink node. In order to distribute the networks energy consumption, clustering approach is utilized (Khan, Gansterer & Haring, 2013). Therefore, the network is divided into groups or clusters, where the clusters consist of cluster head. The process of data collection and transferring of data to sink node by multi-hop communication is performed by cluster head. This method improves the lifespan of network but the issue is, if the nodes near the sink nodes were run-out of energy earlier than another node still persists. (Zhang, Ma & Yang, 2008).

The following figure illustrates the movement of data starting sensor nodes until arrive the Base Station (BS) in stationary WSNs.

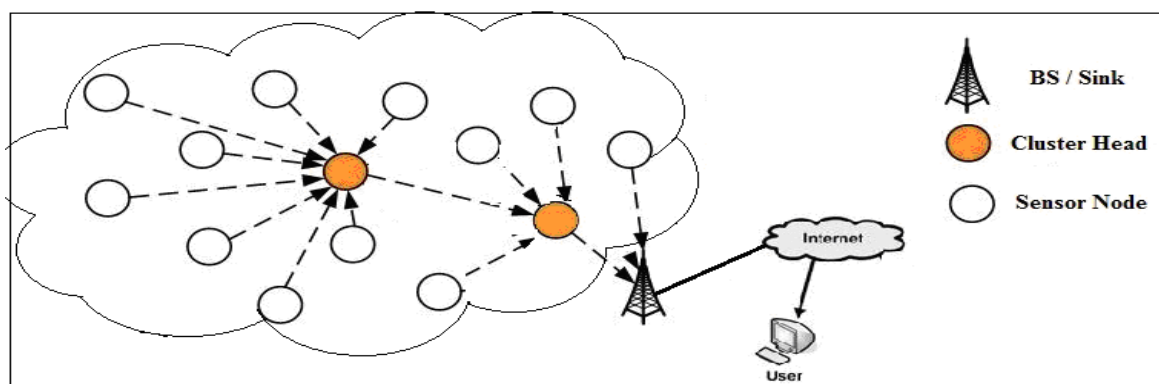


Figure 1: Basic Structure of WSNs

1.4. Data Gathering in WSN Using Mobile Element

Use mobile element to solve some problems that existing in stationary structure of WSN (Khan, Gansterer & Haring, 2013). Mobile part is utilized in WSNs for collection of data from sensor nodes and transfer to on behalf of the sensors themselves before buffer overflow, some mobile element has limited memory therefore the mobile element is capable of collection of data from limited number of nodes of sensors (Somasundara, Ramamurthy & Srivastava, 2004). The data generation rate of sensor nodes will differ, so that the mobile element will be considered to call the nodes having huge rate of generation more recurrently. Utilizing the mobile element will improve the lifespan of network by neglecting multiple-hop data communication (Ekici, Gu & Bozdog, 2006) (Norman, Joseph & Roja, 2010). In addition, simplifying the integration of these mobile elements into WSNs would make it feasible for some applications, such as soldiers in battlefield (Gao, Zhang & Das, 2011). Figure 2 illustrates a mobile element gathering data from sensor nodes that exist in communication range and transferred data to base station (BS).

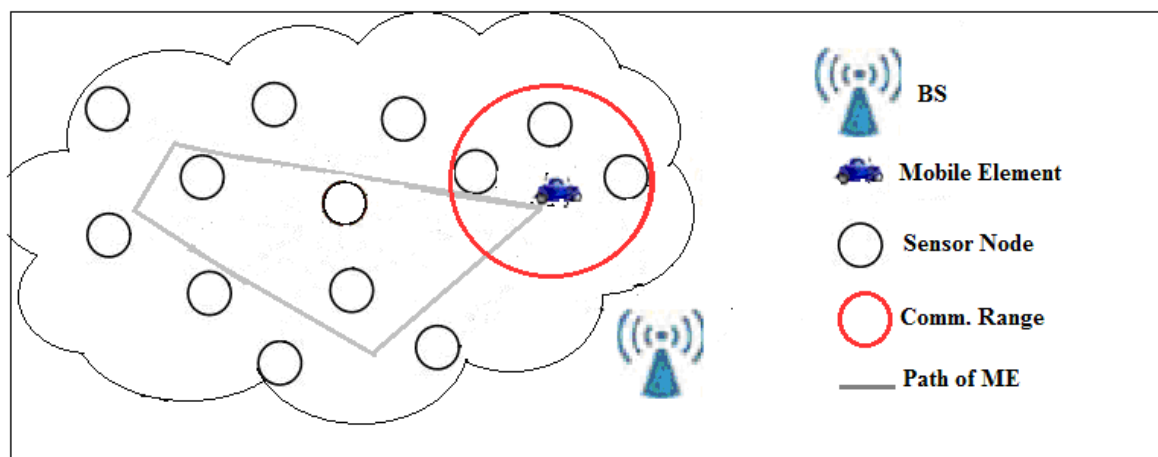


Figure 2: Basic Structure of WSNs use Mobile Element

1.5. Problem Definition

Wireless Sensor Networks (WSNs) have limitations such as restricted power source, narrow bandwidth for communication and restricted power calculation. The data observed by the sensor nodes require to be communicated to Base Station (BS) where the processing of data is performed. The available approaches use the Multiple-hop routing of data to Base Station, where several nodes that send data to Base Station. This will lead to reducing the network lifespan and decrease the life of the battery for sensor nodes that close to base station. Design of well-organized technique to enhance the lifespan of network will make use of Mobile Element (ME). The mobile elements operate as transporter machine that move around the sensing field for collection of data from the sensor nodes and communicating to base station.

There are many studies that suggest solutions using mobile elements. This research will focus to reduce the energy consumption and minimize the data delivery latency, through improve the movement of mobile element to gathering data in WSNs.

This research aims to answer the following questions:

A- What is the optimal path that satisfies the followings?

- i- Covered all sensor nodes given their locations and they are in communicating range.
- ii- Minimum latency deadline imposed by the application being considered.
- iii- Minimum tour length of a mobile element that avoid the use of multi-hop communication.

B- Will the optimal path achieved decrease the energy consumption of sensor nodes? And prolong the network lifetime?

C- Does the optimal path achieved improve the performance of WSN?

1.6. Objectives

This study addresses the problem of collection of data with mobile element in an attempt for the following objectives:

A- Investigate the optimal path that satisfies the following:

- iv- All sensor nodes will be covered given node's locations and communication range.
- v- Ensuring the minimum possible latency that match the latency deadline imposed by the application being considered.
- vi- Minimizing the tour length of a mobile element while avoiding the use of multi-hop communication

B- Based on the optimal path achieved, the energy consumption of sensor nodes will be minimized which in turn will prolong the network lifetime.

D- Improve the performance of WSN via increasing its throughput while keeping energy consumption as minimum as possible.

1.7. Motivation

As WSNs have been emerged in many important aspects of the real world, such as industry, agriculture and military, it is necessary to further investigate its usability for using mobile elements for data collection in WSN. Since the main problem that WSNs facing is the energy consumption, the ultimate aim of energy-efficient gathering technique is to maximize the lifespan of sensor nodes. In this thesis, therefore, gathering technique with mobile element will be framed to sketch the best path of the mobile element, so that the consumption of energy is decreased.

1.8. Limitations

The constraints of gathering of data considered throughout this thesis are as follows. The first one is the buffer size of the mobile elements. The second one is represented by the data collection latency associated with low speed mobile element. In fact, data gathering

with single mobile element leads delay the data collection phase and sometimes exceed the time deadline. However, using multiple mobile elements is resolved this problem in spite of the additional network cost required in this case. Moreover, adopting data gathering within environment of inaccessible areas is a challenge. However, it is worth mentioning that this research covers the applications where sensor fields are accessible by mobile element.

1.9. Contributions

The main contributions of this work are:

- A novel approach, referred to Intersection Points of Communication Range Algorithm that concentrate on lifespan of network maximization and network latency reduction is planned. The novel method implemented the idea of collection points that allows the mobile element to visit these points instead of visiting individual sensor and so that the utilization of energy of the sensor nodes is appreciably enhanced.
- Energy and load balancing algorithm, known as Collaborative Data Collocation Algorithm, with several mobile elements is developed. By this approach, the workload stability between the mobile elements is observed and so the latency in gathering of data is decreased.

1.10. Thesis Structure

The remaining part of this work is explores as follows. The Chapter 2 describes the theme of the work by exhibiting the basic ideas of wireless sensor networks. Chapter 3 shows the proposed methods for gathering of data in wireless sensor networks, results and discussed in fourth and fifth chapters, finishing part of the proposed work are offered in this report and the upcoming mechanism were recommended.

CHAPTER TWO

Literature Review and Related Works

2.1. Literature Review

In order to decrease the consumption of energy of sensor nodes, by decreasing the multiple-hop data transferring, the integration of Mobile devices is done in the WSN. In latest years developed many methods that utilize the flexibility for gathering of data in WSN. These methods can be classifying based on the property of sink mobility and the wireless communications technique for transfer of data.

2.1.1. Classify Mobility

Ekici, E et al (2006) classified the mobility in collection of data in WSN are as follows:

- **Mobile base station (MBS)-based solutions:** Goal is to balance the energy of network by changing the position of mobile element during operation time and send the gathered data by sensors to MBS with no extensive period buffering. In (Mollanejad, Khanli & Zeynali, 2010) proposed a dynamic optimum method to save energy through replacement of base. Where the base station changes its location each round depends on less residual energy of sensor nodes.
- **Mobile data collector (MDC)-based solutions:** Mobile data collector in which the mobile elements that move around the network and gather the buffered data through single-hop from the sensors. (Kumar & Sivalingam, 2010) proposed a novel method for mobile data gathering, which includes

two techniques to decrease data latency. In the beginning, the RCC method is to identify the collection of points that stop for the Mobile collector. Second, utilization of vast range in wireless communication between the sink for transmitting buffered data and mobile collector.

- **Rendezvous-based solutions:** In this, the conclusion is a mixture method in which sensor transmits the information to a rendezvous points by utilizing the multiple-hops forwarding. Data stay behind there to buffered where it to be uploaded to the mobile machine. This method integrates between using multi-hops forwarding and mobile data collector. Xing. G.(2012) proposed a new method depend on rendezvous points, in which several nodes act as RPs to gather and buffer data from nodes of source, up to it has been uploaded to the component of mobile when it reaches the destination.

The following table illustrates the comparison of mobility based communication to those classifications

Table 1: Comparison of Mobility-Based Communication (Bojkovic, Z., & Bakmaz, B., 2008)

Class	Mobile base station	Mobile data collector	Rendezvous
Multi-hop communication	Yes	No	Yes
Long-term buffering	No	Yes	Yes
Mobility	Controlled	Random, predictable, controlled	Controlled
Message latency	Lo	High, medium	Medium
Platform mobility	Low to very high	High, medium	Medium, high
Energy consumption	High	Low	Medium, low

2.1.2. Mobility Types of Mobile collector

A mobile element may move around the network utilize any one of the following methods (Ekici, Gu & Bozdog, 2006), (i) Random Mobility (ii) Controlled Mobile elements and (iii) Predefined Mobility.

2.1.2.1. Random Mobility

The movement of mobile device will follow a desired path in the network and also won't have any control. The mobility of this kind is appropriate for understanding the surrounding animal's behavior. (Lindgren, Mascolo, Lonigan & McConnell, 2008) proposed Seal-2-Seal protocol to logging contacts between mobile nodes, where the sensor nodes are existing on animals for monitoring wildlife.

2.1.2.2. Controlled Mobility

Mobile elements move around the network and project the surroundings data gathering from the sensor nodes. In the mean time, the progressive path is still controlled and it may be altered at any moment. In (Ma, M., & Yang, Y., 2008) projected a novel data collection method which utilizes the mobile collector known as M-collector. This leads to a journey which starts from sink and traversing the sensor nodes to gather the data and upload the gathered data which in turn returns to the sink. If there is any change in the topology of network, there will be an impact in the mobile collector way alteration.

2.1.2.3. Predefined Mobility

The course of the mobile element is resolute and it may not be altered throughout the lifespan of network. The earlier description of the character of mobility is appropriate for structural health monitoring and infrastructure surveillance applications, (Flammini, et

al., 2010) projected a caution based on wireless sensor network systems to surveillance in transportation in railway.

The methods presented in this research are implementing the controllable and fixed route of the mobile element.

2.2. Related Works

Mobile devices or mobile elements (MEs) are development that added to wireless sensors network can move around the sensing fields and gather data from sensors. As a result of utilizing mobility, reducing multi-hop wireless transmissions to save the energy and can replenish their energy supplies. The main drawback of this method is increased latency, and resolute the velocity of many ME systems is very low this mean there are long time to visit large sensing field where the necessity delay of many applications may not be meet.

2.2.1. Rendezvous Based Approach

Perspective of Xing et al (2008) for mobile elements can gather large volume of data without roaming a lengthy remoteness to achieve large-bandwidth data with least delay in communication, proposed a rendezvous-based approach. Where some nodes act as rendezvous points (RPs) in which source node data were saved. Mobile elements (MEs) approach the RPs and collect the cached data's and transfer it to base station before reputed time. The following figure show ME-based data collection.

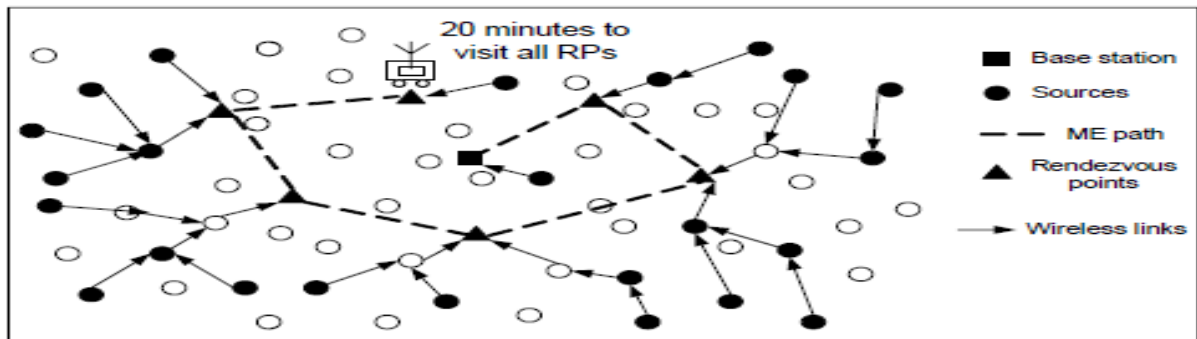


Figure 3: ME-based data collection (Xing et al, 2008).

