HIGH PERFORMANCE COMMUNICATION FRAMEWORK FOR MOBILE SINKS WIRELESS SENSOR NETWORKS

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A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

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September 2009

This thesis is dedicated to my
Father Chao Long Chang (1938-2007) &
my family

ACKNOWLEDGEMENTS

I would like to express my deep felt gratitude to Prof. Madjid Merabti for his patience and guidance and Dr. Hala Mokhtar for her precious help and support during this research. I would also take this opportunity to thank my late father, my mother, my school and college teachers for their guidance and support to enable me to reach this stage in my life. I am also very grateful to my wife Ching-Shan Huang, and my daughter Chih-Ling Chang for their continuous love and support throughout a difficult and trying period in our lives. I would also like to extend my thanks to my sisters Mei-Ling Chang, Mei-Chou Chang and niece Mei-Ling Chen for their support to my family while I was away from Taiwan. I also want to acknowledge my office friends Dr. Paul Fergus and Dr. Omar Abuelma'atti for their encouragement, deliberations and support throughout my PhD studies. I want to thank Dr. John Haggerty and Dr. David Llewellyn-Jones and Mr Rodney Donohoe for those long discussions which helped to overcome difficult periods during my studies. I also want to acknowledge the cooperation of Faycal Bouhafs, Huma Javed, Arshad Muhammad, Gurleen Arora, Robert Hegarty and Kashif Kifayat. Additionally I would like to thank the academic, administrative and technical staff of the School of Computing and Mathematical Sciences. I am particularly grateful to all the people mentioned above in particular and to all those that I have not mentioned that have helped me by their sincere and continuous support throughout the course of my Ph.D.

I want to dedicate this thesis to my late father Chao-Long Chang and mother Nan-Tzu Wen who has been a source of inspiration, selfless love and devotion throughout my life.

ABSTRACT

A wireless sensor networks typically consist of thousand of nodes and each node has limited power, processing and bandwidth resources. Harvesting advances in the past decade in microelectronics, sensing, wireless communications and networking, sensor networks technology is expected to have a significant impact on our lives in the twenty-first century. Proposed applications of sensor networks include environmental monitoring, natural disaster prediction and relief, homeland security, healthcare, manufacturing, transportation, and home appliances and entertainment. However, Communication is one of the major challenges in wireless sensor networks as it is the main source for energy depletion. Improved network lifetime is a fundamental challenge of wireless sensor networks.

Many researchers have proposed using mobile sinks as one possible solution to improve the lifetime of wireless sensor networks. The reason is that the typical many-to-one communication traffic pattern in wireless sensor networks imposes a heavy forwarding load on the nodes close to the sinks. However, it also introduces many research challenges such as the high communication overhead for updating the dynamic routing paths to connect to mobile sinks and packet loss problems while transmitted messages to mobile sinks. Therefore, our goal is to design a robust and efficient routing framework for both non-geographic aware and geographic aware mobile sinks wireless sensor networks.

In order to achieve this goal in non-geographic based mobile sinks wireless sensor networks, we proposed a spider-net zone routing protocol to improve network efficiency and lifetime. Our proposed routing protocol utilise spider web topology inspired by the way spiders hunt prey in their web to provide reliable and high performance data delivery to mobile sinks. For routing in geographic aware based mobile sinks wireless sensor networks, we proposed a fault-tolerant magnetic coordinate routing algorithm to allow these network sensors to take advantage of geographic knowledge to build a routing protocol. Our proposed routing algorithm incorporates a coordinated routing algorithm for grid based network topology to improve network performance. Our third contribution is a component level fault diagnosis scheme for wireless sensor networks. The advantage of this scheme, causal

model fault diagnosis, is that it can “deeply understand” and express the relationship among failure behaviours and node system components through causal relations.

The above contributions constitute a novel routing framework to address the routing challenges in mobile sinks wireless sensor networks, Our framework considers both geographic and non-geographic aware based sensor networks to achieve energy efficient, high performance and network reliability. We have analyzed the proposed protocols and schemes and evaluated their performances using analytical study and simulations. The evaluation was based on the most important metrics in wireless sensor networks, such as: power consumption and average delay. The evaluation shows that our solution is more energy efficient, improves the network performance, and provides data reliability in mobile sinks wireless sensor networks.

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CHAPTER 1

1 INTRODUCTION

In many situations, users might be interested in gathering information about specific physical phenomena and want to continuously retrieve information about the monitoring object while in motion. Therefore, a new kind of wireless network has appeared in the last few years; Wireless Sensor Networks (WSN). WSN technology is highly anticipated as one of the most promising technologies in the next decade due to its potential applications such as home appliances, intelligent security, medical telemetry, disaster relief, environment monitoring and military surveillance. These applications are resulting from advances in micro-electro-mechanical systems (MEMS), signal processing, wireless communications and networking which led to the development of smart sensors. These smart sensors are expected to be remotely deployed in large numbers and to operate autonomously in unattended environments providing a vision of "Ambient Intelligence" [M.Abdur'09].

In an ambient intelligence environment, devices can cooperate together to support people in carrying out their everyday life activities, in easy, natural ways using information and intelligence that is hidden in the network connecting these devices. In these circumstances, a critical wireless technology needs to coordinate a large number of wireless sensing devices. All sources of information have to collaborate in providing as precise a picture of the real world as is required and transfer information to the place where it is needed. Like many WSN application scenarios, such a network will normally consist of hundreds or thousands of such unattended sensing nodes that communicate through wireless channels for information sharing and cooperative processing.

These unattended wireless sensor nodes are expected to have significant impact on the efficiency of many military and civil applications such as combat field surveillance, security and disaster management. Networking sensor nodes can assist in gathering geographical and meteorological variables such as position, temperature and humidity. For example, in combat field surveillance, the use of networked sensors can limit the need for personnel involvement in dangerous reconnaissance missions. These sensor nodes in military applications can be used to detect moving targets, chemical gases, or the presence of micro-agents. In disaster management situations such as earthquakes, sensor networks can be used to selectively map the affected regions directing emergency response units to survivors.

As the sensor nodes are small in size, each is only capable of a limited amount of processing. Energy consumption in a sensor node is a dominant consideration due to small and finite sources of energy. In order to make optimal use of this energy, communications should be minimized as much as possible. Many solutions, both hardware and software related, have been proposed to optimize energy usage. Moreover, sensor nodes are deployed in regions which have no infrastructure and have no human intervention which require nodes to be responsible for self-connectivity and self-reconfiguration in case of changes. In addition, in many cases, multiple sensor nodes are required to overcome environmental obstacles like obstructions, line of sight constraints and etc... In most cases, the environment to be monitored does not have an existing infrastructure for either energy or communication. It therefore becomes imperative for sensor nodes to survive on small, finite sources of energy and communicate through a wireless communication channel.

Sensor nodes differ from nodes in an ad hoc network in the communication pattern: while ad hoc network nodes may contact any other node in the network, sensors nodes send data only to the data collection node, i.e. the "sink". Sink nodes can be static or mobile and are responsible for collecting the data from all sensor nodes. This should be achieved in a fair way. The range of the sensors' radio signal is in general quite short, thus multi-hop communication is needed between source sensor nodes and sinks. As a result, the volume of traffic in the network is focused in the neighbourhood of the sinks. Subsequently, those sensor nodes in the neighbourhood of static sinks have their energy resources depleted. This also means that the lifetime of the network depends on these critical nodes. To overcome this limitation, "Mobile Sinks" can be used in different scenarios. Examples of mobile sinks are PDAs, laptops carried by users to gather sensor readings, or process and aggregate sensed data from the local environment.

Different from a typical WSN, mobile sinks wireless sensor networks (MSWSN) consist of a large number of sensors with several mobile monitoring terminals, called mobile sinks. This promising solution would enhance performance, extend network lifetime and facilitate congestion avoidance by routing data to a nearby mobile sink. However, it also introduces many problems and research challenges such as the high communication overhead for updating the dynamic routing paths to connect to a mobile sink, and require a reliable data transport scheme because of sink mobility. Several applications can use MSWSN. For example, a fire fighter collects wind direction information, temperature, and weather conditions from a WSN deployed in the scene of a forest fire. The fire fighter collects the sensed information by using a PDA to monitor the current situation to reduce the damage of the wildfires and also maintain data communication. The sensor nodes around the fire fighters can relay temperature related measurement values to track current forest fire situations. Some solutions have been proposed, for example [J.Youn'04] [R.R.Kalva'05] [Khanna'07] [Stefano'08] [Yanzhong'09], for routing data in such scenarios.

Another major issue for WSN is fault tolerance. Since sensor nodes are typically operated with limited energy and deployed in a harsh environment that suffers numerous attackers such as a malicious node attack, fault tolerance becomes vitally important for wireless sensor networks. It can gracefully respond to unexpected failure and properly enable the system to operate continually. However, the drawbacks of existing fault tolerance mechanisms are that they are very complex and consume too much energy and code compiling resources. Therefore, how to implement low cost and highly reliable fault tolerance mechanisms is one of the key issues in WSN.

This thesis addresses the communication and routing mechanisms required to provide high performance and fault-tolerance for MSWSN applications. In this chapter, we first describe the potential applications for WSN and the problems of designing a high performance routing mechanism. We then present the objectives and contributions of this research.