Developed two rendezvous point algorithms where mobile elements paths are constrained and mobile elements ways are not inhibited in the data routing tree. The foremost one called (RP-CP) and the goal is to obtain the best possible rendezvous points when the mobile element moves by the side of the data routing tree. The next is RP-UG and attempt to locate the best possible rendezvous points that get a advantageous balance between journey distance for mobile element and energy saving. Results in simulation illustrate that these techniques decrease the consumption of energy considerably to expand the network's lifespan.

Xing et al (2012) propose approach dependent on performance bottleneck of WSNs that produce from improved latency in data gathering and the little progress in velocity of mobile base stations called rendezvous-based data collection method by recognize node's subset operate as rendezvous points (RPs), that buffers and data collection from sources and communication to the base station. This method merged the features of supervised mobility and the data caching in same network and balanced between data collection delay and energy consumption.

This method has many advantages: Firstly, there is trade-offs between consumption of energy and delay in transferring of data by optimizing the select of rendezvous points

(RPs), movement path of mobile elements, and transmission of data routes. Secondly, the mobile elements can pick up huge data without traveling a long distance by using rendezvous points (RPs) that reduce from impact of deliberate movement rate of mobile elements over network. Next is the mobile nodes contacting the other nodes in the network through RPs at programmed times, which reduces the interruption to the network topology formed by mobility. Through the efficient rendezvous algorithms, authors show mobile elements may travel liberally in the scattered area or should travel by the side of fixed tracks.

In this research, MEs move to specific locations and data collection directly from each sensor nodes to increase the network lifespan, instead of use some nodes as collocation points

2.2.2. Trajectory of Mobile Element

Maximum amount shortest path (MASP) is a new algorithm proposed by Gao et al (2011) to increase the data's that are collected and decrease the consumption of energy by utilizing suitable mapping between sensor nodes and sub-sink. And focus on path-constrained mobile elements over large location of WSNs that existence in many applications such as surveillance of health of great buildings. In the given figure, where M is mobile element and move over path L, multiple-hop communication area (MCA) and direct communication area (DCA) are two regions, where DCA between trajectory L1 and trajectory L2 and sensor nodes within the DCA, called sub-sinks, MCA for far sensors and called member. mobile element M obtain data from nodes of sensors while travelling near to them, because fixed path and speed to mobile element M then the time duration between individual sub-sink and the fixed mobile element, the throughput of WSN is based on the

connection between the gathered data and the amount of members belong to individual sub-sink, the complicated here to proficient assignment is to reduce energy consumption to the sub-sinks members.

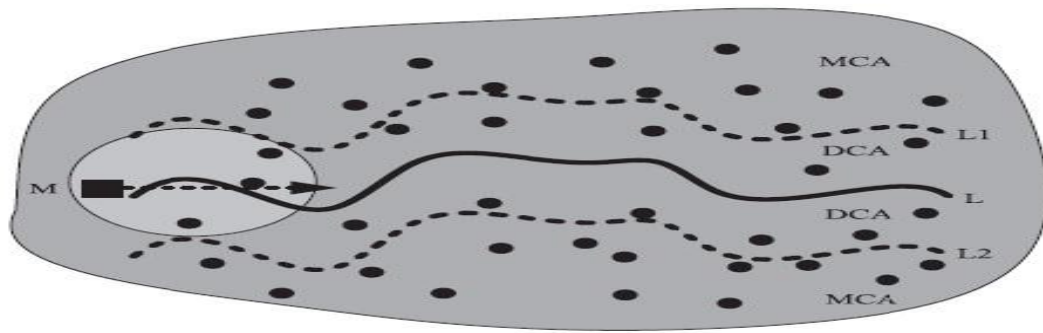


Figure 4: An Example of Path-Constrained Mobile WSNs (Gao, Zhang & Das, 2011).

Due to the restrictions of accessible path infrastructure and power of communication for all sensors to send data in one-hop mode to mobile element, authors depend on multiple-hop communication to avoid the traffic when transition to reduce energy consumption, and used the shortest path tree (SPT) to decide the route data and cluster heads. During their simulations the sink mobility techniques with MAPS and SPT execute superior than the static sink method to energy consumption. MASP can sustain with least density to the sensor networks and many elements of mobile. And too, they develop region partitioning based solution algorithms and a circulated result (MASP-D) algorithms to reduce complexity.

In this research, use the single-hop communications instead of the multi-hop communications to increase the life time of the network.

Shangguan et al (2011) understanding the heterogeneous collection of data issues for a Mobile Element (ME) and propose a new method called (RP-ME) which goal is to obtain the most excellent position for the rendezvous points also the finest trajectory for the

mobile element; the benefits from this are to decrease the energy bottleneck points and to prolong the lifespan of network. Author criticized the previous researches WSNs that assumptions like as the link quality are always implicit fair sufficient and rate of data generation on dissimilar sensor are assumed identical these predictions may not tender a holistic outlook of the distinctive ad-hoc networks because link quality can lead to data loss and retransmission effect on link quality and send data like images from far areas in a battlefield cannot be used when transmitting.

(Al-Hasanat, Matrouk, Alasha'ary & Alqadi, 2014) introduce Connectivity Based Data Collection algorithm that divides sensor nodes into clusters to reduce from multi-hop communication. Where sensor nodes transmitted its data to mobile element by single hop when exist in communication range of ME, and use multi-hop to far sensor nodes. Outperform to this algorithm when compared with LEACH-C.

2.2.3. Communication Model

There are some factors effect on communications range in WSNs and also utilizes huge amount of energy such as radio abnormality as well as channel fading, these are important challenges to framing of energy efficient protocols for data transmission. To solve these problems Cooperative MIMO (Multiple Input Multiple Output) communication proposed to long range transmission. In (Medhia, N, & Sarmab, N., 2012) propose mobility based cooperative MIMO based data transferring model namely MACO MIMO to sensors expire out consistently and gradually by consuming least transmission energy, here mobile sensors move to identify location and collect data from sensors and then send it cooperative sensor node or sink. there are two types of sensors, the first called Listeners, and the second called Supervisors, where Listeners act as sense and send data to Supervisors, but

Supervisors (Rechargeable controllers minimize the workload on clients) have higher capacity and can move over the field. Pairing of supervisors is denoting a bunch of the listener sensors to divide up the workload in a cluster and simply control the cooperative distance between two cooperative supervisors.

The benefits from using this model of communication are applying the identical energy cost by the nodes and excellent regular lifespan of the network. When we decide a few expensive re-chargeable supervisors, we can neglect the issues of energy cost in the selection of cluster head, using to serious purpose like in Warfield and nuclear reactor plants to reach a few sensors in safety way. Listener sensors employed in the significant area in which controller sensors can be recharging by mobility to adjoining secure place.

The method presents in this thesis is a range based data gathering with Single Input Single Output (SISO), and adopted the Received Signal Strength (RSS).

2.2.4. Redundant Sensor Nodes

Khedr, & Osamy (2012) show energy problem when there are redundant of sensors which mean there are many of connections between sensors when collecting data and also redundant of data, this lead to consume power. Proposed MCMS method depends on the divide-and-conquer approach. Sensors are habitually maintained by a battery and it has been impracticable to restore or revitalize the power of batteries in every sensor network in some area such as battlefield or remote desert. So, some sensors located in an unreceptive mode to use the inbuilt redundancy of large number of sensors. To enhance the lifespan of the network, the connectivity in network will be maintained and their whole region is covered by the active sensors. Thus author building the minimum connected sensor to cover problem and use the sensor relocation method to find the redundant sensor nodes to

neglect the partition in network and the whole coverage. Where the sensor relocation includes two phases: the first phase is to determine the redundant sensor node which is present in the WSN that are located in the nearby regions the next phase is to re-identify the continuous sensor nodes to restore faulty node. The research was based on concept of the cascaded movement and proactive characteristics.

In the following figure, if A is a redundant node and D is a faulty node. D can be replaced by A (D replaces A) using the cascaded movement or using direct movement (A go to D).

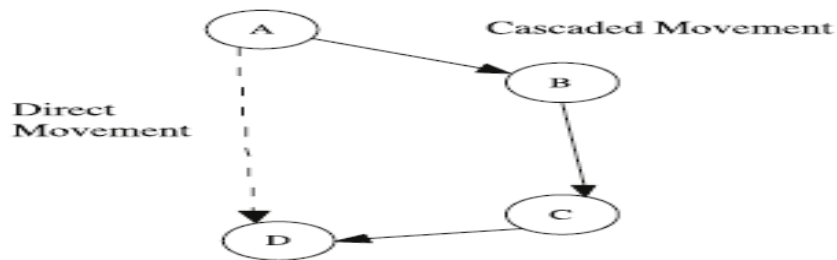


Figure 5: An illustration of Faulty Node Replacement by Redundant Node (Khedr, & Osamy, 2012).

MCSC algorithm is intended to determine redundant nodes of sensor network where the smallest sensor nodes can envelop whole area. And let the redundant node of sensor network to discover the problems in the MCSC by re-positioning the redundant sensor node which is reliant on the shortest path algorithm. This algorithm consists of four phases: firstly, initial phase, which organize the network into grid partition, individual grid comprises of cluster head and its associates. Secondly, the connection segment comprises of procedures, that determines the hop count and build the linked routing path. Thirdly, finding, which choose the sensor node so as to cover the majority of the networks, finally, mobility, to recovers failure sensor nodes, where each sensor node ensure the energy level

is equivalent to the pre determined threshold values, it propel the recovery communication to the head of cluster.

2.2.5. Multiple Mobile Elements

Instead of using single mobile element to gather data in WSN such as (Gu, Bozdag, Brewer & Ekici, 2006), (Xing, Wang, Xie & Jia, 2008), (Khedr & Osamy, 2012), recently multiple mobile elements is an important trend in literature. In this section, discusses some of the related works encouraging of using multiple mobile elements for gathering data.

In fact, using multiple mobile elements is a straightforward approach to improving the network scalability, latency and throughput. To keep away from the data thrashing due to buffer spread out, Yaoyao et al (2006) proposes PBS algorithm to program the arrangements of elements in mobile in a sensor set of connections. This approach divides the related mobile elements into two sub-problems. Then, all nodes are correspondingly divided into various parts within a group, and then the scheduling of algorithm will produce a node for visit of the schedules of the mobile element to reduce the overhead of moving back across the distant nodes.

Using MPP problem for the mobile elements to extend the life span of WSN instead of using the single path was also investigated. In (Zhu, Guo & Tosun, 2009) fixed K and adaptive K schemes were planned numerous paths and have the mobile element to go after these paths were designed in order to stability the energy use on separate sensor nodes. As a result, the multi-path can prolong the life time up to four times.

Hence, latency is the most important issue when concerning data collection data with multiple mobile elements. He, Xu, & Yu (2009) focus on main disadvantage of huge latency in collection of data, where data collection latency is determined by the speed of the

entity of mobile and length of tour which is present in entity of cell. In earlier work it is focused to determine the problem by reducing the length of tour in mobile entity, dependent on the base station (BS) can move over the networks. But now when base station (BS) cannot move, it can identify some mobile elements (MEs) to move over wireless sensors networks to collect data and returned to base station (BS). To reduce from latency in data collection, make length for each mobile elements travel as short as possible. The author proposed three different processes to deal with this problem; "The primary methods works on the ideas based on the clustering of the stop points and further assigning them to the elements in the cell. The final one is the method of heuristics, which gives a solution for the problem by improved dealing of problems in large scale". First and foremost, method is area-splitting, which divides the networks in various parts; each mobile entity is used for gathering of data from one of the stop points. Second method is the Lloyd's Algorithm based Method that deals with sensor networks that are randomly organized. Third method is The Genetic Algorithm based Method to get the ultimate answer by using the genetic algorithm which is considered as intelligent algorithm which apply it to optimize problems.

Other research, such as (Kim, Abay, Uma, Weili, Wei & Tokuta, 2012), has focused on optimal trajectories of multiple mobile to reduce latency of data collection in WSN using the k-travelling salesperson with neighbor (k-TSPN) where each mobile element can broadcast data to the sink in its appropriate position, and the k – rooted path cover [k-PCPN] with neighborhood each and every elements in the mobile are linked to the sink at its appropriate position.

Moreover, other study such as (Le, Oh & Yoon, 2014) endeavored to accomplish latency for low collection of data's with a less consumption of energy. Hence, a co-operative data gathering hierarchy scheme has been proposed. In this algorithm, two kinds of mobile elements were suggested. First one called mobile collector (MC) used to collect nodes data which are present in the sensor. The other one is called mobile relay (MR) which is used to group data from mobile collector and transfers the collected data to the node present in sink.

The present methods in this research use the mobile collector, used to group data from nodes of sensor and transmits it to sink directly, and instead of based on extra mobile relay to transfer the data to sink. This leads to reducing the cost of network equipment and reducing the delay time.

On the other hand, authors in (Wang, Zuo, Shen, Li & Lee, 2014) relied on using multiple mobile elements instead of one or a static sink. It proposed an algorithm, where multiple mobile elements used to collect data while moving on predetermined paths. Mobile elements will stay at particular points that are fixed to gather data from sensor nodes. This algorithm splits the network into two important areas to gather data, the first one, concentric sphere of deployed region with radius (r), and the other area which is divided into eight sub-areas. Where the mobile elements move along the diameter of the sphere and other two sinks which are present moves along the arc lines to gather the packet data of sensor node. The simulation results showed that this algorithm efficiently modified the hot spots trouble and prolonged the network life span of WSNs. our research, particularly when use multi mobile elements, the network divided to horizontal and then to

vertical if the path constraint not satisfied. Hence, not require to additional mobile elements, where our goal use the minimum number of mobile elements.

CHAPTER THREE

The Proposed Methods

3.1. Overview

Sensor nodes, which deployed in a specific field, are sensing data and transfers to sink. Then base station is once again analyzed for the data by end user of applications (Norman, Joseph & Roja, 2010). Further the sensor nodes are provided with low energy resources there is a problem in transmitting the data's directly to the sink nodes. (Rajagopalan & Varshney, 2006). Therefore, it is necessary for the adequate data algorithm for gathering to gather the data's from the nodes in energy efficient manner for achieving the goals of sensor network which is used for increasing the lifetime of networks.

There are many techniques used to extend the existence time of the sensor network, some of them depends on clustering approaches, such as (Rajagopalan & Varshney, 2006) (Maraiya, Kant & Gupta, 2011), and some of them depends on rendezvous approach (Xing, Wang, Xie & Jia, 2008) and other studies depends mobile data collector (Alqaralleh, & Almi'ani, 2012).

This chapter endeavors to design a path for a mobile element such as,

- All sensor nodes are covered
- The data gathering latency is minimized.

The first condition ensures that the mobile element will traverse all nodes, in order to avoid the using of multi-hop communication. This is important to increase the network lifetime of sensor nodes since using single-hop communication for short distance (He, Zhuang, Pan & Xu, 2010) (Norman, Joseph & Roja, 2010) (Park, Moon, Yoo & Lee, 2012)

this will indeed decrease the consumption energy of sensor nodes. The second condition, data gathering latency is reduced at a given speed of the mobile element. In fact, by satisfying this constraint, sensor nodes would have the opportunity to increase its sensing rate, and therefore, increase the network throughput. Reducing the data gathering latency can be achieved via either increasing speed of mobile element or minimizing the path length. So as a former option, increasing speed of mobile element will significantly increase the cost of manufacturing and power consumption. This study focuses on reducing data gathering latency via minimizing tour length of mobile elements.

This chapter proposes two new data gathering algorithms. The first one, based on using a single mobile element, called as intersection points of communication range (IPCR). The second is based on multiple mobile elements, called as collaborative data collocation algorithm (CDCA).

3.2. Section One: Single Mobile Element of Data Gathering

IPCR is a new data gathering algorithm referred to as Intersection Points of Communication Range between a mobile element and sensor nodes is proposed. Where move mobile element from sink (start point) to specific location (intersection point) for group of sensor nodes. And then move to next intersection point until return to start point; hence visit all intersection point in shortest path represent as Travel Sale-Man Problem (TSP). The efficiency of the IPCR algorithm is assessed through simulation. To fair comparison has been made between the IPCR algorithm and the optimal Travel Sale-Man Problem (TSP) algorithm, due to IPCR algorithm based on TSP. Results obtained by the IPCR algorithm have matched with optimal TSP algorithm. Moreover, the data gathering latency and network throughput of IPCR are evaluated and compared with the CBDC

which is also known as connectivity based data collection algorithm. The outcomes emphasize superiority of using the IPCR algorithm over the CBDC algorithm.

3.2.1. Genetic Algorithm

A genetic algorithm (GA) is classified as search heuristic algorithm which used to generate useful solutions to optimization and search problems. A Genetic Algorithms complexity is $O(O(\text{Fitness}) * (O(\text{mutation}) + O(\text{crossover})))$. The following is the processes of GA (Norouzi, A., Babamir, F. S., & Zaim, A. H., 2011).

- **Initialization:** identify the population initialization by randomly selecting the paths.
- **Fitness:** The function is a scoring process to each path according to their qualifications.
- **Selection:** new population is generated by selecting members of the current generation
- **Crossover:** producing new generation
- **Mutation:** change in the previous solution to better solution
- **Terminate:** Process is repeated until a termination condition has been reached.

3.2.2. Problem Formulation

In this section, data from N stationary sensor node needs to be collected by a single node known as a mobile element. All sensor nodes are using static transmission power, i.e. same level of transmission power. The mobile element must follow a limited path through a set of collection points in order to satisfy its energy and time constraints. In addition, in this

path it is preferable to use single-hop communication between sensor nodes and the mobile element.

The following table represents all notations used in this section.

Table 2: The Notations

Notation	Description
N	Number of sensor nodes
S	Set include collection points
C	Collection point
C_M	Number of collection points in set
n	Sensor node
n_p	Number of sensor nodes in one of collection points
$ S $	Length of the set
q	Speed of ME
m	Meter
s	Second
l	Path length of data collection round to ME
τ	Time to each sensor node to send its data to the sink
K	Packet size
R	Data rate
$TDMAC(i)$	Waiting time of mobile element in $C(i)$

Let

$$S = \{C_1, C_2, \dots, C_M\}, \quad (3.1)$$

Represents the collection points of the mobile element, that

$$C_i = n_1, n_2, \dots, n_p, \quad (3.2)$$

Is the set of member of sensor nodes that belong to the collection point of C_i , and n_p which is number of members in this set. Note that for a network without connectivity.

$$|S| = M = N, \quad (3.3)$$

In this case the mobile element must visit the location of each sensor node to gather its data, which is the worst and unrealistic scenario. However, for a fully connected network, we have

$$|S| = 1, \quad (3.4)$$

Indicating that the mobile element is required to visit one location to collect data from all sensor nodes, which is the desired but uncommon scenario. In this chapter we are interested with the most realistic scenario, where

$$1 < |S| < N \text{ and } N > 1. \quad (3.5)$$

In this case, the mobile element has to traverse $|S|$ collection points and collect data from their member nodes via single-hop communication.

When the data collection round begins, the mobile element moving from the sink node location passing through the selected collection point with a speed of q m/s. Hence, l/q second is required to complete a single data collection round of length l . During every round, each sensor node should send its data to the mobile element. Two approaches are suggested to organize data collection and prevent out-of-synchronization problem. Therefore it is not necessary that a sensor node be awake all the time to transfer data to mobile element. This leads to maximize the network lifetime.

In the first approach, sensor nodes are designed to send their data every l/q second. The problem of out-of-synchronization still occurs if the instance of the mobile element is slowed down or even delayed some where in the network. In the second approach, use to stop to collected data (SCD) algorithm (Rajagopalan & Varshney, 2006). Hence, when the mobile element arrives at the collection point, it starts to use a time division multiple access algorithms (TDMA) slot for data collection. Every sensor node needs τ to send its data to the sink node on collection point, such as

$$\tau = \frac{K}{R} \quad (3.6)$$

K is the packet size, R is the data rate that ignoring propagation delay, the mobile element needs to wait the TDMAC(i) slot at a collection point i as

$$TDMAC(i) = \tau \times np \quad (3.7)$$

Therefore, total latency of a single data collection round is computed such as

$$Latency(s) = l/q + \sum_{i=1}^M TDMAC(i) \quad (3.8)$$

Where l is the path length of the mobile element. Here, the system throughput (productivity of system each round) can be calculated as

$$Throughput(bps) = \frac{K * N}{Latency} \quad (3.9)$$

3.2.3. Proposed Algorithm

Each sensor nodes, starts to broadcast a beacon message to determine its neighbors, based on the received signal strength (RSS). Then, RSS measured is used to compute the inter-sensor distances and how closes these nodes to each other. Consequently, each sensor can determine its neighbor, which helps to provide some information about the selection of collection points of the mobile element. The MATLAB programming tool is used to define the transmission range, the candidate points as well as network life time simulation.

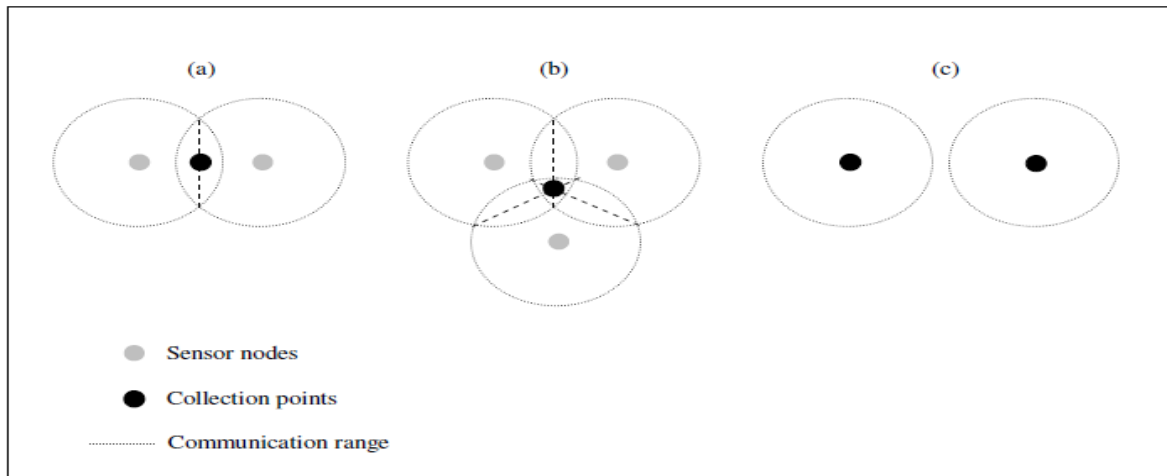


Figure 6: Examples on Collection Points Determination of (a) Two Overlapped Nodes, (b) More than Two Overlapped Nodes and (c) Isolated Nodes.

Assume that $d_{i,j}$ and $r_{i,j}$ represents Euclidean distance and communication range between nodes i and j , respectively. The two nodes are connected with each other if

$$d_{i,j} < 0.5 r_{i,j} \quad (3.10)$$

The mobile element is required to visit an overlapped area between two or more nodes with unnecessarily that these nodes are connected to each other. Hence, the communication ranges of two nodes are overlapped if

$$d_{i,j} < r_{i,j} \quad (3.11)$$

Generally speaking, for M nodes with an overlapped area, there is a location for the mobile element which has to stop and collect data. That location is determined as the centroid of this area as shown in figure 6, for example, for two nodes (figure 6(a)), the collection is defined as the centroid of a line connecting the interconnection points of the communication ranges of the two nodes. When the form has more than two nodes, the collection points is determined as the intersection points of all lines connecting the intersection points of communication ranges of all nodes, in figure 6(b) as an example.

When the nodes is isolated. The location of these nodes is used as collection points for the mobile element, in figure 6(c) as an example. After determining the collection points, travel sales-man Problem (TSP) algorithm is used to obtain the shortest path through these collection points. Once the mobile element completes a data collection round, it uploads the data into the sink node and starts a new round. It is worth mentioning that this flow neglect the path established which consumption ones at the setup phase, the power consumption of this phase is negligible. The following figure illustrates the flowchart of the IPCR algorithm.

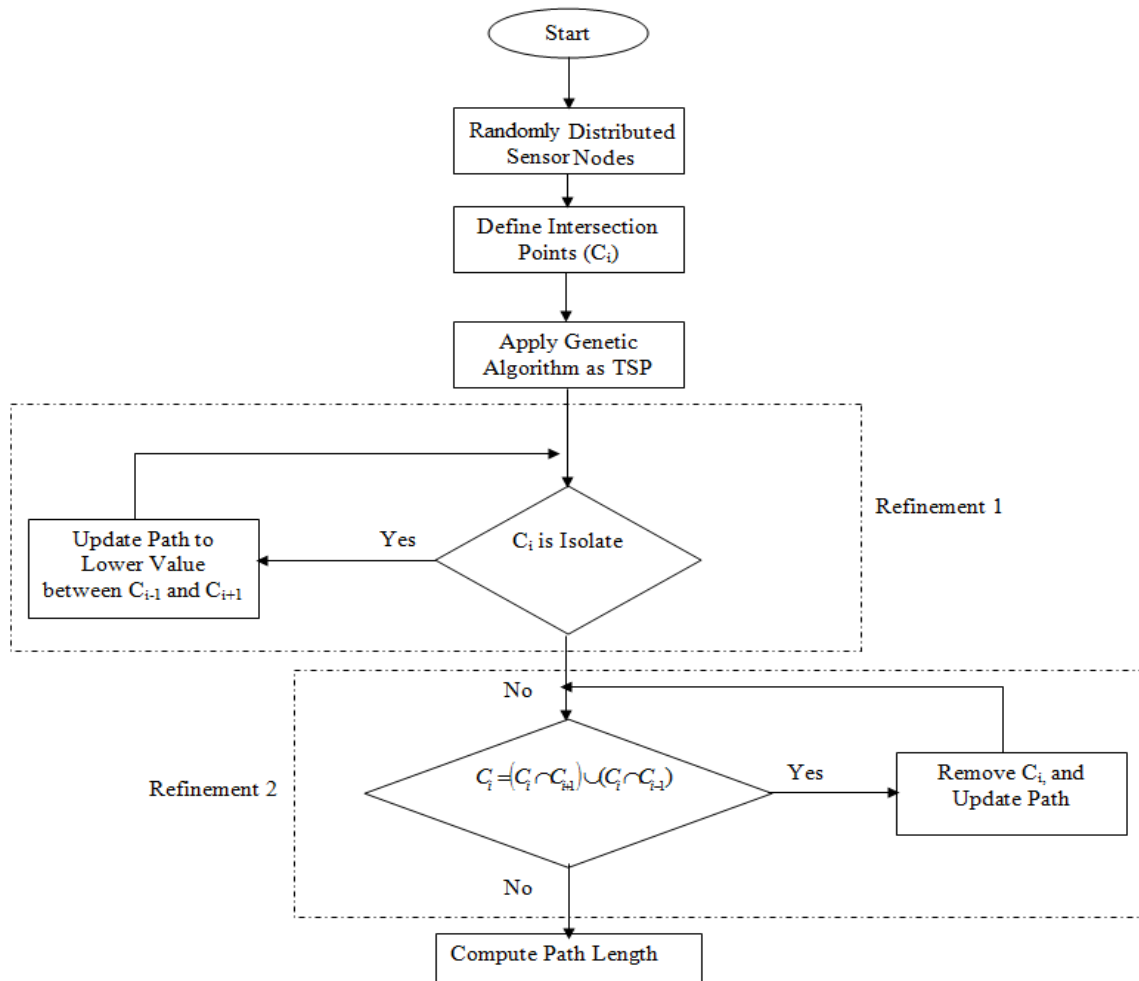


Figure 7: Flowchart of IPCR Algorithm

3.2.3.1. Path Refinement

One refinement on the path length of the mobile element is possible to be on isolated node where it is a collection point. However, it is fair enough for the mobile element to visit points on communication ranges where the isolated nodes are. As a result, the total tour length of the mobile element is minimized. In the IPCR algorithm, a new collection of an isolated nodes is calculated as the centroid of a line that connect the intersection points between this nodes communication range and the path line of the mobile element. This scenario is clearly shown in figure8(c) for many isolated nodes.

Furthermore, it is possible that a collection point which linked to a set of sensor nodes, while these nodes were already linked by another adjacent collection point. Turn to lead the increase of the path length of the mobile element; the collected points should be removed. To accomplish this task, assume that the tour of mobile element after computed by TSP algorithm is given as

$$T = \{C_1, C_2, \dots, C_M, C_1\}, \quad (3.12)$$

Then the collection points will be removed from T. When the sensor nodes associated with the collection point C_i are already associated with C_{i-1} , C_{i+1} , such as

$$C_i = (C_i \cap C_{i+1}) \cup (C_i \cap C_{i-1}), \quad (3.13)$$

Figure 8 show an example on this scenario. In figure 8(a) sensor nodes distributed randomly and defined intersection points. Figure 8(b) applying TSP algorithm on intersection points. Figure 8(c), update the path of ME to each isolated nodes. Figure 8(d), update the path of ME based on removing some intersection point.