1.1 Wireless Sensor Nodes Hardware

Recently, micro-electro-mechanical systems (MEMS) technology has made many promises to revolutionize nearly every product category (e.g. automotive electronics, medical equipment, smart portable electronics, computer peripherals, and wireless devices, etc.). This technology enables WSN for many monitoring, surveillance and control applications. Vitally, this technology reduces the cost, size and power consumption of sensor nodes to an acceptable quality. As Fig.1-1 below shows, a sensor node generally comprises integrated hardware (microcontroller, sensing unit, memory, power supply and transceiver), and also includes software (power management, system management, and configuration mechanisms). Moreover, because of their small size, low cost, and low power consumption, communication between units can be used to build up a network or 'mesh' of sensors. There are a number of research projects that focus on hardware components of wireless sensor nodes which specialize in shrinking the size, energy consumption, and costs, based on the use of off-the-shelf components. However, in this thesis, we focus on the networking aspects of WSN. For the sake of completeness, the discussion begins by presenting a processor specifically designed for sensor networks.

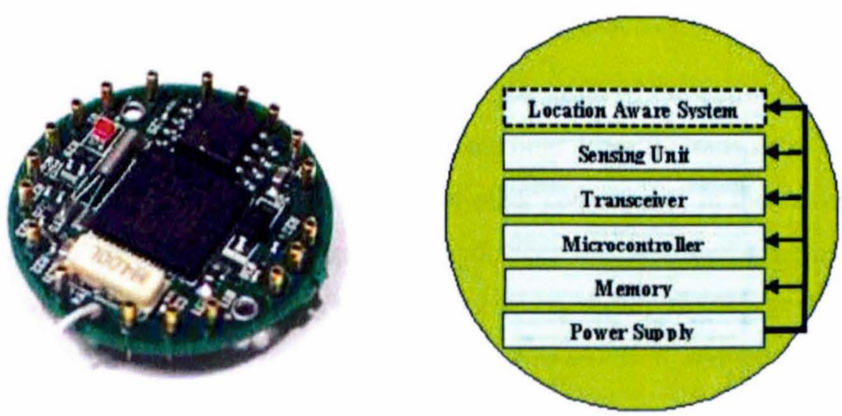

Figure 1.2 : The Sensor Node Hardware Architecture

Sensing Unit: A sensing unit is the interface that measures the physical data of the area to be monitored. This sensing unit's task is to sample physical signals and convert analogue signals to digital ones. The continual analogue signal sensed is digitized by an Analogue-to-Digital Converter (ADC) and sent to controllers for further processing. Characteristics and requirements of sensor nodes should be small size, consume extremely low energy, perform in high volumetric densities, and operate in unattended environments. Each sensor node has a certain area of coverage for which it can reliably and accurately report the phenomena that it is observing. Moreover, sensors are classified into two categories; passive and active. Passive sensors sense the data without interacting with the environment and only sample the analogue signal. Active sensors are actively probing the environment, for example, a sonar or radar sensor which generates shock waves to detect target objects.

Transceiver: Each wireless sensor node includes a wireless communication module to interact with other nodes. The functionality of a transceiver is provided by combining both transmitter and receiver into a single device. This transceiver has various choices of wireless transmission media such as Radio Frequency (RF), Optical communication (Laser) and Infrared. RF based communication is the most relevant that fits to most of the WSN applications due to its free use, huge frequency spectrum allocation and global availability. Compared to other devices in the sensor node, the radio module consumes the largest amount of power in the node system. If the radio module has a low-power listen mode or intermittent sleep mode and short message transmit times, it will allow the sensor node's lifetime to be extended. So power trade-offs and antenna selection is important for radio performance optimization and must be considered when choosing a transceiver.

Microcontroller: A microcontroller controls the operation of the entire sensor node. The main task of the microcontroller is to take readings from its transceiver, perform data processing and control the functionality of other components in the sensor node. Because of their flexibility to connect to other devices and are often programmable, they can coordinate with other devices to monitor incoming signals, perform data processing and decide whether to send out a message or switch to sleep mode.

Memory: There are two different types of memory in WSN; Random-Access Memory (RAM) and Read-Only Memory (ROM). The RAM is to store data and interim results. RAM memory used for allowing fast access to results in computations and Non Volatile Random-Access Memory (NVRAM) to store results during power down. RAM also saves space in embedded applications. Different from RAM, ROM provides storage to hold both the program and the data. ROM can contain programs and fixed configuration data. Current research prefers an "All in One" approach based on NVRAM with high speed read time and fast write time.

Power Supply: The power supply is one of the most important components because it provides the energy for sensing, communication and data processing. Energy expenditure is less for sensing and data processing but more for data communication. From a power consumption point of view, processing is a much cheaper operation than transmitting [L. Doherty'01]. The energy cost of transmitting 1 Kb a distance of 100 m is approximately the same as that for the execution of 3 million instructions by a 100 million instructions per second/watt processor. Batteries are the main source of power supply for sensor nodes. There are two types of battery; chargeable and non-rechargeable. Current sensors are able to extend their lifetime by energy saving or renewing their energy from acoustic energy, thermal energy, vibration energy or solar energy.

Location Aware System: This location aware system is an important optional component which provides geographical location information for sensor network applications. This requires network functionalities designed with an emphasis on spatial / location aspects. A key feature that makes WSN different from traditional networks is they can be viewed as a bridge to the physical world. In location aware WSN or named geographic based WSN, each sensor node is able to obtain its location information through an equipped GPS processor [Patwari'02] or some localization techniques [C. Wang'05]. There are a variety of localization systems and techniques for WSN that will be introduced, such as sensor nodes equipped with a GPS signal receiver (with tradeoffs in cost, complexity and energy consumption) or that acquire their geographical locations without GPS. However, by leverage with cost, complexity and energy consumption, sensor nodes are able to detect and monitor the actual physical phenomena at geographical locations which are very useful in object tracking applications in WSN.

Each of these components has to operate whilst balancing the trade-off between low energy consumption on the one hand and the need to fulfill their tasks on the other. For example, both the communication device and the controller should be turned off as long as possible. To wake up again, the controller could, for example, use a preprogrammed timer to be activated. Alternatively, the sensors could be programmed to raise an interrupt if a given event occurs – say, a temperature value exceeds a given threshold or the communication device detects an incoming transmission. Such preprocessing can be highly customized to the specific sensor yet remain simple enough to run continuously, resulting in improved energy efficiency.

1.2 Salient Features of Wireless Sensor Networks

In the previous section we discussed the hardware of sensor networks. In this section, we study some of the salient features of wireless sensor networks.

Sensor Limitation – In many sensor networks, sensor nodes have restricted power (probably a few hundred mAh), limited computing capability, small memory (probably a few hundred Kbytes of RAM), low data transmission rates (up to 20 Kbps) and limited communication range (10-50 meters) [Hill'00]. These limitations have a direct impact on the functioning of the network as a whole and different protocols have to be designed to take into account these limitations. To compensate for this resource limitation, energy-efficient operation is a key technique.

Densely Deployed – Different from traditional network applications, a large number of nodes are deployed. The number of nodes can be from a few hundred to hundreds of thousands depending on the application. From a network viewpoint, a network consisting of a large number of sensor nodes will require nodes to act as relay nodes to avoid using long-distance antenna which has high power consumption. Hence, multi-hop communications will be a particular feature of WSN to improve the energy efficiency of communication.

Data Centric Addressing – In traditional networks, data communication between two specific devices is enabled as each device has the others network address. When users want to query data from a network, typically, they need to know where the data is. The aim of a sensor network is to collect events occurring in the sensor field and produce a different networking viewpoint from traditional networks. This introduces a new networking dimension from a node-centric to a data-centric network. Moreover, sensor nodes are densely deployed which leads to similar sensed and replicated data from neighbouring nodes. In this case, the data-centric approach is closely related to query concepts known from databases; it may also combine well with collaboration, in-network processing, and aggregation. Especially in resource-limited wireless sensor networks, sensor nodes in a data-centric network will need to co-operate and the sensed data will require aggregation.

1.3 Problem Definition

Unlike traditional networks, where the focus is on maximizing channel throughput or minimizing node deployment, the major consideration in a wireless sensor network is to extend system lifetime, improve network performance and enhance system robustness. Because of the low cost tiny devices used the operation of the network is highly energy sensitive. The system lifetime of the network largely depends on the energy of the sensor nodes nearest the sink(s) that relay all messages on the last hop. Therefore, to overcome this limitation, the mobile sink(s) could move away from depleted areas. However, mobility raises several routing issues. Thus, new protocols are required to provide efficient routing between the source nodes and the mobile sink.

First, energy efficiency is a dominant consideration. As mentioned before, this is because sensor nodes only have a small and finite source of energy. Many solutions, both hardware and software related, have been proposed to optimize energy usage. Since network topology will change more frequently in MSWSN, previously used routing protocols for traditional WSN will not be adaptable. Consequently, a new routing mechanism is required to reduce the communication costs in deciding the routing technique to be used.

Second, in many WSN applications, it is desirable that users do not experience a substantial amount of delay after they request sensor data. However, in many wireless sensor network applications, a large number of nodes are deployed within a certain geographical area. The main challenge is how to provide a high performance data dissemination mechanism in large scale sensor networks, in order to maintain network and network conditions. Hence, routing in large scale sensor networks needs to be scalable with high network performance routing mechanism to achieve user / application requirements.

Third, during the routing process, the sink can be stationary or mobile. This property of the sink will affect the routing protocol, since all nodes in the network cannot be continuously aware of the current position of the sink and the routing mechanism needs to find the mobile sink. Moreover, the routing topology created by a routing protocol may greatly vary in time to cause extra overhead in the network layer. Hence, the new routing protocol should provide a light-weight and robust routing mechanism to support the efficiency-robustness tradeoff for routing in mobile sink wireless sensor networks.

Finally, since these sensor nodes are typically operated with limited energy, computing, communication capabilities, and randomly deployed in harsh environment, they are likely to suffer numerous attacks. These limitations and attacks render WSN more prone to failure than in conventional wireless networks. Therefore, a reliable and energy efficient error-handling mechanism is required to ensure the robustness of the sensor network, which can avoid failures and break the hierarchical connectivity assumption.

1.4 Scenarios

To motivate our research, we consider a target scenario which is the fire rescue services facing a forest fire. Typically, sensor nodes are deployed randomly (e.g., via aerial deployment), and are expected to self-organize to form a multi-hop network. These sensor nodes will cooperate with a fire fighting team to group as an early alarm and fire rescue system. Normally, a fire fight team may consist of a set of firefighters, a few fire engines and at least one incident commander vehicle. During the process of forest fire rescue, the incident commander vehicle is in charge of the whole operation, including sensor data collecting and monitoring the fire. A mobile sink, in this scenario, can be any data collection terminal device carried by firefighters, fire engines or an incident commander vehicle to gather sensor readings from the monitoring region. Fig. 1-2 presents a view of forest fire field scenario.

In this scenario, the fire fighting team is more concerned with physical phenomena associated with geographical location(s)/region rather than raw readings of some specific sensor nodes. For instance, the incident commander is more likely to request information such as "tell me the current temperature in zone 36" instead of "tell me the current temperature readings at sensor nodes 2, 3, 11, and 16". Based on the geographical location information, the incident commander can better arrange and control the fighting team. For example, he can find firefighters with some specialty functions and send them to where they are needed. Due to the importance of geographical location information, sensor nodes equipped with a GPS signal receiver are able to support some systems such as Geographic Information System (GIS) to provide a clear view of the fire situation.

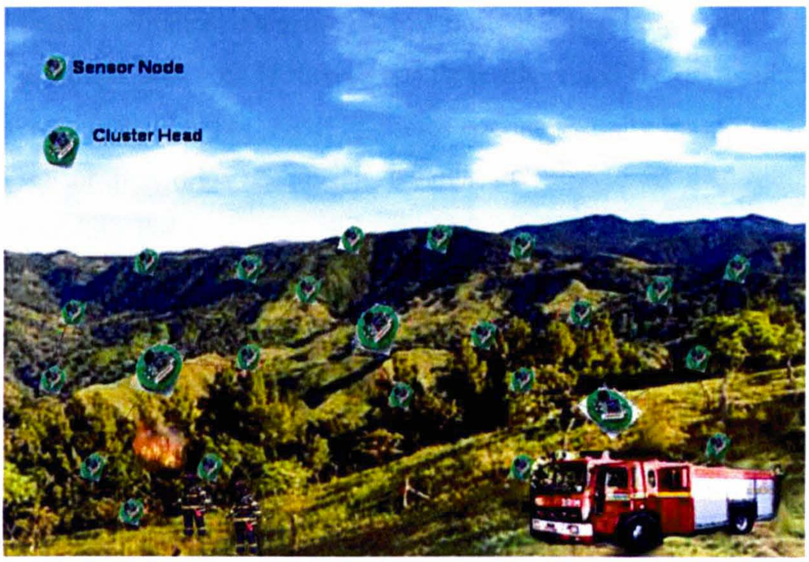

Figure 1.2 : A Scenario View of Mobile Sink Wireless Sensor Networks

1.5 Research Objectives

The goal of this research is to design a robust and energy efficient routing protocol that satisfies MSWSN requirements. This routing protocol must be able to extend the system lifetime of MSWSN and provide reliable and high performance data delivery to the user. This goal will be achieved via the following detailed objectives:

- Energy Efficiency: In many WSN scenarios, sensor nodes' power will have to rely on a limited supply of energy (such as batteries) and to replace these energy sources in the sensor networks field is usually not practical. Radio communications consume the most energy on the sensor node; therefore, how to design energy efficient routing mechanism for MSWSN becomes one of the principle issues in MSWSN.

- ➢ Network Performance – As the number of sensor nodes increases, network latency and packet collision become significant factors which defeat the purpose of data transmission. However, mobile sinks wireless sensor networks applications are typically time-sensitive, so it is important to design a new routing algorithm which is able to reduce communication overhead and provide high performance in MSWSN.

- ➢ Fault Tolerance: Due to the low-cost and low-power, sensor nodes are normally deployed in remote hostile territory and are susceptible to attacks from many sources. Fault tolerance becomes vitally important for wireless sensor networks because it is able to respond to unexpected failures enabling the system to continue to operate. However, the drawbacks of current fault tolerance mechanisms are that they will consume large computing resources if high complexities of fault tolerance mechanisms are implemented. Therefore, how to implement low cost and high reliability fault tolerance mechanisms needs to be resolved.

1.6 Novel Research Contributions

In this thesis, we present a new communication framework for wireless sensor networks based on mobile sinks. We propose a novel communication solution that consists of new routing algorithms and mechanisms in order to address the emphasized challenges and achieve our research objectives. Our contributions can be summarized as follows:

- **A Routing Topology for Non-Geographic Aware Mobile Sinks Wireless Sensor Networks:**

We put forward a new routing topology for sensor networks that provides a concentrated data dissemination algorithm in MSWSN [Chang'07-a, Chang'07-b]. It is inspired by a spider building a web topology that can provide high performance, energy efficiency and reliability to routing in MSWSN. Our algorithm provides a spider-net zone routing topology to improve network efficiency. Instead of changing the whole routing path when the mobile sink moves, this routing mechanism builds a spider-net routing topology based upon the location of the reference node. Moreover, as sensor networks are prone to node failure by hardware, software or an environmental issue, this mechanism therefore also has connection link redundancy incorporated to increase reliability. The main idea of this connection link redundancy is to ensure that node failure will not impact on data dissemination processes, thus guaranteeing that mobile sinks gather data from proper cluster heads only.

- **A Fault Tolerance Coordinate Routing Algorithm for Geographic Aware Based Mobile Sinks Wireless Sensor Networks:**

  We present a fault-tolerant coordinate routing algorithm based on geographic aware in MSWSN [Chang'07-c, Chang'07-d]. The proposed scheme uses the concept of hierarchical sensor networks where nodes have more energy resources and are able to acquire their geographical location. Thus they are more capable of data aggregation and for long-range communication. The network nodes take advantage of geographic knowledge to build a routing protocol. This routing algorithm incorporates a coordinate routing algorithm on grid based network topology to improve network performance. Moreover, since sensor networks are prone to failure because of node malfunction, and network environmental issues, the proposed solution also provides a simple network connection fault tolerance mechanism to increase reliability. The main idea of this fault tolerance mechanism is to ensure mobile sinks gather "correct" data from proper cluster heads only.

- **A Causal Model Based Fault-Diagnosis Algorithm in Wireless Sensor Networks :**

  We consider the component-level failure from the sensor nodes in WSN [Chang'09]. Due to their small size, low cost and high density sensor nodes are normally deployed in harsh and unremitting environments. It is therefore not uncommon for the sensor nodes to malfunction. These sensor nodes may suffer from system, resource, and/or communication faults which result in sensor node abnormal behaviour. Therefore, it is desirable that nodes can have a fault tolerance capability. The advantage of the Causal Model Method is that it can "deeply understand" and express the relationship among failure behaviours and node system components through causal relations. The proposed method uses a reputation checker, ontology manager and action planner schemes to provide an efficient fault tolerance algorithm in WSN.

1.7 Thesis Structure

The thesis is structured as follows:

Chapter 1 introduces the problem of communication in WSN. It outlines the salient features of wireless sensor networks and the requirements based on their inherent limitations. We highlight the resource constraints of WSN and the need of new energy efficient and application specific routing protocols for mobile sinks wireless sensor networks. Then, we describe the four major issues in routing for mobile sinks wireless sensor networks. Finally, we outline the aims and the contributions of our work and the structure of the thesis.

Chapter 2 surveys the existing routing and communication protocols for wireless networks in general and wireless sensor networks in particular. This chapter presents a background on WSN with mobile sinks, data dissemination mechanisms and fault tolerance algorithms. In this chapter, we also describe the mobile ad hoc network routing algorithms we used as a basis for our work.

Chapter 3 presents the proposed communication mechanism and our framework for designing a fault-tolerant routing algorithm. It presents an overview of the proposed communication mechanisms and describes the role of each component. We will demonstrate how we integrate these components to reach the goals of our project and provide a roadmap for the subsequent chapters.