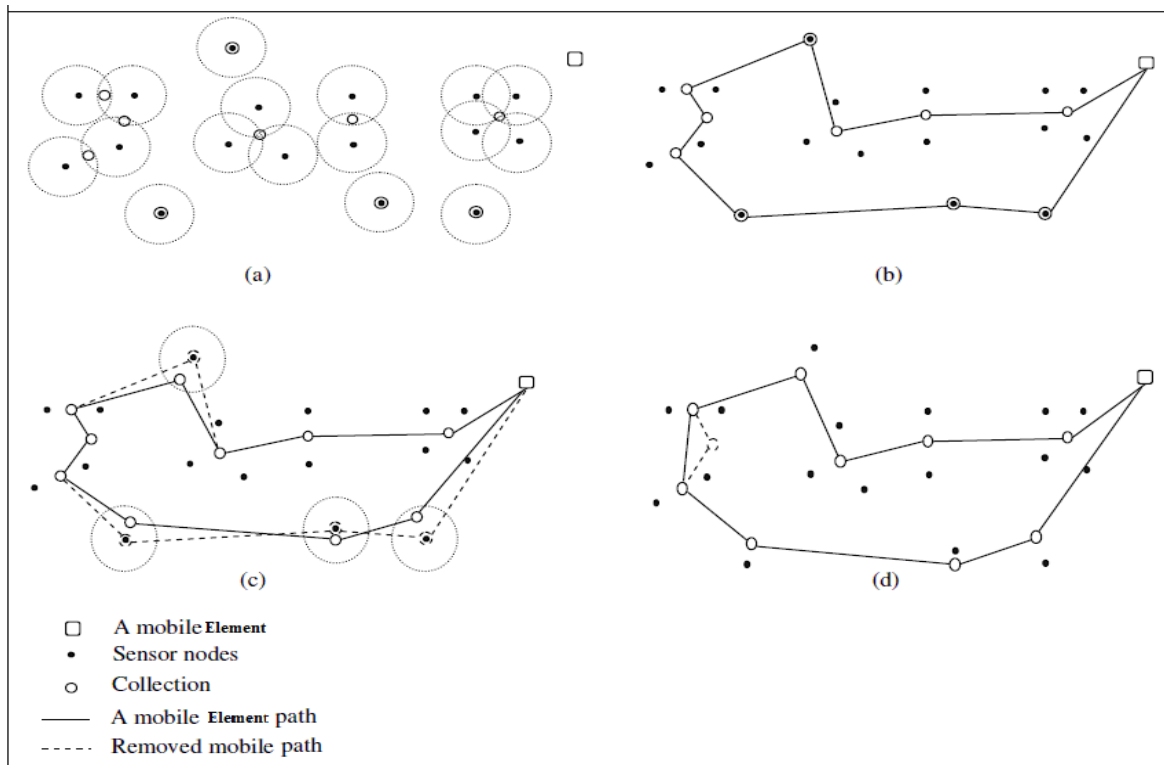


Figure 8: Examples on Sensor nodes distribution within a sensor field including a ME

3.3. Section Two: Multiple Mobile Elements of Data Gathering

Using single mobile element for data gathering in Wireless Sensor Networks (WSNs) would sometimes lead to high data gathering latency, particularly for large sensor fields. In addition, it is often difficult for a single mobile element to traverse long path and collect data from all nodes due to the limited energy resources (Dantu, Rahimi, Shah, Babel, Dhariwal & Sukhatme, 2005). Therefore, integrating several mobile elements for that task such as (Tang, Wang, Geng, Zheng & Kim, 2012), (Xing, Li, Wang, Jia & Huang, 2012), (Shangguan, Mai, Du, He & Liu, 2011) led to limit the path length of these nodes which in turn reduce their energy consumption of these mobile elements and minimize the overall data gathering latency.

In this context, a network with multiple mobile elements can be then divided into parts, where each part is allocated with a mobile element. Each mobile element is required to collect the data from all sensor nodes that belong to it and upload the collected data into a sink node.

Despite the mentioned benefits of using multiple mobile elements in WSNs, it introduces additional budget to the network, which is usually not acceptable for many applications. Therefore, the main challenge is to reduce data gathering latency but with the minimum possible number of mobile elements.

This section aims to:

- Reduce the number of mobile elements that engaged with data gathering.
- Increase the Network throughput through reducing data gathering latency.

In order, to achieve these goals, a new data gathering technique called Collaborative Data Collection Algorithm (CDCA), is introduced. The key idea of the proposed algorithm is dividing the network field into fixed parts of equal areas. Then, each part is allocated to a mobile element for which this mobile element moves in a predetermined path and collects data from sensor nodes of that part. The path is designed based on the communication range of the mobile element so that all nodes should be covered. In addition, the path length should be satisfied with the path constraint of the mobile element which is given in advance.

The benefits of using this algorithm are:

- The Travel Sales-Man Problem algorithm is not required since the mobile element will move into a predetermined path.

- The locations of sensor nodes do not need to be provided prior as the mobile element will collect data from nodes on-fly and will not visit each node's location individually.
- CDCA is highly scalable algorithm as removing or merging new nodes into the network make no affects on the trajectory of the mobile element.
- Since the nodes are usually distributed in a uniform random topology, mobile elements will be allocated with almost similar number of nodes, which in turn provides an efficient load balance in terms of data buffering and power consumption.
- All mobile elements have identical path lengths. This leads to reduce the data collection latency in addition to provide a consistent data collection frequency of sensor nodes.

3.3.1. Problem Formulation

Consider that a WSN consists of N sensor nodes that are uniformly and randomly distributed within an area of $K \times L$ meter and M Mobile element used to collected data. All sensor nodes are using static transmission power, i.e. same level of transmission power. Suppose that the speed for each mobile element is fixed. And each mobile element must follow predefined path that satisfy energy constraints and cover all sensor nodes. The Base Station is located at the origin point. The problem considered in this chapter is to collect data from N sensor nodes every round using M mobile elements. Achieving this task requires the satisfaction of the following conditions.

1. Covering all sensor nodes in the network field.
2. Satisfying path constraint of the mobile element. Such that

$$l > C \quad (3.14)$$

The following table represents all notations used in this section.

Table 3: The Notations

Notation	Description
N	Number of sensor nodes
l	Total path length of each ME
C	path constraint
K	y-direction (y axis)
L	x-direction (x axis)
M	Total number of mobile elements
M_x	Number of mobile elements in x-direction
r	Communication range of mobile element
l_y	Vertical path length of the mobile element
M_y	Number of mobile elements in the y-direction
l_x	Horizontal path length of the mobile element

3.3.2. Proposed Algorithm

In this section, the Collaborative Data Collection Algorithm (CDCA) is discussed. The algorithm attempts, as necessary, to divide the network area horizontally into sub-areas depending on the communication range of the mobile element. Hence, the number of mobile elements is computed in order to cover all sensor nodes; satisfying the requirement of condition (1) given in the problem statement. M_x represents the number of mobile elements in the horizontal direction,

$$M_x = \left\lceil \frac{K}{3(r - \tau)} \right\rceil \quad (3.15)$$

Where r is the communication range of the mobile element and τ represent the shortcoming of the communication range of mobile elements since this communication will be reduced in practice due to environment conditions (Goldsmith, 2005). The value of τ is chosen carefully in order to insure that every sensor node will be included within the

communication range of at least one mobile element. It is worth mentioning that the above equation is computed to ensure that in addition to covering all sensor nodes, every mobile element is also connected to its direct neighbor of mobile elements. This is important to allow mobile elements cooperation.

According to equation (3.16), the vertical path length of the mobile element can be defined as

$$l_y = 2 \left(\frac{K}{M_x} - (r - t) \right) \quad (3.16)$$

Figure 9 shows the scenario of computing the path of the mobile element in the horizontal direction. However, the computed path may not meet with the path constraint given in the second condition (2). In this case, the network is further divided in the vertical direction. It is clear from Figure 10 that the number of mobile elements in the vertical direction is obtained as

$$M_y = \left\lceil \frac{l_y + 2l - (r - \tau)}{C} \right\rceil \quad (3.17)$$

Accordingly, the mobile element will move horizontally l_x , such that

$$l_x = 2 \left(\frac{l}{M_y} - (r - \tau) \right) \quad (3.18)$$

The overall number of mobile elements that satisfies the above mentioned conditions, is given as

$$M = M_x \times M_y \quad (3.19)$$

Similarly, the total length of a single mobile element is given as

$$l = l_x + l_y \quad (3.20)$$

More details exist in Appendix.

The CDCA can be briefly described in the following three phases:

Phase I

The main conditions (covering all sensor nodes in the network field and satisfying the path constraint) must be achieved. In this algorithm, to specify the number of mobile elements that used to collect data from all sensor nodes, the network field is divided horizontally into sub-areas, for each sub-area a mobile element is assigned. Figure 9 illustrates an example of three mobile elements to cover all the sensor nodes distributed in the area. But when the path length of ME is greater than some of constraint, the network area must be divided vertically: such as

$$l \leq C \quad (3.21)$$

Figure 10 represents the horizontal and vertical division of the network area. Dividing in order to satisfy the both conditions described previously.

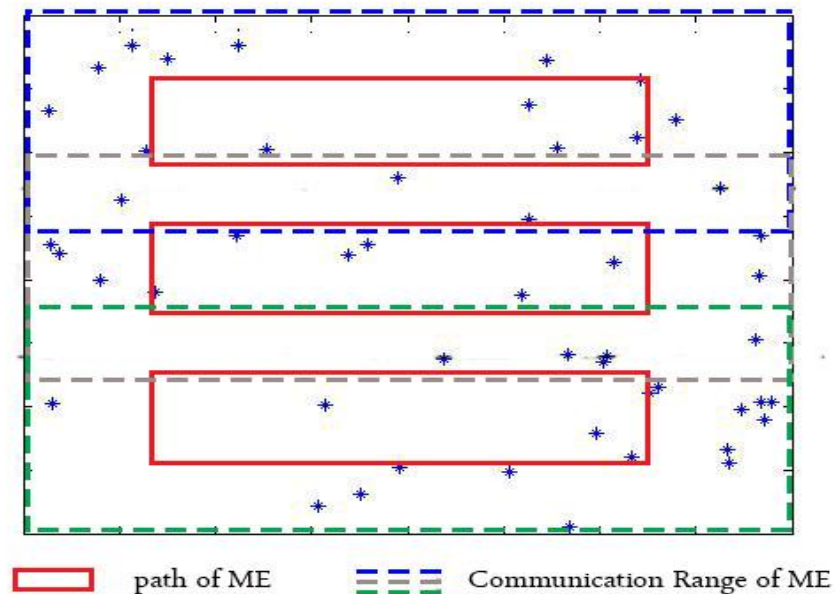


Figure 9: Horizontal Division of the Network Area

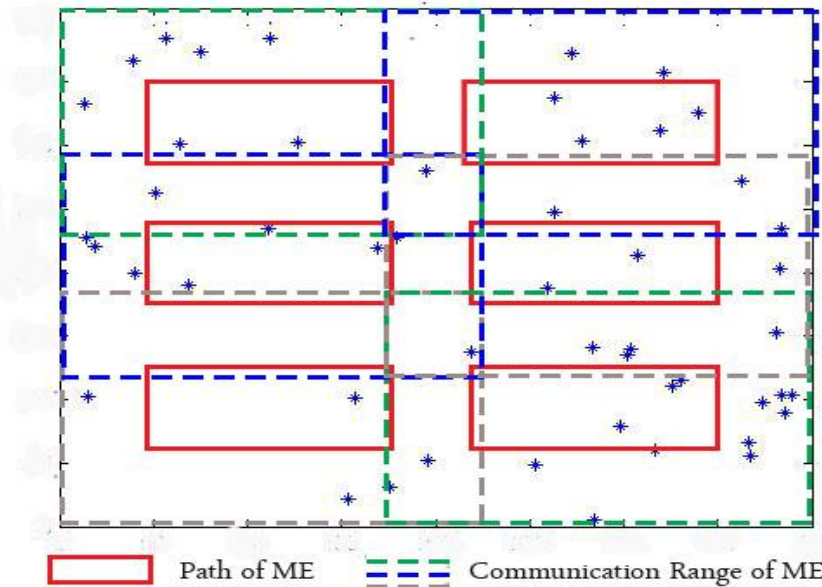


Figure 10: Horizontal and Vertical Division of the Network Area

Phase II

To allow cooperation between mobile elements, specific startup times for every mobile element should be defined. To do this, assume that a mobile element starts its data collection round at t_0 , and then its neighbors of mobile element should start their collection round at $t_0 + t$. The startup matrix of all mobile elements should be:

$$T = \begin{bmatrix} t_{1,1} & \dots & t_{M_y} \\ \vdots & \ddots & \vdots \\ t_{M_x} & \dots & t_{M_x, M_y} \end{bmatrix}$$

Hence, the data collection times for all mobile elements are defined as

$$T = \begin{bmatrix} t_0 & t+t_0 & t_0 & t+t_0 & \dots \\ t+t_0 & t_0 & t+t_0 & t_0 & \dots \\ 0 & t+t_0 & t_0 & t+t_0 & \dots \\ t+t_0 & t_0 & t+t_0 & t_0 & \dots \end{bmatrix}$$

Where, $t = \frac{l}{2s}$, and l is the path length of the mobile element and s is the speed of

the mobile element.

The Figure 11(a) illustrates the locations of 3x3 mobile elements at startup times.

The locations of mobile elements at $t+t_0, t+t_0 + \frac{lx}{4s}, t+t_0 + \frac{l}{s} - \frac{ly}{4s}$ are shown in Figure

11(b), (c) and (d), respectively.