Chapter 4 presents the details of our novel network routing topology for non-geographic aware MSWSN to improve network efficiency. This chapter describes the design of this protocol and demonstrates its advantages through simulation.

Chapter 5 presents our fault tolerance coordinate routing scheme for geographic aware MSWSN. We compare the conditions that affect the power nodes (cluster heads) failures in WSN without a fault tolerant mechanism through simulations compared to the effectiveness of our scheme. In this chapter, we also show how our guarantee scheme performs in order that mobile sinks gather "correct" data only from proper cluster heads.

In chapter 6, we describe a generic fault diagnosis algorithm which considers the component-level failure from the sensor nodes in wireless sensor networks. This chapter expresses the relations among the failure behaviour and node system components through causal relations.

Chapter 7, we summarize our work. We conclude the findings and the problems that we have encountered before, discussing the major issues and future work in the area of MSWSN.

CHAPTER 2

2 MOBILE SINKS WIRELESS SENSOR NETWORKS BACKGROUND

A wireless sensor network (WSN) consists of a number of microcontroller-integrated smart devices called sensors. Each sensor has sensing, processing, transmission and power properties. Sensors deployed in an application field are automatically controlled to form a virtual organization. The sensing unit measures ambient conditions and transforms them into an electrical signal. Each sensor node is capable of only a limited amount of processing. Transmission units forward the data to its neighbours using multi-hop wireless network technologies. Combining the outputs retrieved from the individual sensor nodes, the user can precisely and reliably monitor the studied environment from a remote site.

Figure 2.1 : Wireless Sensor Networks Applications Diagram

There are many exciting applications based on WSN functionality, such as military, environmental, health, home and commercial applications [Akyildiz'02] [Stojmenovic'05]. Figure 2.1 shows four typical applications of WSN (environment monitoring, disaster relief, weather forecasting and medical telemetry), and each can be monitored. These specific applications of WSN are different from other wireless networks such as WLAN or ad hoc networks and introduce a number of unique technical challenges as listed below:

- Large Numbers: In many WSN applications, large numbers of densely distributed nodes are deployed. Potentially, large amounts of sensing information will be relayed to their neighbouring nodes until each sink node reaches its capacity beyond which network congestion and packet collisions will occur. Therefore, an efficient routing protocol and MAC mechanism is required to reduce communication overheads.
- Limited Resources: Energy issue is the most important concern in WSN. Since sensors are usually small in size and battery powered, their computational and energy capacities are very limited. However, in many WSN applications, sensors are required to run for long periods of time with little human maintenance. It is necessary therefore to find a method whereby the sensors can conserve power.
- Ad Hoc Deployment in Harsh Environment: In many cases, sensors are deployed in monitoring areas without pre-deployed network infrastructure. As an example, sensors deployed in a military hostile environment to collect information from an enemy. A typical deployment approach would be dropping these sensors from an aircraft. Hence, in such a situation, sensors are required to have a self-organizing and fault tolerant capability.
- Unattended Nature: The unattended nature of WSN makes them attractive to surveillance applications. WSN used in such applications are highly vulnerable to node failure and have no tamper-resistant capability.

Therefore, the network management and routing topology must be flexible and robust.

- Frequent Topological Changes: Frequent topology changes can occur due to physical environmental changes, battery outage and/or time-varying channel conditions. Therefore, the routing protocol must be adaptable to take frequent topology changes into consideration.

Considerable research has been carried out on some important aspects of WSN, such as energy efficiency, routing protocols, dynamic topology, and network applications. The proposed solutions aim at optimizing energy usage, minimizing essential routing paths, co-ordinating sensor nodes, and maximizing system lifetime. The major consideration in WSN is to improve network performance as well as network lifetime. In traditional WSN, the nodes near the sink clearly forward a significantly greater volume of packets than nodes further away from the sink. Equally transmission delay will be increased resulting in a decrease in network performance. Furthermore, sensor nodes closer to the sink will drain their energy resources first because these sensor nodes are required to transmit their own packets and to forward packets on behalf of other sensors. This reduces availability within the WSN.

Instead, a better approach is to let the dispatch mobile sink collect data. Mobile Sinks Wireless Sensor Networks (MSWSN) consists of a large number of sensors with several mobile monitoring terminals called mobile sinks. A simple example of a mobile sink is a Personal Digital Assistant (PDA) or a mobile phone carried by a user to gather sensor readings, and to process and aggregate sensed data from the target environment. This promising solution has the potential to enhance performance, extend network lifetime and reduce energy consumption and latency by routing data to a nearby mobile sink. However, routing in MSWSN also introduces many new problems and research challenges because of its inherent characteristics from other wireless networks like personal area network or mobile ad hoc networks. It may cause new routing problems such as high communication overheads needed for updating the dynamic routing paths connected to mobile sinks together with unreliable data transmission that results from node failure.

In this chapter, we investigate the research efforts found in the literature on routing protocols and fault tolerance mechanisms for wireless networks in general and on MSWSN in particular. In the following sections, we will first introduce the network architecture and sink mobility models for MSWSN. Then we will discuss the routing protocols in ad hoc networks and WSN in recent years. The objective is to provide deeper understanding of the current routing protocols in WSN and MSWSN and identify some open research issues that can be further pursued.

In section 2.1, we survey wireless sensor networks routing applications developed by the research community. In section 2.2, we describe the general requirements for an efficient routing protocol and fault tolerance mechanism required to develop a general framework for wireless sensor networks. In section 2.3 the role of mobile sinks in wireless sensor networks, the hierarchical network architecture and sink mobility models are considered. The technique is explained and shows how it can prolong system life and achieve better network performance. In section 2.4, wireless communication is surveyed and the specific characteristics and properties in developed communication protocols in wireless networks are outlined. An explanation as to why these protocols are not suitable for wireless sensor networks is given.

Section 2.5, describes the three main categories of routing protocols for wireless ad hoc networks found in the literature; specifically, proactive, reactive and hybrid routing. Section 2.6, describes the three main categories of routing protocols for wireless sensor networks found in the literature, these being data-centric, hierarchical clustering and geographical based routing. In section 2.7, we discuss the routing protocols for mobile sinks in wireless sensor networks; expose the main requirements related to this field, and the existing solutions found in the literature. Section 2.8 exposes the fault tolerance problem and mechanisms of wireless sensor networks and explains the different types of failure which may occur in the sensor node. Finally, the subject is summarized in Section 2.9.

2.1 Wireless Sensor Networks Applications

Wireless sensor networks have attracted much attention in the research community over the last ten years, driven by a wealth of theoretical and practical challenges and an increasing number of practical applications in the civil sector. "One deployment, multiple applications" is an emerging trend in the development of WSN due to the high cost of deploying hundreds and thousands of sensor nodes over a wide geographical area and the application-specific nature of sensor networks [Min Chen'07]. Such a trend requires sensor nodes to have various capabilities to handle multiple applications such as habitat monitoring, environment observation, military purposes, and smart home or office applications [Cerpa'01][Wang'03].

In order to enable remote monitoring of an environment, the sensor nodes must send their sensory readings to a remote base station or a mobile sink, through which the user can access the collected data. These sensor nodes can form a single-hop or multi-hop wireless network to perform users demand from remote sites. In a single-hop WSN, a sensor node can communicate with any other sensor node inside its communication range or directly to its sink. In multi-hop WSN, communication between sources to destination nodes may involve a sequence of hops through a connection chain to reach the sink. Moreover, a combination of these two types of communication is also possible. By combining the data retrieved from the individual sensor nodes, the users can precisely and reliably monitor the studied environment from the remote site. In this section scenarios of WSN applications and classification of WSN applications based on their basic characteristics and data delivery features are considered.

Environment Monitoring: One of the most frequently mentioned application types for WSN is environment monitoring. A typical scenario is the surveillance of the monticule around the mouth of a volcano. An understanding of its volcano eruption processes is important for the geognosy. Closely related to environmental control is the use of WSN to gain an understanding of the plant growth process, animal behaviour and habitat monitoring. The main advantages of WSN here are the long-term, unattended, continual operation of sensors close to the objects that have to be observed. Since sensors can be made small enough to be unobtrusive, they have no effect on the observed animals or plants. A large number of reserved sensors are required to prolong the lifetime of the network [Li, Yingshu'08].

Disaster Relief Applications – WSN can be used to assist and control disaster areas when they occur. Sensor nodes can take temperature readings and normally can determine their own location relative to each other by the use of GPS. These sensors can be quickly deployed from an aircraft in an area where a forest fire rages. These sensor nodes can collectively produce a map of the area showing relative temperatures. This information will be very useful for firefighters to determine the scope of the forest fire area and show access points for rescue action. Similar scenarios are possible for the monitor and control of huge violent waves, Tsunami. For example, a tsunami can propagate long distances (hundreds or thousands of sea miles) before it strikes a disaster shoreline from the earthquake source as shown in Figure 2.2. These sensors attached to buoys (an underwater buoys sensor network) around the coastline can detect the tidal variation pattern to decide if it is a normal or unusual tide [Li, Yingshu'08].