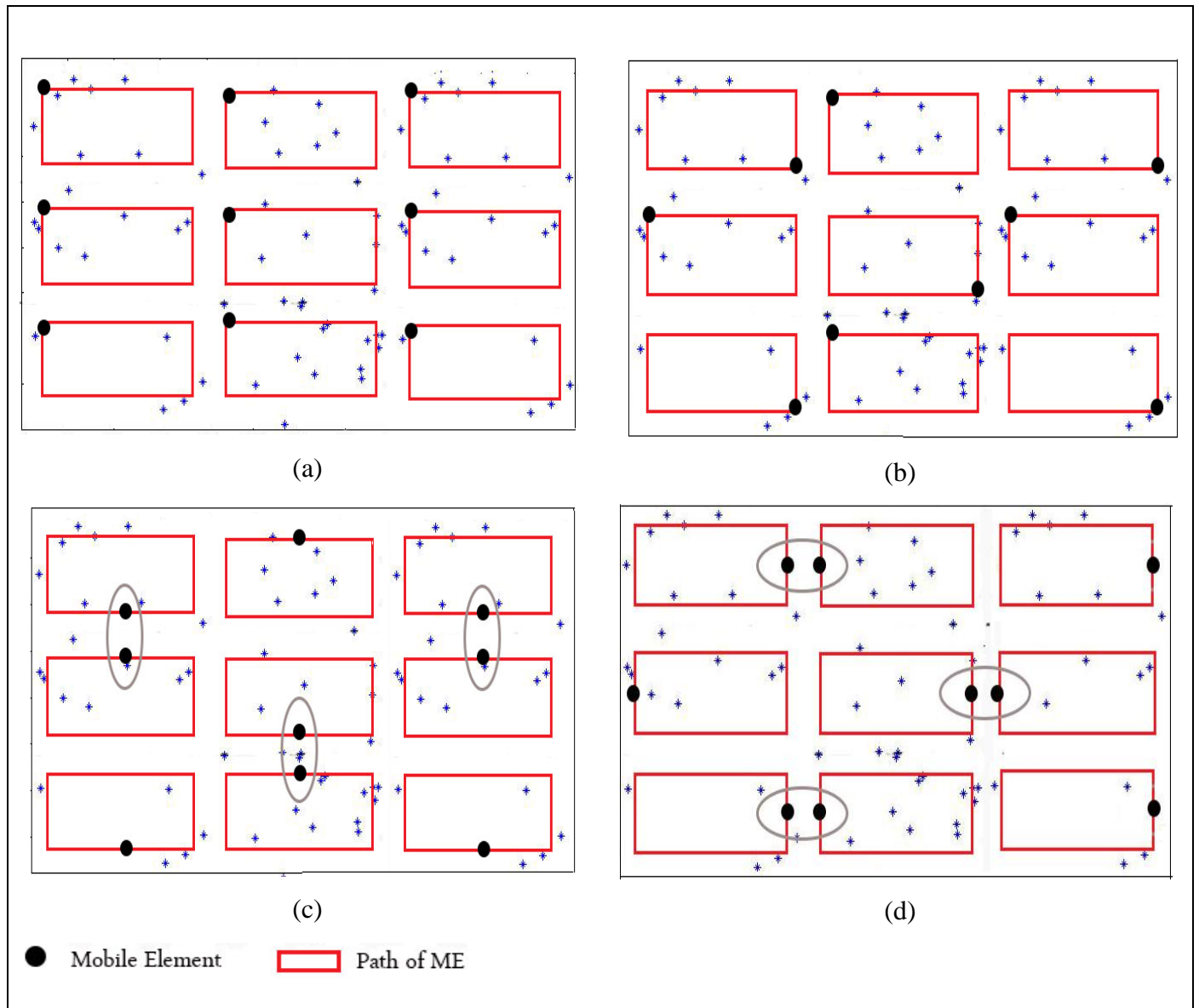


Figure 11: Startup Time of Mobile Elements

In addition, at Phase II, each mobile element gets an integer ID number, and then do traverse it is tour to define the set of sensor nodes for which it belongs. The node selects the

mobile element with the highest Received Signal Strength RSS value. Then it records the arriving time of the mobile element to compute its data collection time. For example, assume that t_c^0 is the very initial arrival time of a mobile element for a node, then the collection time for this node at round i is:

$$t_c^i = t_c^0 + \frac{il}{s} \quad (3.22)$$

Where s is the speed of the mobile element. Furthermore, in this phase mobile elements can identify the overlapping times with the neighbors as shown in Figure 11.

Phase III

In this phase data collection is taken place. Each mobile element starts collecting data from all nodes in its partition and then sends these data to the closest mobile element, in order to be delivered to the sink node. The following figure illustrates flowchart of CDCA algorithm works.

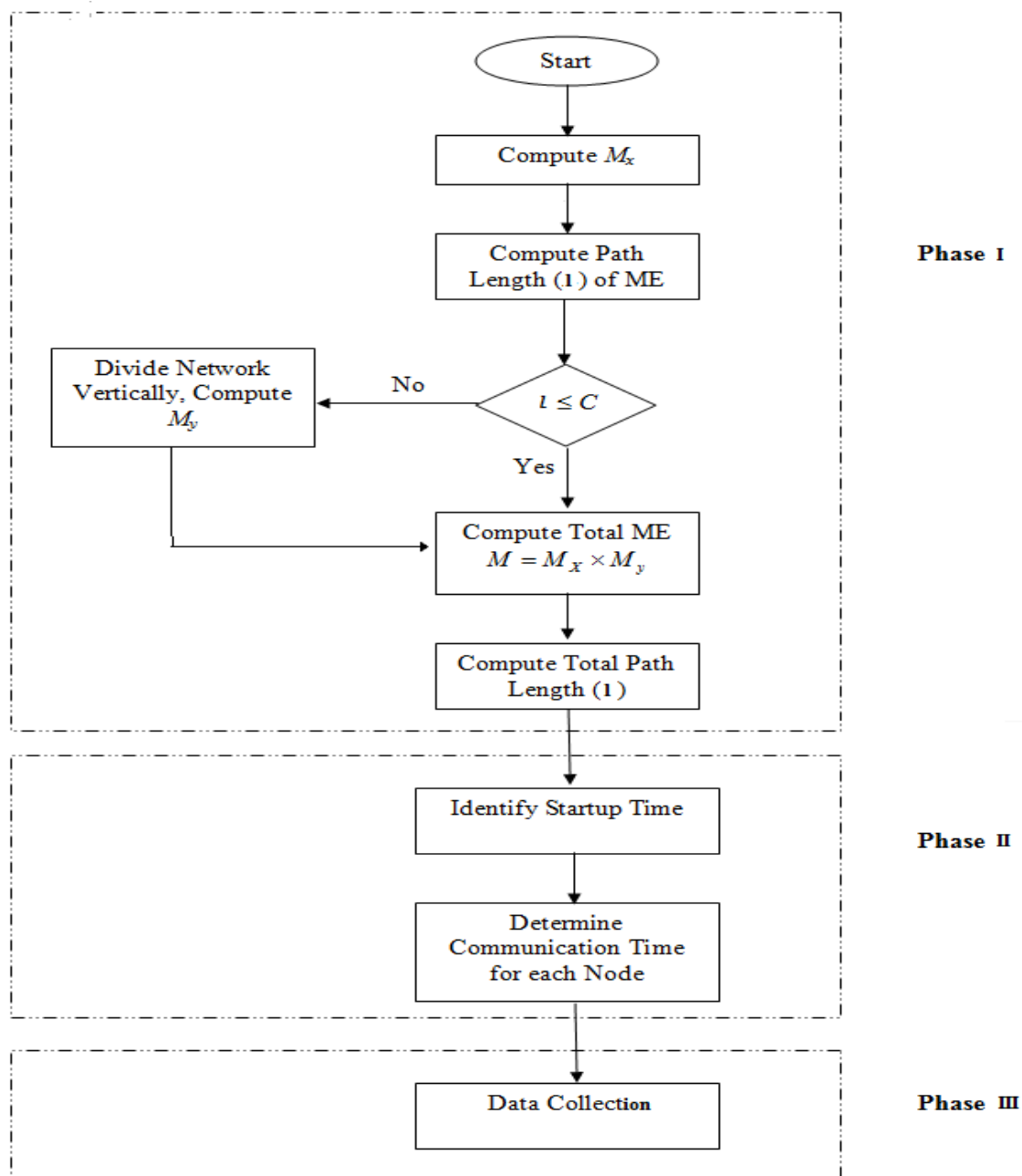


Figure 12: Flowchart of CDCA Algorithm

CHAPTER FOUR

Results and Discussions

4.1. Simulation Tool

Using MATLAB version R2010a for the implementation our algorithm, MATLAB is a programming language developed by MathWorks and Stands for MATrix LABoratory. MATLAB provides a language and environment for numerical computation, data analysis, visualisation and algorithm development and data elements is a matrix (Array). MATLAB is available for different platform such as Windows, Macintosh and UNIX systems¹. For compared to the optimal algorithm defined by the Mixed Integer Linear Programming (MILP) modeled in Gurobi/Matlab optimization tool.

4.2. Section One: The Performance Evaluation of IPCR Algorithm

In this section, we study the performance of the intersection point of communication range (IPCR) algorithm. In this experiment, the trajectory of the proposed algorithm is compared with the optimal TSP algorithm obtained by the mixed integer linear programming (MILP). In addition, the efficiency of our algorithm is compared with the connectivity based data collection algorithm (CBDC) (Al-Hasanat, Matrouk, Alasha'ary & Alqadi, 2014) in terms of data collection latency, number of collection points and network throughput. Networks of different levels of connectivity and a varying number of sensor nodes were considered in this simulation.

¹ <https://www.ma.utexas.edu/users/haack/getstart.pdf>

4.2.1. Simulation Scenario

Sensor nodes are randomly and uniformly deployed within 400x400 meter square area. Transmission rate of all sensor nodes is set to 250 kbps. The mobile element moves at speed of 1 m/s. The initial energy of each node is assumed to be 10 joules. The transmission power and reception power are set to 21 and 15 milliwatt, respectively. In this chapter, energy consumption is accounted for data transmission and reception only; during other time periods, sensor nodes supposed to be entered in the sleep mode where the energy consumption is negligible.

The following table illustrates the parameters which used in our simulation. This parameters used in other research such as (Goldsmith, 2005).

Table 4: Simulation Parameters

<u>Parameter</u>	<u>Parameter Value</u>	<u>Description</u>
speed	1 m/s	Speed of mobile element
d_0	1m	Standard to short distance
np	2.3 dB	path loss exponent 2-4
pt	0.001	1 mW, 0 dBm transmitter power for Zigbee nodes (IEEE 802.15.6)
RSS_th	-85.00 dBmW	Threshold power at which the signal can be received
p0	-40 dBmW	Reference received signal strength at $d_0=1m$
DataSize	800	Bits or 100 Byte for each packet
DataRate	$250*10^3$	bits/s

In this simulation scenario, the connectivity of sensor nodes is measured as (Li, 2007).

$$\text{connectivity} = \frac{\sum_{i=1}^N \sum_{j=1}^N w_{i,j}}{N^2 - N} \times 100\%. \quad (4.1)$$

Notice that $w_{i,j}$ mostly depends on the received signal strength (RSS) sensitivity threshold RSS_{th}^2 of the sensor nodes, or equivalently the communication range d_{th} . Since the network connectivity is an RSS strictly dependant parameter, it can't be readily controlled. For this reason, we use a range of RSS_{th} values and records the corresponding network connectivity values. Table 3 lists typical RSS sensitivity values (RSS_{th}), the corresponding communication range (D_{th}) and the connectivity percentage used in the simulation experiments to the number of sensor nodes is 300.

4.2.2. Path Length of Mobile Element

In order to examine the efficiency of the new proposed algorithm (IPCR algorithm), the total path length of the mobile element is compared with the one achieved using the optimal travel sale-man problem (TSP) algorithm. It is implemented using the mixed integer linear programming (MILP) (Ma, M., & Yang, Y., 2008). As the MILP TSP is a brute force search method, it is difficult to run this algorithm for large network sizes. A small network sizes are used for this comparison.

Intuitively, when the number of sensor nodes is increased, the path length of the mobile element will be increased. The IPCR with limited numbers of collection points will obtain a shorter path length than the TSP MILP when considering all nodes. Therefore, to

² The RSS sensitivity is a threshold value specified by the transceiver circuit of the sensor node. If the RSS of the received packet is less than the RSS_{th} value, the packet will be discarded. The corresponding communication range d_{th} is computed as $d_{\text{th}} = d_0 10^{(P_0 - \text{RSS}_{\text{th}}) / 10v}$ (Goldsmith, A., 2005), where d_0 is the reference distance, P_0 is the reference power and v is the path loss exponent (in this chapter we used $d_0 = 1$, $P_0 = -40\text{dB}$ and $v = 2.3$ (Goldsmith, A., 2005)).

provide a consistent and reasonable comparison, in the first scenario the optimal TSP algorithm is solved for all nodes and then is applied for the collection points obtained by IPCR algorithm in the second scenario.

Figure 13(a) shows the path length of the mobile element as a function of increasing number of sensor nodes. The most identical performance in the comparison with the optimal solution when the TSP MILP applied for collection points only. In addition, the two algorithms demonstrate a slight increase of the path length in a comparison with TSP MILP on all nodes. This result, which is also confirmed in the subsequent results, emphasis the advantage that the (IPCR) algorithm is highly scalable in the path length of the mobile element which is less dependent on the number of sensor nodes. Similarly, the IPCR performs almost identical performance to the optimal TSP at a wide spectrum of communication ranges. Indeed the TSP MILP on the original nodes demonstrate a constant path length of the mobile element as this algorithm compute the tour length on all nodes and without considering communication ranges of sensor nodes into account.

Table 5: Typical RSS Sensitivity Values (RSS_{th}), (D_{th}) and the Connectivity

RSS_{th} dB	D_{th} meter	connectivity 100%
-55	4	≈ 0
-60	7	0.001
-65	12	0.002
-70	20	0.007
-75	33	0.01
-80	54	0.1
-85	90	0.15
-90	148	0.30
-95	245	0.60
-100	404	0.90

4.2.3. The Number of Collection Points

Collection points of the IPCR algorithm serve as stop station where the mobile element has to wait and collect data from neighboring nodes. Reducing the number of collection points definitely lead to improve the performance of data gathering by reducing network latency and increasing throughput which will be figured out in the subsequent sections. For this reason, the numbers of collection points are evaluated for the IPCR algorithm at varying number of sensor nodes (from 100 to 500 nodes) and at multiple levels of communication ranges, as shown in figure 14(a) and (b), respectively. The collection points for the Connectivity Based Data Collection (CBDC) algorithm in addition to the traditional TSP algorithm were also computed.

Generally speaking, increasing the number of sensor nodes leads to increase the number of CPs as shown in figure 14(a). In contrast to the TSP algorithm where each node is consider as collection point by itself, the CBDC and IPCR algorithms show insignificant increment of there collection points. More specifically, the IPCR outperforms the CBCD algorithm at the entire range of sensor nodes. Increasing the communication range of sensor nodes, yield to reduce the number of collection points for the CBDC and IPCR algorithms as shown in figure 14(b). While for the TSP algorithm the number of collection points is fixed at 300 which is the number of sensor nodes used in this simulation scenario. It is clear from this figure that the lowest numbers of collection points are found with the IPCR algorithm as a function of increase number of sensor nodes and increasing communication ranges.

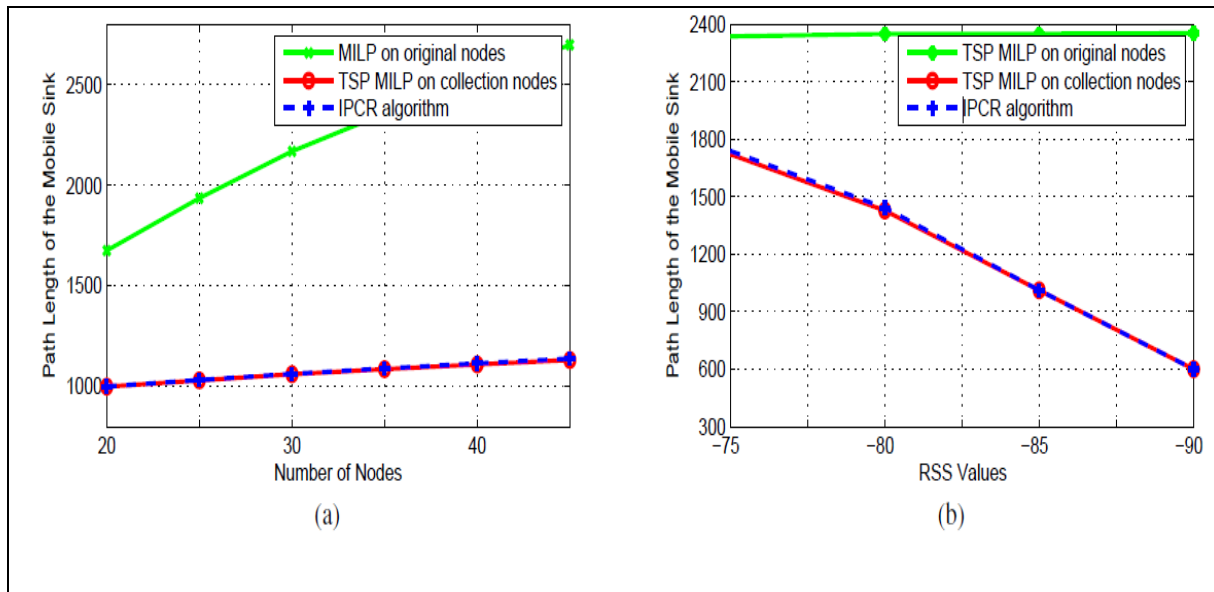


Figure 13: Path Lengths of Mobile element, (a) Increasing Number of Sensor Nodes, and (b) Increasing RSS Values.

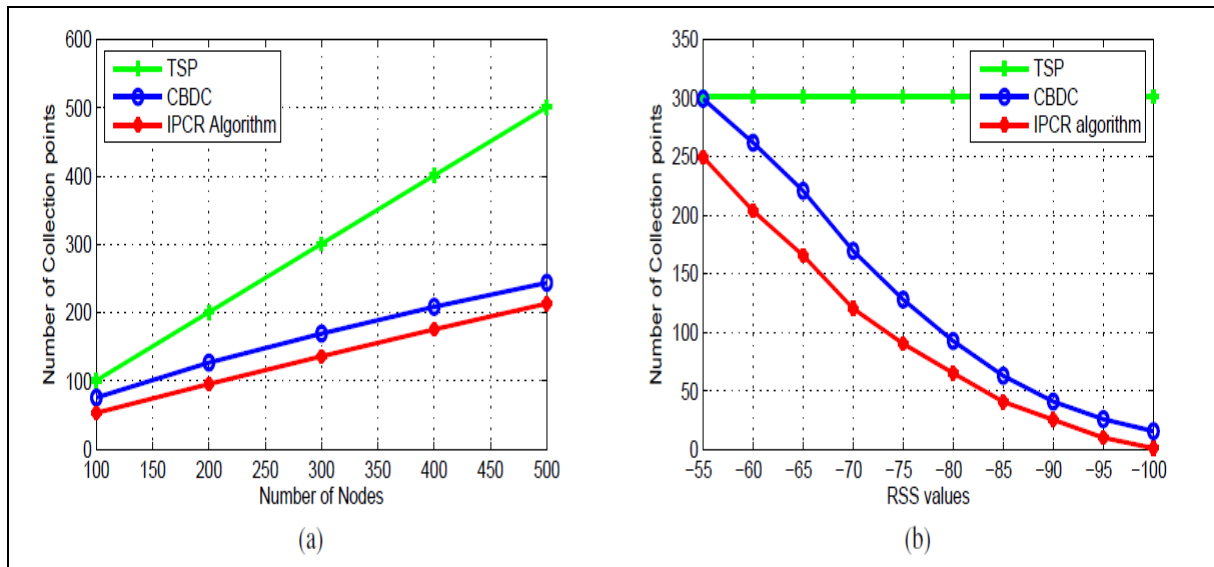


Figure 14: Number of Collection to IPCR, CBDC and TSP Algorithms, (a) Increasing the Number of Sensor Nodes, and (b) Increasing RSS Values

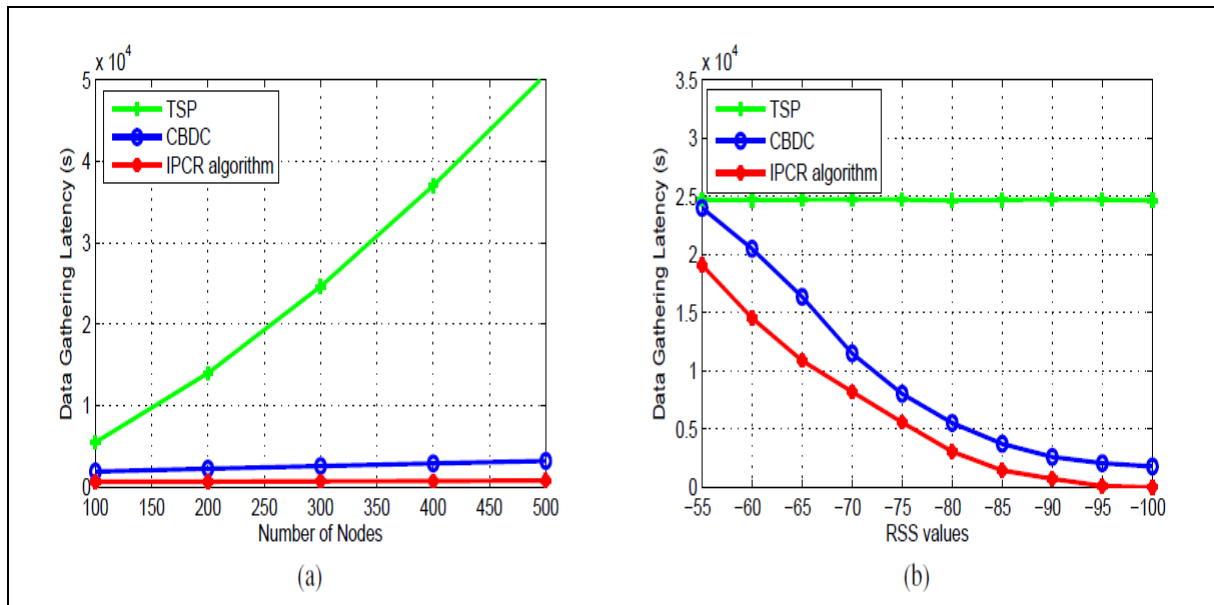


Figure 15: Data Gathering Latency of the IPCR, CBDC and TSP Algorithms, (a) Increasing the Number of Sensor Nodes, and (b) Increasing RSS Values

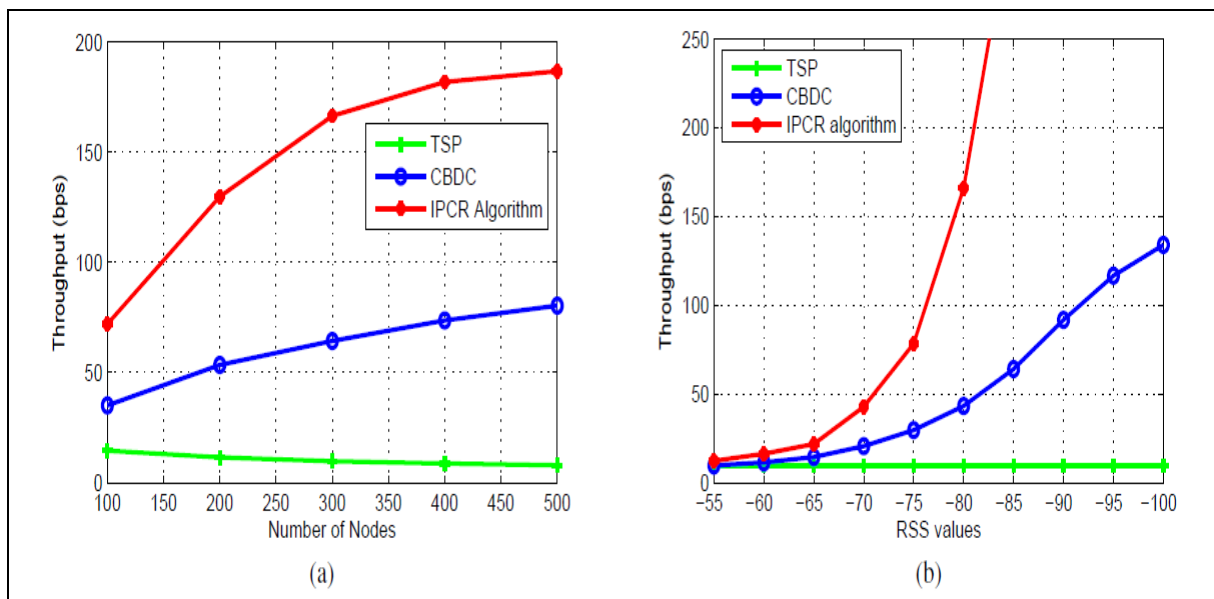


Figure 16: Network Throughput of the IPCR, CBDC and Algorithms, (a) Increasing the Number of Sensor Nodes, and (b) Increasing RSS Values

4.2.4. Data Gathering Latency

The data gathering latency is defined as the time needed until the mobile element completes one collection round. Figure 15(a) and (b) represent the relationship between the data gathering latency versus the number of sensor nodes and the RSS value, respectively. As shown in figure 15(a), the latency for IPCR algorithm is almost constant irrespective to the number of sensor nodes. Although the gap between the IPCR and CBDC algorithm is small, it expands as the number of sensor nodes increases. On contrast, TSP algorithms demonstrate the highest latency. On the other hand, the data gathering latency is decreasing as the communication range is increasing. This is quite apparent for the CBDC and IPCR algorithm. Notice that for the IPCR algorithm in addition to achieving the lowest latency, it almost reaches zero latency at communication ranges above -90 dBm, (in other word, when the network connectivity is greater than 30%). However, the data gathering latency due to CBDC stabilizes at 1.8×10^3 second. Moreover, when the network connectivity is weak, the latency difference between the IPCR and CBDC is the maximum, while this difference declines as the connectivity is getting strengthening. Again, the latency of the TSP algorithm is constant since it is independent of the communication range.

4.2.5. Network Throughput

To investigate the performance of these algorithms in term of network throughput, the throughput of the three algorithms is evaluated and the results are displayed in figure 16. In figure 16(a), the throughput as a function of the number of sensor nodes is plotted. It is clear from this figure that the IPCR algorithms performs better throughput than the other algorithms. This is due to the fact that the IPCR algorithm used lower number of collection points and therefore achieved the minimum latency. This matches with equation (3.9),

which shows that reducing the data collection latency yield to increase the network throughput. Although the CDBC shows lower throughput than the IPCR, its throughput is increasing as a function of increased number of sensor nodes. It is worth to note that at high number of sensor nodes the network throughputs were almost saturated despite the increment of nodes. This is due to the higher data collection latency found at large network sizes, as already explained in the previous section. Unsurprisingly, the throughput of the TSP algorithm slightly deteriorates as the number of sensor nodes increased. This is readily justified, since the data gathering latency in this algorithm is significantly high.

Furthermore, increasing the communication range of sensor nodes at a fixed number of sensor nodes also leads to increase the throughput of the sensor network, as shown in figure 16b. The most interesting trend form this figure is that the IPCR algorithm presents an exponential increment of the network throughput as the connectivity of the sensor network becomes greater than 10%.

4.3. Section Two: The Performance Evaluation of CDCA Algorithm

In this section, the performance of the algorithm is evaluated through 200 independent simulations run by Matlab. The CDCA algorithm is compared with the Area Splitting Algorithm (ASA). The efficiency of these algorithms is evaluated through a number of mobile elements, tour latency, and loads assignment of the mobile elements.

4.3.1. Simulation Scenario

In experiment, a set of sensor nodes are uniformly and randomly deployed within a two dimensional square sensor fields. The sink node is located at the origin point of the sensor field. The mobile element speed is set to 1m/s at which it is designed to move through a predefined route from point and returns to same point to collect data from sensor

nodes using single hop communication. This experiment is performed using Monte-Carlo simulation by Matlab. The following table presents the simulation parameters.

Table 6: Simulation Parameters

<u>Parameter</u>	<u>Value</u>	<u>Description</u>
R	40m	Communication Range
K, L	300 x 300	Network Area
N	100	Node Number
τ	2m	Tao
c	800m	Path Constraint

As mentioned in the introduction section, by using additional mobile elements the network latency is reduced. However, this reduction will be at the cost of network design and implementation. The number of mobile elements must be increased to allow the limitation of the maximum tour length (path constraint). In fact, as the path constraint increases the data collection latency is increased. This is due to fact that at high path constraint the ME is allowed to traversing long tour and therefore small number of mobile element is sufficient to cover the whole nodes. Figures 17, 18 and 19 illustrate the relationship between the path constraint and the number of mobile elements as a function of communication ranges, network area and τ values

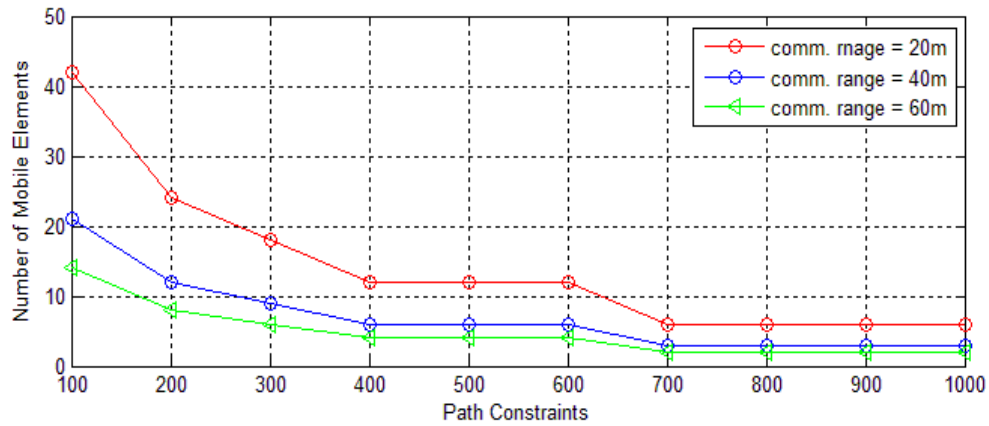


Figure 17: Path Constraints versus the Number of Mobile Elements for 20m, 40m, and 60m Communication Ranges of Mobile Elements.