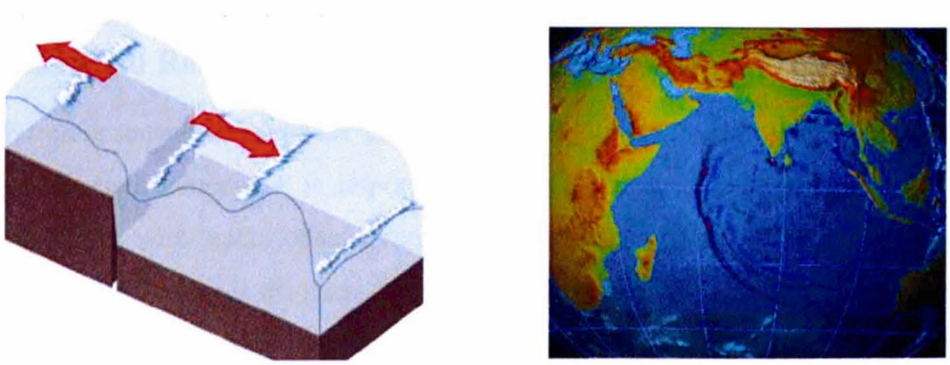

Figure 2.2 : Tsunami Propagation Cause and Phenomenon

Medical Telemetric: Partially related to disaster relief applications is the medical telemetric service. The use of WSN in medical telemetric applications is a potentially very useful, but also ethically controversial, application. When sensors are directly attached to injured patients information about the condition of an injury can be gained in greater detail compared to basic human medical observation. Patient monitoring by these sensors with associated alarm systems can free up medical staff from long term surveillance. This technique in association with doctor tracking systems within hospitals can be literally life saving [Li, Yingshu'08].

Wealth Applications: Increasingly more and more electronic appliances are used in the home. Significant commercial opportunities exist for home and garden automation. Given the great market potential a breakthrough in this sector will surely mark a big milestone in sensor network research. An example application in this category is described in [Mani'01] Mani et al. shows a "Smart Kindergarten" that builds a sensor-based wireless network for early childhood education. It is envisaged that this interaction-based instruction method will soon take the place of traditional stimulus-responses based methods [Li, Yingshu'08].

To summarize, sensor networks is a highly application-specific field, the requirement and constraints, such as bandwidth and power consumption, are the main concerns of sensor networks applications. As a result, the design issues with respect to the features of sensor networks concern sensor network limitation, system scalability, network reliability, efficient routing design, and fault tolerance mechanisms.

2.2 General Requirements for Wireless Sensor Networks

Wireless sensor networks are expected to be easily deployable even in remote and dangerous environments. It is important therefore that the sensor nodes are able to communicate with each other even in the absence of an established network infrastructure. Battery is the main power source in sensor nodes; the situation has not yet reached the stage where sensors can operate for long periods without recharging. However, in many cases, it is not feasible to recharge or replace the battery power of these sensors. Therefore, all the aspects of the node, from the sensor hardware and communication protocols, must be designed to be extremely energy-efficient and provide a defined network lifetime. In addition, sensor networks need to maintain sufficient coverage and quality of network connectivity to capture timely changing targets. This section explores the problems to support new architectures and protocols in WSN. Listed below are the required mechanisms for WSN including energy efficiency, nodes self-organization, dynamic topology and fault tolerance.

Energy Efficiency: In many WSN scenarios, sensor nodes' power will have to rely on a limited supply of energy (such as batteries) and replacing these energy sources in the sensor networks field is usually not practical. Therefore, how to provide energy efficient operation becomes one of the principle challenging techniques for WSN. Energy efficiency is a key requisite to support long system life in WSN.

Network Performance: As the number of sensor nodes increases, network latency and packet collision become significant factors in reduced data transmission throughput. Indeed, wireless sensor network applications are typically time-sensitive, so it is important to receive the data in a timely manner. Therefore the question of how to reduce the amount of data to be transmitted for provision of good network performance would be an essential factor requiring resolution in multi-hop wireless sensor networks.

Connectivity and Coverage: Sensor nodes in WSN are deployed in regions which have no infrastructure at all. Consequently, the user does not have complete control over the placement of each node. Sometimes, nodes could experience temporary or permanent failure due to changing environmental conditions such as heat and humidity, and this may impact the network connectivity. Hence it is necessary to dimension the number of nodes in the network and their communication range, and also design routing protocols so that sensing coverage of the entire region of interest is assured.

Dynamic Topology: In many sensor network applications, sensor nodes can either be deployed randomly over the area of interest or can have a range of mobility. Due to movement of sensor nodes, running out of energy or crashes in the network, the topology of sensor networks changes very frequently. Therefore, when the network topology has been changed, the update of the routing information has to be taken into account when designing communication protocols.

Fault Tolerance – Due to their low-cost and low-power tiny sensor nodes are normally deployed in remote hostile territory where they may suffer numerous attacks. Fault tolerance becomes vitally important for wireless sensor networks where they must be able to respond to failure and ensure that the system continues to operate. The drawbacks of the current fault tolerance mechanisms are that they consume large computing resources if high complex fault tolerance mechanisms are implemented. The implementation of low cost and high reliability fault tolerance mechanisms is a major challenge in WSN.

WSN differs from traditional networks in that the requirement demands new networking concepts like energy efficiency and network performance trade-offs to satisfy application necessities. Due to these low cost and low power tiny sensor nodes being deployed in remote hostile territory, designers have to keep "energy" in mind when they design new network architectures in WSN. When node energy gets depleted, the accuracy of the sensory data will be reduced. To extend the life of the network, better energy consumption is needed. Moreover, since sensor nodes are prone to failures resulting in lost communication links, WSN require a robust data dissemination approach and fault tolerance mechanism. This must guarantee the network connectivity and data delivery of the gathered sensory data to the user. It is important to propose a robust and energy efficient data dissemination approach and fault tolerance mechanism that ensures a reliable delivery of the collected information to the user at minimum costs.

2.3 Mobile Sinks Wireless Sensor Networks

Traditional wireless sensor networks consist of many small sensor nodes with limited energy resources and one or more sinks to which the sensors send their measurements. Sensor nodes are usually fixed and perform the relay of data towards the sink. Intermediate sensor nodes in WSN are required to relay information packets between the source nodes and the sink(s) by multi-hop communication. Consequently, the volume of traffic in the network is focused in the neighbourhood of the static sinks. This is mainly because nodes around the static sink transmit their own packets and they also forward packets on behalf of other sensors that are located farther away. Subsequently, nodes in the neighbourhood of the static sinks are the first whose energy resource gets depleted and result in the problem of holes in the WSN. This uneven energy consumption will also reduce network life.

There are two solutions to the above problems. On the one hand, if some sensor nodes withdraw from the network due to energy exhaustion which causes the network connectivity and sensing coverage losses, there must be other supplementary sensor nodes to be deployed. On the other hand, the sensor nodes should be capable of finding and reaching the sink node in possibly different positions, whether or not there are multiple sinks which are able to change their location. The first approach is frequently relating to the network design algorithm. In order to provide energy efficiency and prolong network life the focus should be on the second one; to utilize mobile sinks which have the capability to change their position.

Mobile sinks in wireless sensor networks (MSWSN) have many advantages compared to stationary sinks because they naturally avoid energy dissipation in the neighbourhood nodes of the static sinks. Additionally, mobile sinks can provide timely and efficient ways to visit some areas of the network which will result in the loss of data, while infrequently visiting some regions will result in long delivery delays. Despite these advances, the influence of the velocity of mobile sinks on network performance and reliability has not been fully investigated. A number of researchers have proposed different architectures and solutions using mobility devices traversing the sensor network environment [Lindsey'02] [Yao'02] [Rahul'03] [Somasundara'06] [BretHull'06] [K.Xing'07] [Yanzhong'09]. In this section, the architecture of mobile sink wireless sensor networks is reviewed with scenarios and various routing protocols for mobile sinks in wireless sensor network.

2.3.1 Hierarchical Architecture and Operation Mode

As mentioned in [Chen'06], it has been recognized that a multi-tiered network structure will enhance the network scalability for large scale deployment, as well as of benefit to routing and energy efficiency. As illustrated in Figure 2.3, a mobile and multi radio enabled hierarchical architecture has been designed for mobile sinks wireless sensor networks, which consists of three tiers:

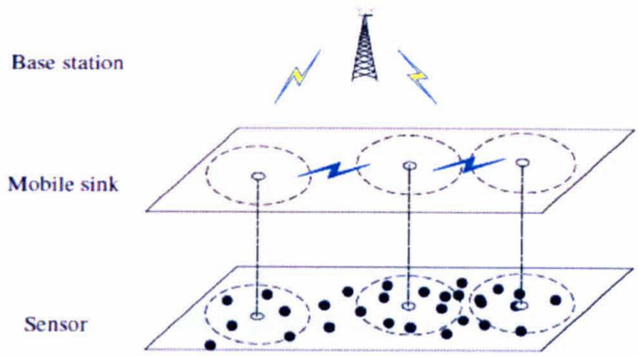

Figure 2.3 : Three-Tiered Mobile Sinks Wireless Sensor Networks with Cluster Structure

- **Sensor Tier:** sensor tier denoting various types of static sensor devices that are capable of collecting information and resources.
- **Mobile Sink Tier:** mobile sink tier composed of mobile phones, laptops, and other mobile/roaming devices. The mobile sinks will act as relays for information gathering.
- **Base station Tier:** base station tier referring to the final information fusion point, from which the task manager can retrieve data of interest.