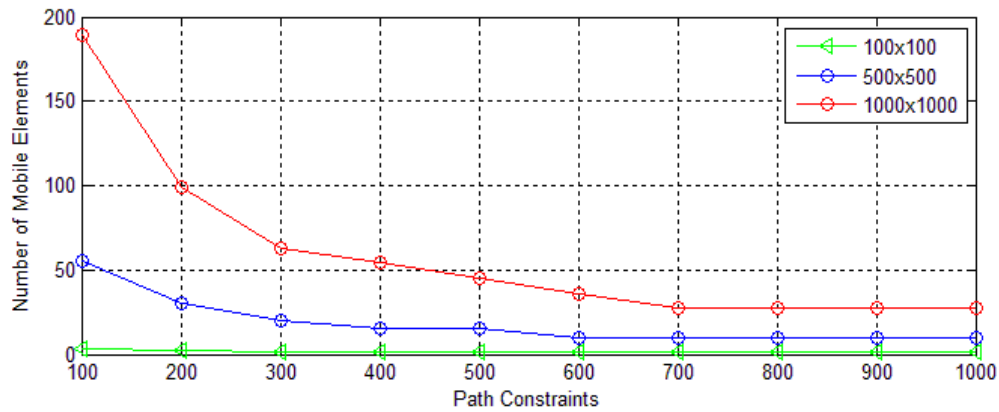


Figure 18: Path Constraints versus the Number of Mobile Elements for 100x100m², 500x500m² and 1000x1000m² Network Areas.

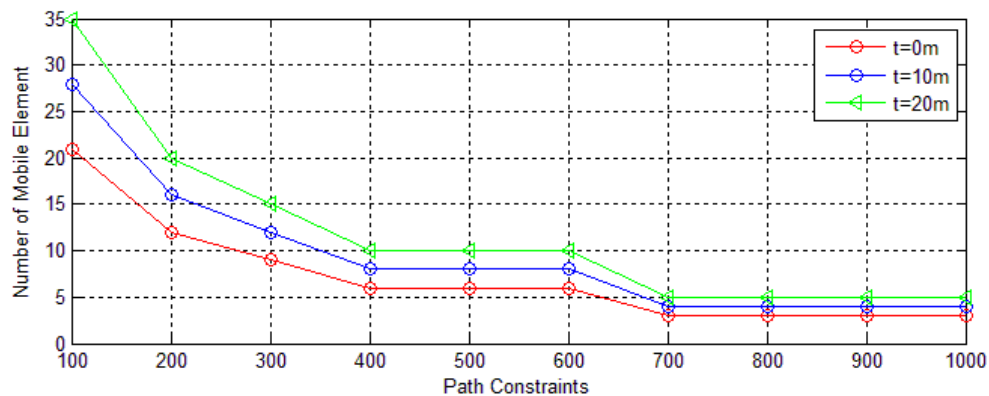


Figure 19: Path Constraint and Number of Mobile Elements Based on τ values

It is clear from Figure 17 that reducing the communication range led to increase the number of mobile elements. For example, when communication ranges 20m, 40m, and 60m are considered, the number of mobile elements at 100m path constraint is 42, 21 and 14, respectively. Note that these values of communication ranges were used for the Zigbee protocol IEEE 802.15.4 (Lee J. S., Su, Y.W., & Shen, C.C., 2007).

On the other hand, Figure 18 illustrates the performance of CDCA algorithm for three different network areas: 100x100m², 500x500m² and 1000x1000m². It is observed that for a large network area, the number of mobile elements is considerably higher than that for small network area. Moreover, the number of mobile elements remains constant when the path constraint is greater than a specific value; this value in this figure is about 700. This indicates that the number of mobile elements is not only depended on the path constraint, there are also other factors such as the shortcoming of the communication ranges between two neighbor mobile elements, which is presented by τ .

To show the effect of this value on the number of mobile elements, it was set to 0m, 10m and 20m and the communication range is fixed at 40m, the result is plotted in Figure19.

Since the communication range will decrease as $(r-\tau)$, the number of mobile elements will be decreased at high values of τ .

4.3.2. CDCA and ASA Comparison

The main objective of this part of simulation is to compare the performance of the CDCA and the ASA algorithms in terms of number of mobile elements required for a given path constraint, load balancing on these mobile elements and total network latency.

4.3.2.1. Number of Mobile Elements

The number of mobile elements is examined at 100 sensor nodes and for different network areas as varied from $100 \times 100 \text{m}^2$ to $500 \times 500 \text{m}^2$. The corresponding number of mobile elements for both algorithms is shown in Figure 20(a). CDCA algorithm requires lower number of mobile elements than the ASA; particularly large network areas. The number of mobile elements for the ASA algorithms suddenly increases when the network area is greater than $200 \times 200 \text{m}^2$.

Consequently, this leads to enlarge the performance gap between the two algorithms substantially. Then, the effect of the path constraint on the number of mobile elements for the two algorithms is investigated. As shown in Figure 20(b), the number of mobile elements of the CDCA algorithm is decreased as the path constraint increases. However, the ASA algorithm needs 100 mobile elements at small path constraint up to 700m, this number is equal to the number of sensor nodes; indicating that every sensor node requires one mobile element which is non preferable scenario . This highlights the invalidity of using the ASA for small path constraint. When the path constraint becomes larger than 700m, the number of mobile elements is rapidly decreased to exhibit almost the same performance at path constraint greater than 1000m.

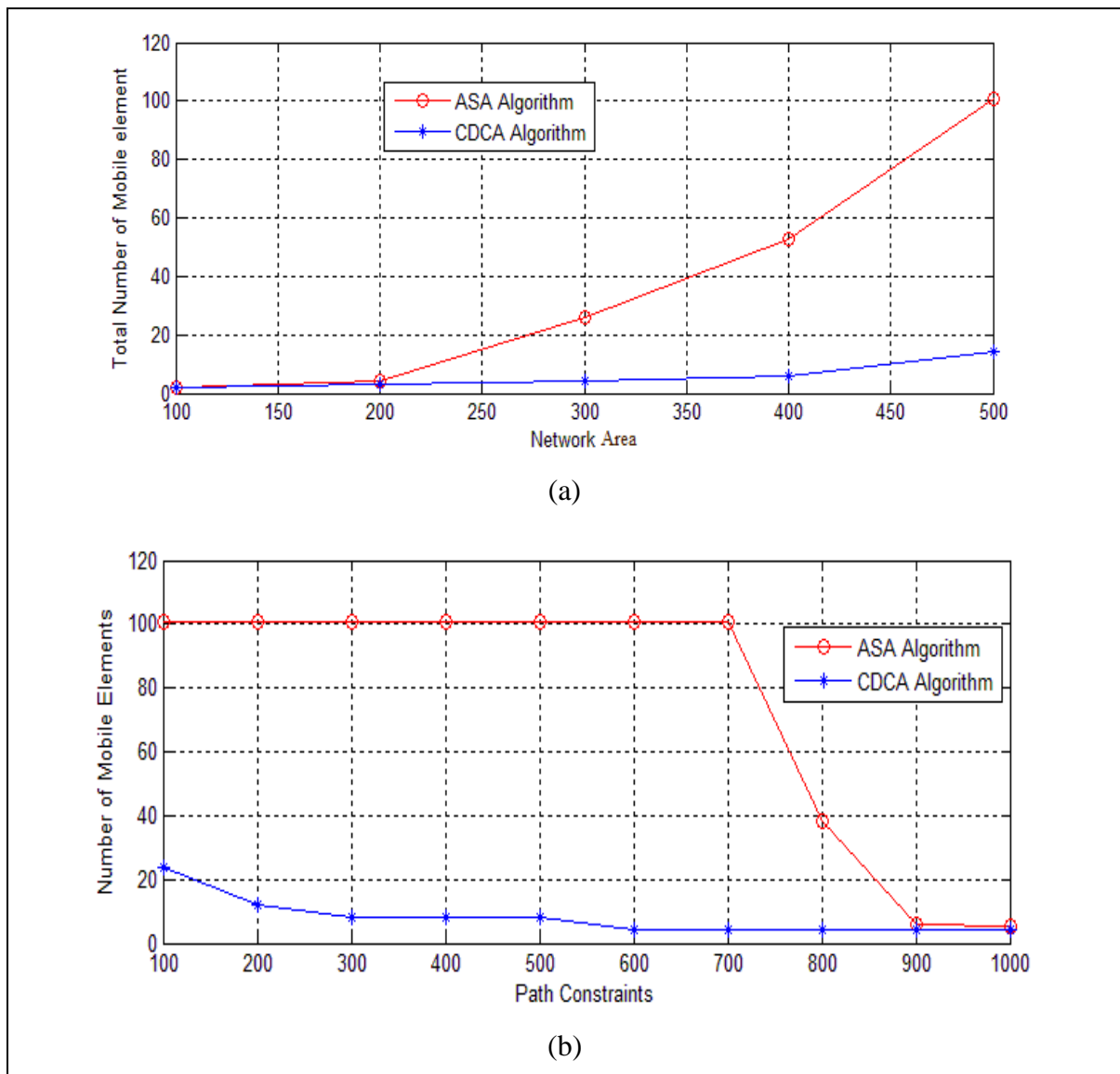


Figure 20: The Number of Mobile Elements as a Function of (a) Increasing Network Areas, and (b) Increasing Path Constraints of the Mobile Elements.

4.3.2.2. Load Balance on Mobile Element

The load balance with multiple mobile elements is one of important consideration when designing an efficient data gathering algorithm. By achieving this goal, the network latency will be reduced in addition to better usage of the mobile element resources such as buffer utilization and power consumption of the mobile elements.

The most common factor used to measure this criterion is the Variation Coefficient (VC). VC is defined as the percentage of standard deviation of tour lengths of all mobile elements and their mean value (He, Xu & Yu, 2009). The smallest VC, in this case, however, CDCA algorithm all mobile elements will traverse an identical path lengths and therefore, the VC will be zero. For a fair and consistent comparison, the VC is computed based on the number of sensor nodes, which can be written as:

$$vc\% = \frac{\sum_{i=1}^M \sigma_i}{\frac{1}{M} \sum_{i=1}^M N_i} 100\% \quad (4.2)$$

Where σ_i is the standard deviation of the number of sensor nodes belonging to mobile element i , N_i is number of sensor nodes belonging to the mobile element i , and M is the total number of mobile elements. Note that the lower VC is the better the load balance for each mobile element. Figure 21(a) illustrates the VC for CDCA and ASA algorithms, at varying network area. The VC of the two algorithms is almost similar at low network areas. Despite this, as the network area increases, the performance gap between the two algorithms is expanded. This result is apparent since the CDCA algorithm demonstrates a consistent increase in the VC. While this value for the ASA algorithm rapidly increases.

Figure 21(b) shows the VC as a function of increasing density of sensor nodes. Surprisingly, the VC of the CDCA algorithm decreases as the number of sensor nodes increases, while this value is substantially increased for ASA algorithm. This emphasizes the efficiency of using CDCA algorithm for dense sensor networks. Figure 21(c) shows the VC obtained by the two algorithms; the load balance is improved for both algorithms, but

the CDCA algorithm has lower CV percentage than ASA over the entire range of path constraint.

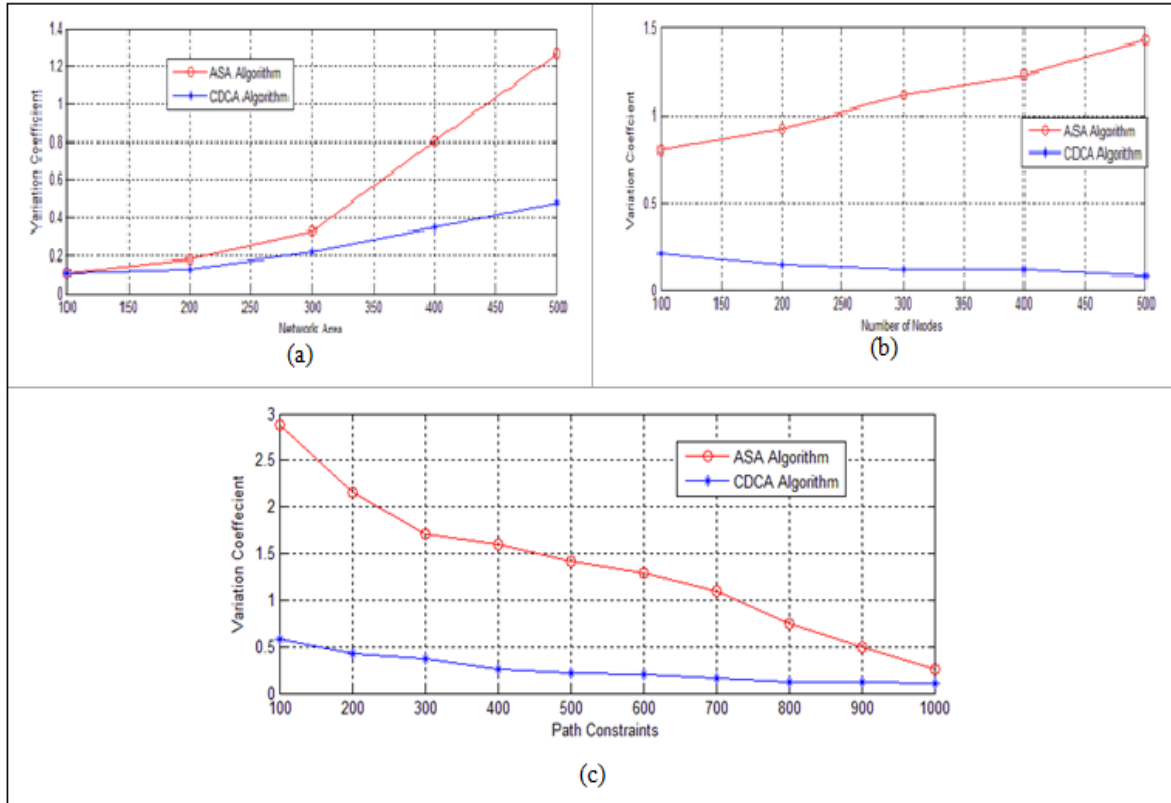


Figure 21: Variation Coefficient (VC), (a) Increasing Network Area, (b) Increasing Number of Sensor Nodes, (c) Increasing Path Constraints.