2.3.2 Sink Mobility Models

The main idea of a mobile sink is that the sink has significant and easily replenished energy reserves and can move inside the area of the sensor network. In [I. Chatzigiannakis'06], they introduce different sink mobility models for effective data collection. They propose purely random walk, random walk with limited multi-hop data propagation, predictable random walk and deterministic walking models.

A. Random Walk

The simplest of all possible mobility patterns is the random walk, where the mobile sink can move arbitrarily in any direction at varying speeds. In this model, data is collected in a passive manner. Periodically a beacon message is transmitted from the sink. Each sensor node that receives a beacon attempts to acquire the medium and transmit its data to the sink. However, this will lead to many collisions, thus an appropriate MAC layer protocol with an efficient back-off function is essential for the proper deployment of this protocol. Clearly, this approach minimizes energy consumption since only a single transmission per sensed event is performed; however time efficiency may drop due to the long duration required to visit sensors.

B. Random Walk with limited multi-hop data propagation

Another form of random walk is performed by using a set of predefined areas and random transitions between the areas according to their connectivity. In this model, the mobile sink will periodically broadcast a beacon message, which carries a hop counter HC, a time to live counter TTL. Each sensor node maintains a hop distance from the sink and a timestamp to indicate the last time hop distance was updated and the network address of a parent sensor node. This approach assumes and uses more knowledge of the network; it can accelerate to visit network nodes, reduce the distance travelled by the sink (when compare to random walk) and leads to improved time efficiency. On the other hand, it is also more expensive in terms of communication and computational cost on the sensor nodes.

C. Predictable Random Walk

The idea of using a logical graph can be extended in a way that certain areas of the network are favoured (i.e. more frequently visited) by the sink in order to improve the data collection process or to overcome problems that arise from the network topology. This approach uses knowledge collected by the sink in order to speed up the coverage of new areas or increase data delivery in areas with many nodes. Overall, when compared to the random walk approach faster network coverage is expected to be achieved, together with higher delivery rates and lower latency but with an increase in computational overheads at the sink and communication costs at the favoured sensor nodes.

D. Deterministic Walking

This approach uses a simple form of controlled mobility where the mobile entity moves on a predefined trajectory. The sink moves in a predetermined way from one edge of the network area to the other and returns along the same path. Since the mobile sink covers only a small network area it is necessary to collect data with a multi-hop data propagation protocol. This approach can have lower data transmission latency, lower than any of the three previous approaches. However, this approach imposes a significant overhead on the sensor nodes that collect network knowledge and cannot adapt to changing network conditions. In addition, sensors are required to constantly update the current mobile sink location and cannot execute complex movements [Stefano'08].

An example of MSWSN in disaster relief applications can be as illustrated in Figure 2.4, mobile sinks can be like PDA carried by soldiers, vehicles, and UAV which can obtain the survivors information from the sensor nodes that deployed in the disaster area. In order to know whether there are survivors in the random walk route, the mobile sink can send out a beacon message such as "Hello" message via sensor networks.

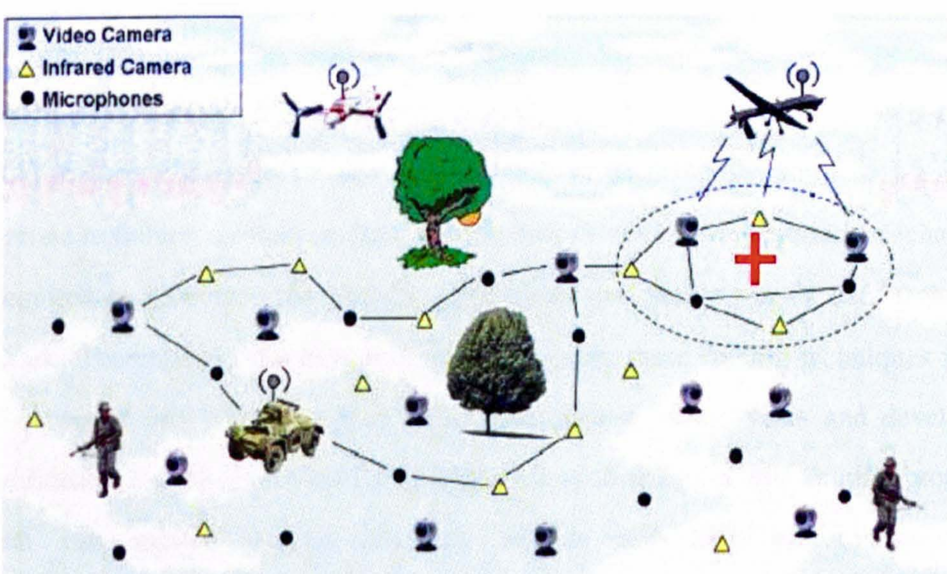

Figure 2.4 : A Sketch Map of Mobile Sinks Mobility Model

In traditional WSN, sensor nodes in the vicinity of the sink will have "static sink neighbour problems," that is the static sink will induce a very heavy traffic load in the network. Consequently, this would result in a very short network lifetime, since sensor nodes have only limited energy resources. One solution to overcome this limitation is to use a mobile sink. However, as mentioned above, a mobile sink also brings new challenges to sensor networks. The mobile sink may take a random walk, move on a predetermined fixed path or may move as a predictable random path in terms of optimize network life. Different sink mobility models suggest that different data collection protocols are appropriate in each case. There is certainly a large space of options for protocol design, depending on which mobility strategy, and which data collection mechanisms are used. Furthermore, depending on the tolerated delay, sensor nodes may route the messages to the nearest sensor node alone the path of the sink or may route the data directly to the sink, the effect of the sink movement should be most perceived by these nodes.

Several algorithms exist to determine the optimal path of a sink. Some routing mechanisms exist, which route data to mobile sinks moving along a predetermined fixed path. However, in many sensor network applications, low-cost and low-power tiny sensor nodes are deployed randomly over the area of interest and are expected to self form in a multi-hop network. Furthermore, the user does not experience a substantial amount of delay after they request sensor data and the sensor network should perform effectively in the timely delivery of data. Finally, since sensor nodes are prone to failure, a robust or fault tolerant data dissemination approach mechanism is required to guarantee the users / applications can gather sensed data from the network. Therefore, in the next sections, we explore these routing techniques in ad hoc networks and WSN that have been developed in recent years and develop a classification for these protocols. Our objective is to design a new routing protocol which can support energy efficient, reliable and high performance data communication in MSWSN.

2.4 Wireless Communication Networks

As the field of communications networks continues to evolve, a need for wireless connectivity and mobile communication is rapidly emerging. In general, wireless communication networks provide wireless (and hence) mobile access to an existing communication network with a well-defined infrastructure. Ad hoc wireless networks provide a mobile communication capability to satisfy a need of a temporary nature and without the existence of any well-defined infrastructure. In ad hoc wireless networks, communication devices establish a network on demand for a specific duration of time. Such networks have many unique features as described below:

2.4.1 Wireless Communications

Wireless communications rely on signal transmission over a medium without the presence of wires or cables between the sender and receiver. Possible communication media for wireless communication include air, water, or vacuum. Wireless communications share several important advantages, no matter how the protocols are designed, or even what type of data they carry. The most obvious advantage of wireless networking is mobility. Users can connect to existing wireless networks at anytime, anywhere and are then allowed to roam freely. This advantage brings fundamental changes to data networks which make it the main communication choice for ad hoc and sensor networks.

The attractive feature of wireless communications, the absence of wires, also presents drawbacks. Basically, wireless communication can be viewed as the radio waves propagation phenomenon that lets data transfer from one point to another point without any physical medium. These radio waves connecting the sender and receiver render the transmitted signal much more vulnerable to interferences and background noise while traversing the wireless medium. As a result, the expected signal quality of a wireless communication link is relatively lower, less stable, and less predictable than a comparable wired link. The higher vulnerability to interference requires higher quality margins and smarter control of wireless links to maintain communication.

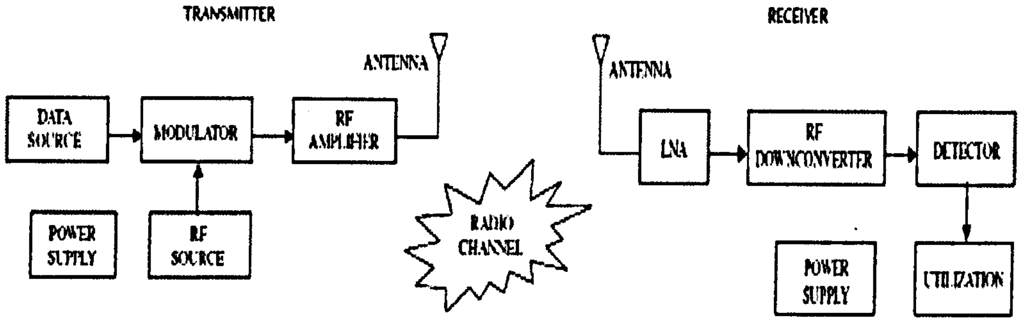

Figure 2.5 : Basic Wireless Communication Model

2.4.2 Communication in Wireless Ad hoc Networks

Wireless ad hoc networks are recognized as a revolution in wireless communications and can even be considered as the technological counterpart of the concept of ubiquitous computing. By exploiting ad hoc wireless technology, various portable devices (mobile phones, PDAs, laptops, and so on) and fixed equipment (base stations, wireless internet access points, etc.) can be connected together, forming a sort of integrated or ever-present network. This technology allows network nodes to communicate directly to each other using wireless transceivers (possibly along multi-hop paths) without the need for a fixed infrastructure. This is a very distinguishing feature of ad hoc networks with respect to more traditional wireless networks, such as cellular networks and wireless LAN, in which nodes communicate with each other through base stations (wired radio antennae).

A Mobile Ad Hoc Network, named MANET, is another type of ad hoc network with autonomous collection of mobile nodes forming a dynamic wireless network. A MANET consists of mobile hosts forming a temporary network on wireless links without the aid of any centralized administration or standard support services. The administration of such a network is decentralized, i.e. each node acts both as host and router and forwards packets for nodes that are not within transmission range of each other. Nodes in the MANET have an ad hoc deployment, dynamically enter and leave the network, have limited power sources, and experience the possibility of link failures. A MANET provides a practical way to rapidly build a decentralized communication network in areas where there is no existing infrastructure or where temporary connectivity is needed, e.g. emergency situations, disaster relief scenarios, and military applications.

2.5 Routing Protocols in Wireless Ad hoc Networks

Routing is a core problem in wireless ad hoc networks for delivering data from one node to another and needs to be designed and implemented separately. Several routing protocols have been proposed for wireless ad hoc networks [Johnson'96], [Perkins'99], [Park'97], [Boppana'01], [Haas'98], [Jiang'99] with the performance and characteristics of different protocols being compared [Broch'98]. Among them, three articles [Broch'98] compare a few (up to four) protocols based on the simulation of the compared protocols and the authors of [Broch'98] provide a short survey including qualitative comparisons of nine protocols. In this section, routing protocols for wireless ad hoc networks are surveyed; we grouped these routing protocols into three categories: proactive, reactive and hybrid and list their advantage and disadvantages.

2.5.1 Proactive Routing

In proactive routing protocols, every node in the network stores information about the next hop and distance to every other node in the network. Routing tables are periodically updated by transmitting the routing information through the network to ensure the nodes have the same information. Link State Routing (LSR) and Destination Sequence Distance Vector (DSDV) [Perkins'94] are classical examples of this group of routing protocols. The Link State Packet (LSP) of a node includes link information about its neighbours. Any link change will cause LSPs to be flooded immediately into the entire network. Every node can construct and maintain a global network topology from the LSPs it receives, and compute, by itself, routes to all other nodes. DSDV is another example of a proactive protocol where every node in the network stores information about the next hop and distance to every other node in the network. Routing table updates are periodically transmitted through the network to keep the nodes updated with the same information.

Table 2.1 shows a snapshot of the routing table at node (A) corresponding to Figure 2.6. For example, if node A has to send data to node E, it uses node B as the next hop on the 2-hop route to node E. The last column in the routing table uses an enhanced sequence number to indicate fresher routes and to avoid routing loops in the network. If node A receives a routing update packet from node B with a sequence number less than 323, then A discards the stale information in the packet to avoid creating a routing loop.

Destination	Next	Metric	Seq. Nbr.
A	A	0	A-543
B	B	1	B-323
C	C	1	C-276
D	C	2	D-188
E	B	2	E-206

Table 2.1: Routing Table at Node A

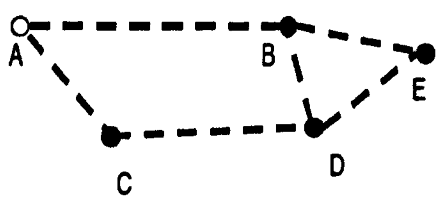

Figure 2.6 : DSDV Routing Protocol Diagram

The advantage of proactive protocols is that they can have faster network connection setup and achieve real-time requirements. The routing tables are updated frequently and therefore, as long as the topology does not change very fast, they reflect the current topology with a certain confidence. On the other hand, when nodes in a wireless ad hoc network move quickly and the network topology changes fast, the proactive routing protocols will generate an excessive routing overhead regardless of the actual need for communication, resulting in critical energy being wasted.

2.5.2 Reactive (On-demand) Routing

Reactive routing protocols, also referred to as on-demand protocols, create routes only when desired by the source node. Unlike proactive routing, the idea of on-demand routing is the source node first will find a route or several routes to the destination (called route discovery) and wait for the response packet back before the source node sends its information. After the route(s) is / are discovered, the source node transmits packets along the route(s). However, due to the fact that the route to a destination may not exist or the route may be broken because the node(s) on the route move away or go down, the broken route needs to be rebuilt. The process of detecting route breakage and rebuilding the route is called route maintenance. This method can guarantee the path only on a hop-by-hop basis, but cannot guarantee an end-to-end path. Most of these protocols include adaptive algorithms to get around obstacles or dynamically back track and try a different set of nodes.

Ad-Hoc on-demand Distance Vector Routing (AODV) [Perkins'99] can be viewed as an on-demand version of DSDV. AODV is an improvement on DSDV because it typically minimizes the number of required broadcasts by creating routes on a demand basis. Instead of setting up routing paths to every node in the network, a node in AODV only initiates a path when it becomes necessary. When a source node desires to send a message to the destination node and does not have a valid route to the destination, it initiates a path discovery process to locate the other node. Once a sender node needs to transmit data, it first broadcasts a Route Request Packet (RREQ) with the sender's id and a unique destination sequence number to all its neighbours. All neighbours that receive the RREQ rebroadcast it. Neighbours also store the neighbour's id from which they received the RREQ, which represents the reverse path to the destination. Any node that has already processed this RREQ discards any duplicate RREQs. Finally, when the destination node receives a RREQ, it sends a RREP which eventually reaches the original sender through the reverse path links. The sender then proceeds with data transmission. Note that nodes in AODV maintain only the next hop routing state, which provides AODV with a high degree of scalability.

Figure 2.7 illustrates the operation of AODV. In order to reach the destination node E, the sender node A floods its outgoing links with RREQ packets as shown in

Figure 2.7(a). Nodes B and C receive RREQ from A, and they locally store the id of node A as the next hop on the reverse path for RREP. Nodes B and C also rebroadcast A's RREQ as shown in Figure 2.7 (b). Upon receiving RREQ from nodes B and C, node A discards these packets since they represent duplicates. Node E receives RREQ from node B, and it records B as the next hop on the reverse path. At this point, both node D and node E sends RREP to node B, and only node E's RREP will be accept which then forwards RREP back to node A in Figure 2-7(c)(d). Subsequently, data transmission can proceed from node A to E on the established path (A-B-E).

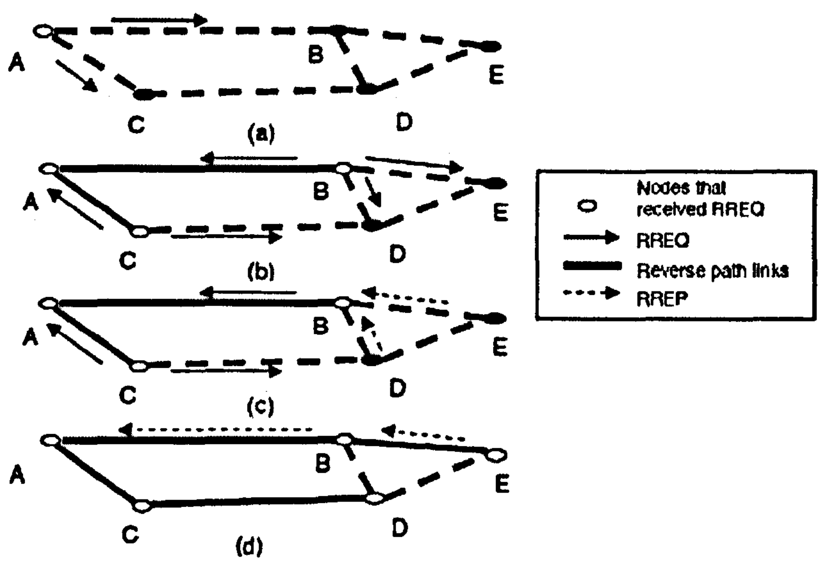

Figure 2.7 (a) (b) (c): AODV Routing Protocol Diagram

2.5.3 Hybrid Routing

Hybrid routing protocols are proposed to combine the merits of both proactive and reactive routing protocols and overcome their shortcomings. Normally, hybrid routing protocols for ad hoc networks exploit hierarchical network architectures. Proper proactive routing approaches and reactive routing approaches are exploited in different hierarchical levels, respectively. The Zone Routing Protocol (ZRP) [Haas'98] is a hybrid routing protocol for mobile ad hoc networks. The hybrid protocols are proposed to reduce the control overhead of proactive routing approaches and decrease the latency caused by route search operations in reactive routing approaches.