4.3.2.3. Network Latency

Latency can be defined as the duration of time required to complete one round of data gathering by mobile elements. As mentioned before, the increasing of the number of Mobile elements leads to decrease the network latency (Tang et al., 2012). Figures 22 illustrate the effect of network areas, number of nodes and the path constraint on the network latency for both algorithms. Figure 22(a) shows a gradual increasing of the network latency for the two algorithms as the network area is increased, however with superiority to the CDCA algorithm. Moreover, in Figure 22(b) the latency is not changed

with the increasing number of nodes for the CDCA. This is not the case for the ASA algorithm; for which the network latency is slightly increased as a function of the number of sensor nodes. This is due to the fact that the ASA algorithm adopts the Travel Sales-Man problem (TSP) algorithm to compute the mobile elements trajectories.

Furthermore, the increasing of the path constraint of mobile elements generally yields to reduce the number of mobile elements and therefore to increase the network latency. Although the ASA algorithm is resulted with an almost constant latency as shown in Figure 22(c), the CDCA algorithm makes the data gathering with lower latency. In this figure, in addition, at a low path constraint, the CDCA reduces the network latency substantially. However, this latency increases with the increasing of the path constraint, nonetheless it still maintain lower latency than the ASA algorithm over the entire range of the path constraints.

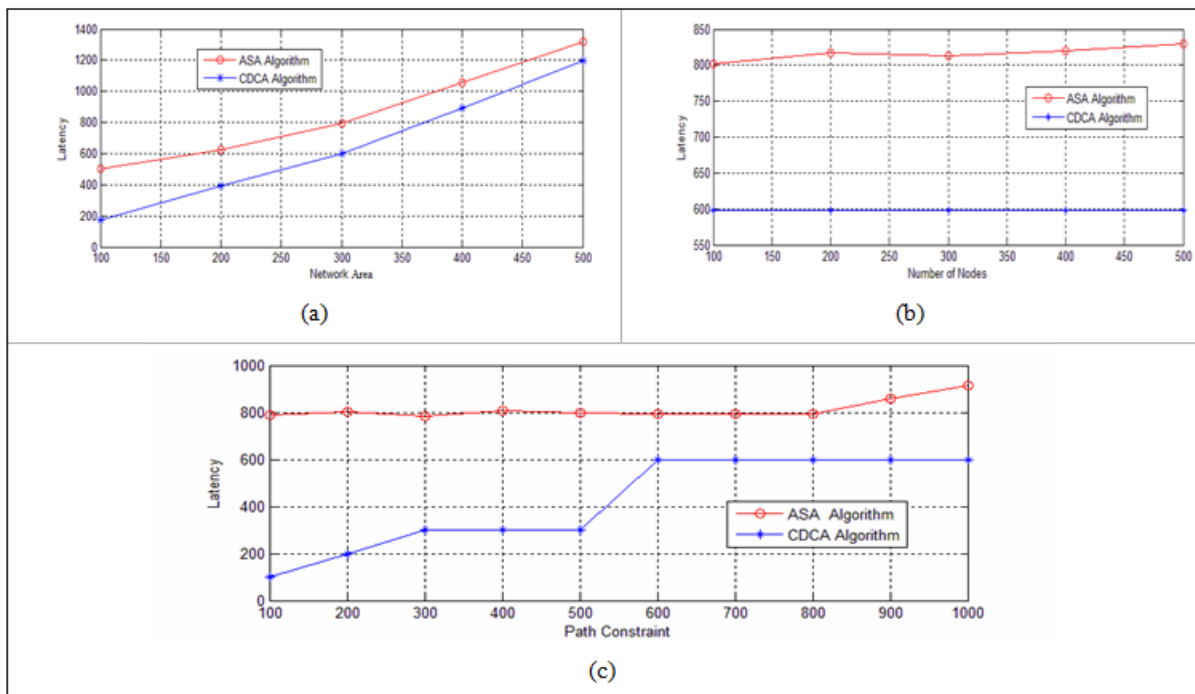


Figure 22: Network Latency, (a) Increasing Network Area, (b) Increasing Number of Sensor Nodes, and (c) Increasing the Path Constraint

CHAPTER FIVE

Conclusions and Future Works

In this thesis presents data gathering in Wireless Sensor Networks (WSN). Two data gathering algorithms are proposed in order to minimize energy consumption and reduce latency in Wireless Sensor Networks (WSNs). The first algorithm, proposes efficient mobile-based data gathering technique, referred to as intersection points of communication range (IPCR) algorithm. The key idea of IPCR algorithm is to obtain an optimal trajectory of the mobile element with the minimum number of collection points and single-hop communication. The simulation results showed that the proposed algorithm is provided a comparable result, which is almost identical, to the optimal travel sales-man problem (TSP) solution provided by the mixed integer linear programming (MILP). More over, the IPCR algorithm exhibited a superior performance in comparison with the connectivity-based data collection (CBDC) algorithm and the travel sales-man problem (TSP) algorithm and in terms of data gathering latency and networks throughput.

The second algorithm, proposes new data gathering technique in WSN based on using more than one of mobile elements to collect data from sensor nodes, referred to as CDCA algorithm. The main idea, focuses on reducing data gathering latency which leads to increase the network throughput, covering all sensor nodes and decreasing number of mobile elements used and in WSNs through dependent on predetermined path of each mobile element instead of using TSP. Simulation results show better performance to our algorithm in comparison with the ASA algorithm in terms of load balance, number of mobile elements and network latency.

In future work, as each mobile element is designed to collect data from large number sensor nodes, the buffer size limitation of mobile elements should be considered. In addition, the way of delivering data through mobile elements to the sink node should be investigated. It would be useful to study the power recharging cycles of the mobile elements in terms of it is time and location.

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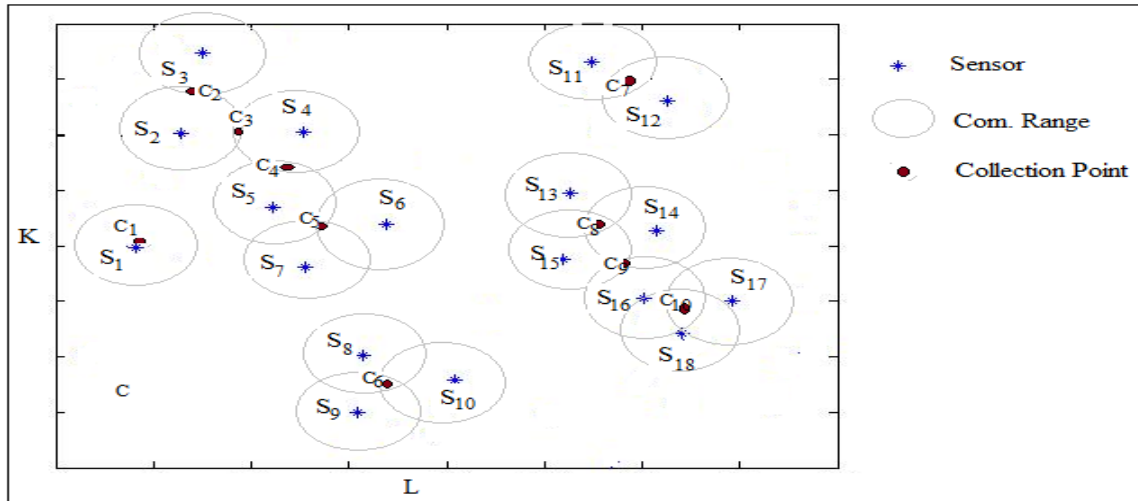
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Appendix

A. IPCR Algorithm Equations

Each sensor network fields include number of sensor nodes. The following figure illustrates sensor nodes distributed randomly in $K * L$ area.



In this figure, we have (18 sensor nodes) and (10 Collection points) where each collection point includes at least one sensor nodes (member) as following:

$$\begin{aligned}
 C_1 &= \{s_1\} \\
 C_2 &= \{s_2, s_3\} \\
 C_3 &= \{s_2, s_4\} \\
 C_4 &= \{s_4, s_5\} \\
 C_5 &= \{s_5, s_6, s_7\} \\
 C_6 &= \{s_8, s_9, s_{10}\} \\
 C_7 &= \{s_{11}, s_{12}\} \\
 C_8 &= \{s_{13}, s_{14}, s_{15}\} \\
 C_9 &= \{s_{14}, s_{15}, s_{16}\} \\
 C_{10} &= \{s_{16}, s_{17}, s_{18}\} \\
 &\vdots \\
 &\vdots \\
 C_i &= \{n_1, n_2 \dots n_p\}
 \end{aligned}$$

Where n is sensor node and p is number of sensor nodes in collection point i . So, the sensor network (S) include collection points, such that

$$S = \{C_1, C_2, \dots, C_M\}, \quad M \text{ is number of collection points}$$

Mobile will move to each C_i and collecting data from sensor nodes. Each node need for a period of time to send sensed data to the mobile element. This time (τ) depends on data rate (R) and package size (G).

$$\tau = \frac{G}{R}$$

If we have n_p sensor nodes in collection point (C_i), this mean the mobile element will waiting in this collection point to period of time ($TDMAC(i)$).

$$TDMAC(i) = \tau \times n_p$$

Latency is define as the time need to mobile element to complete one round. If we assume (W) represent the time of mobile element to complete one round without stop to collect data. According to speed rule:

$$\text{Speed}(q) = \text{distance}(l) / \text{time}(t)$$

$$\text{Time}(t) = \text{distance}(l) / \text{speed}(q)$$

Because speed of mobile element moving in 1 m/s . then

$$W = \text{distance}(l) / \text{speed}(q).$$

Time for all collection point can represent as $\sum_{i=1}^M TDMAC(i)$

Depends on the pervious values, the total time to complete one round (latency) is:

$$\text{Latency}(s) = W + \sum_{i=1}^M TDMAC(i)$$

Or

$$\text{Latency}(s) = l/q + \sum_{i=1}^M TDMAC(i)$$

Throughput is a measure of how many units of information can process in a given amount of time (each round). Assume P is data production of all sensor nodes.

$$P = K * N.$$

According to throughput definition,

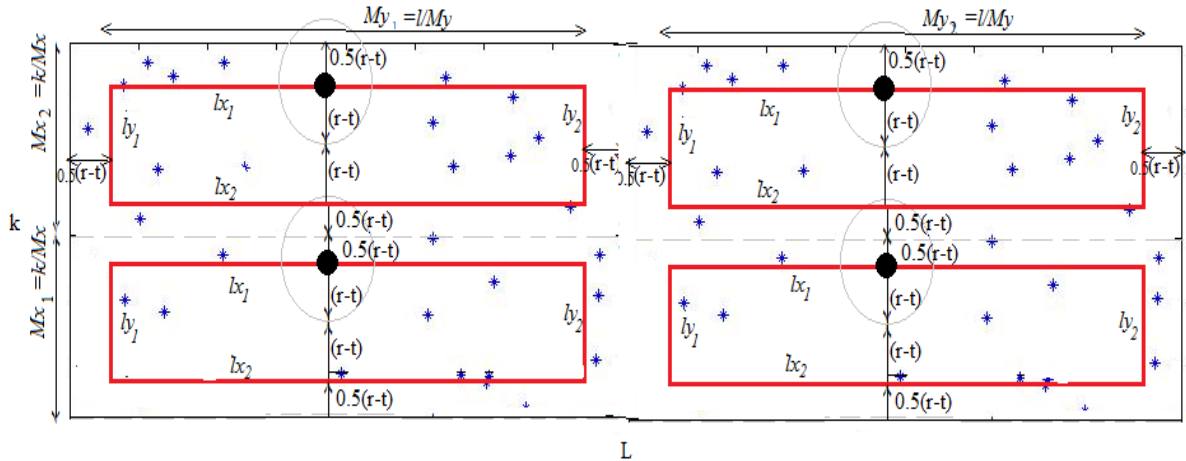
$$\text{Throughput}(bps) = \frac{P}{\text{Latency}}$$

Or

$$\text{Throughput}(bps) = \frac{K * N}{\text{Latency}}$$

B. CDCA Algorithm Equations

The following figure illustrates the predetermined path for four mobile elements.



We have square area $K*L$. Each mobile element has communication range (r) . And use the shortage value (t) of communication range to ensure covers all sensor nodes.

So that,

$$\text{Actual communication range} = (r-t)$$

The value " $0.5(r-t)$ " to ensure each mobile element will connect with neighbors mobile elements.

The first step, compute the number of MEs (Mx) on K-axis. As a shown in figure.

$$K = Mx_1 + Mx_2 + \dots + Mx_n, \text{ where } n \text{ is number of horizontal division.}$$

$$Mx_1 = 0.5(r-t) + (r-t) + 0.5(r-t) + (r-t)$$

$$= 3(r-t)$$

$$Mx_2 = 3(r-t)$$

.

.

.

$$Mx_n = 3(r-t)$$

Because all partitions have the same distance, so the count of Mx is:

$$Mx = K/3(r-t)$$

We will use the ceiling function because it is not logical to have half of mobile element. Therefore

$$M_x = \left\lceil \frac{K}{3(r-\tau)} \right\rceil$$

Every mobile element in each round will move as following:

horizontal path \rightarrow vertical path \rightarrow horizontal path \rightarrow vertical path.

Vertical path (l_y)

$$\begin{aligned} l_y &= l_{y1} + l_{y2} \\ &= K/M_x - (r-t) + K/M_x - (r-t) \\ &= 2(K/M_x - (r-t)) \end{aligned}$$

Depends on the constraint path, we need to compute the number of vertical divisions (M_y) when:

$l > C$, where l is the path length of mobile element, C is path constraint.

$$\begin{aligned} l_y + 2l - (r-t) &> C \\ l_y + 2l - (r-t) / C &> 1 \\ M_y &= l_y + 2l - (r-t) / C \end{aligned}$$

We use the ceiling function because it is not logical to have half of mobile element.

$$M_y = \left\lceil \frac{l_y + 2l - (r-t)}{C} \right\rceil$$

horizontal path (l_x)

$$\begin{aligned} l_x &= l_{x1} + l_{x2} \\ &= l/M_y - (r-t) + l/M_y - (r-t) \\ &= 2(l/M_y - (r-t)) \end{aligned}$$