In ZRP, the network is divided into routing zones according to distances between mobile nodes. Given a hop distance d and a node N, all nodes within hop distance at most d from N belong to the routing zone of N. Peripheral nodes of N are N's neighbouring nodes in its routing zone which are exactly d hops away from N. In ZRP, different routing approaches are exploited for inter-zone and intra-zone packets. The proactive routing approach, i.e., the Intra-zone Routing protocol (IARP), is used inside routing zones and the reactive Inter-zone Routing Protocol (IERP) is used between routing zones, respectively. The IARP maintains link state information for nodes within specified distance d. Therefore, if the source and destination nodes are in the same routing zone, a route can be available immediately. Most of the existing proactive routing schemes can be used as the IARP for ZRP. The IERP reactively initiates a route discovery when the source node and the destination are residing in different zones. The route discovery in IERP is similar to DSR with the exception that route requests are propagated via peripheral nodes. Although hybrid protocols could theoretically integrate favourable features of both proactive and reactive protocols, research on hybrid protocols has so far been limited. The main idea of hybrid protocols is achieving a balance between the energy-efficiency of on-demand route setup and the rapid data transmission in proactive routing. A key challenge for hybrid protocols is determining this optimal balance and providing flexible means for tuning the protocol for different applications.

Since communication in wireless ad hoc networks have specific limitations and properties such as network dynamics, node deployment, energy considerations, data delivery method, and node capabilities, therefore, routing protocols for wireless ad hoc networks cannot be directly used in wireless sensor networks. The routing in sensor networks is very challenging due to the following reasons:

- It is not possible to build a global addressing scheme for the deployment of sheer number of sensor nodes (classical IP-based protocols cannot be applied to sensor networks.)
- Almost all applications of sensor networks require the flow of sensed data from multiple sources to a particular sink.
- The generated data traffic has significant redundancy in it (Needs to be exploited by the routing protocols to improve energy and bandwidth utilization.)
- Sensor nodes are tightly constrained in terms of transmission power, on-board energy, processing capacity and storage.

In summary, ad hoc routing protocols cause global flooding, to maintain consistent and accurate information which results in high network traffic and increased convergence times. However, sensor nodes are tightly constrained in terms of energy, processing, and storage capacities. Thus, WSN is not suitable for frequently flooding to maintain network operation. Moreover, routing algorithms for ad hoc networks tend to exhibit their least desirable behaviour under highly dynamic conditions. The communication overhead for ad hoc networks will increase dramatically which can easily overwhelm network resources. Consequently, these techniques conflict with routing requirements in wireless sensor networks. New routing strategies in wireless sensor networks are therefore required capable of effectively managing the trade-off between energy efficiency and network performance.

2.6 Routing Protocols in Wireless Sensor Networks

Recently, researchers have shown great interest in sensor networks and have focused on the issues involved in the development of energy-efficient, low-cost, secure, and fault tolerant routing protocols for wireless sensor networks. Several routing mechanisms have been proposed and can be classified into three major types:

Data centric routing, Hierarchical clustering routing and Geographical routing protocols. This section will review the related work in these three categories and identify several important desired features of a new routing protocol.

2.6.1 Data-Centric Routing Protocols

Since it is not feasible to assign global identifiers to each node and query a specific sensor node in a wireless sensor network, routing protocols will be expected to select a set of sensor nodes and utilize data aggregation during the relaying of data. In data-centric routing protocols, the sink sends queries to certain regions. The sink waits for data from the sensors located in that region and uses attribute-based naming to specify data characteristics. This will reduce the data required to be transmitted from every sensor node within the deployment region. Because data-centric routing protocols pursue data aggregation instead of finding optimal routes, it introduces latency into the transmission, but the trade-off in energy savings is more than justified.

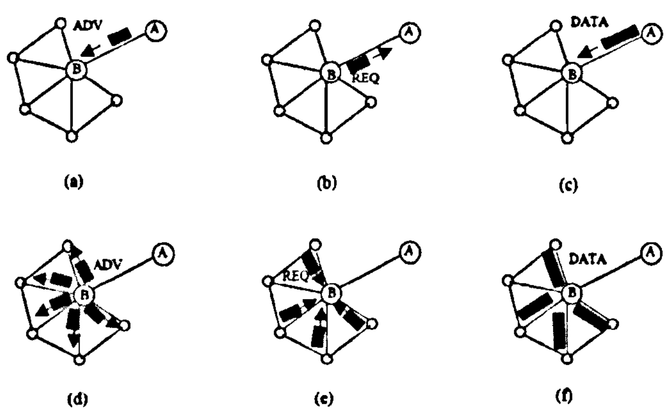

Figure 2.8 : SPIN Routing Protocol Diagram

The two well known protocols in Data-centric routing methods are Sensor Protocols for Information via Negotiation (SPIN) [Heinzelman'99] and Directed Diffusion (DD) [Intanagonwiwat'00]. SPIN is the first data-centric protocol which considered data negotiation before data forwarding in order to eliminate redundant data and save energy. In SPIN, the data is named using high level descriptors or metadata. SPIN has three types of messages ADV (advertisement), REQ (request) and DATA. SPIN uses meta-data negotiation where each node that receives new data advertises it to its neighbours (rather than sending the actual data) and waits to hear their interest in the data before forwarding it, an example of SPIN routing algorithm is shown in Figure 2.8 above.

This meta-data is exchanged among sensors. SPIN solves the problems of the classical flooding mechanism in which each node forwards the data to all of its neighbours. The advantage of the SPIN is that it provides more energy savings than flooding, and it uses metadata negotiation to avoid data redundancy thus achieving significant energy savings. However, SPIN routing mechanism cannot guarantee data delivery for applications that need reliable data delivery. For instance, if the nodes that are interested in the data are away from the source node and the nodes between source and destination are not interested in that data, such data will not be delivered to the destination at all.

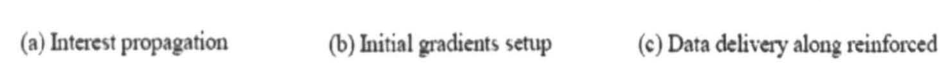

Figure 2.9 (a) (b) (c): Direct Diffusion Routing Protocol Diagram

Another Data-centric routing protocol, Directed Diffusion [Intanagonwiwat'00] has been specifically designed for data-centric routing. The main method in Directed Diffusion is at diffusing data through sensor nodes by using a naming scheme for the data. Users / Applications use flooding to spread interest to the sensor network. As interests diffuse throughout the network, a node that receives an interest from a neighbouring node forms a gradient pointing to the sending node that indicates the direction in which data from a source node will eventually flow. If sensor node data matches the interest, they will send their sensing data back to the sink following the original interest paths. Figure 2.9 above summarizes the Directed Diffusion protocol.

When the sink receives data messages from more than one neighbour, it will reinforce a particular neighbour so that subsequent data messages arrive only from the chosen neighbour. This chosen neighbour also performs the same procedure on its neighbouring nodes that it received a data message from. This process is repeated until data messages propagate only along the reinforced path from source to sink. The interest is defined by name of objects, a list of attribute-value pairs that describe a task. For example, type, interval, duration, location, etc. The advantage of DD is it can avoid unnecessary operation in the network layer in order to save energy and there is no need for global addressing (neighbour-to-neighbour). Related routing protocols have been proposed based on Directed Diffusion and can be found in [Braginsky'02, Schurgers'01, Chu'02]. However, in some cases there is only a small amount of data requested from the sensor nodes and thus the use of flooding is unnecessary. Moreover, because of the naming scheme of DD, this routing algorithm is not suitable for continuous data delivery or event-driven applications.

Rumor Routing (RR) [Braginsky'02] is between event flooding and query flooding (a hybrid protocol) that attempts to balance event and query flooding in sensor networks. In query flooding parts, the idea is to route the queries to the nodes that have observed a particular event rather than flooding the entire network to retrieve information about the occurring events. In event flooding parts when a node detects an event, it adds such event to its local table and generates an agent. Agents travel the network in order to propagate information about local events to distant nodes.

When a node generates a query for an event, the nodes that know the route, can respond to the query by referring to its event table. Hence, the cost of flooding the whole network is avoided. Rumor routing maintains only one path between source and destination as opposed to Directed Diffusion [Intanagonwiwat'00] where data can be sent through multiple paths at low rates. Simulation results have shown that rumor routing achieves significant energy saving over event flooding and can also handle node failure. However, rumor routing performs well only when the number of events is small. For a large number of events, the cost of maintaining agents and event-tables in each node may not be amortized if there is not enough interest on those events from the sink. Another issue to deal with is tuning the overhead through adjusting parameters used in the algorithm such as time-to-live (TTL) for queries and agents. This TTL is an efficient method for delivering queries to events in large networks and perform well in networks with infrequent events.

2.6.2 Hierarchical Clustering Routing Protocols

The idea of the hierarchical clustering routing protocol is taken from traditional infrastructure networks; a hierarchical network structure is an effective way to organize a network comprising a large number of nodes. The benefits of these hierarchical cluster-based routing protocols provide scalability and efficiency for wireless sensor networks. The main aim of hierarchical routing is to efficiently maintain the energy consumption of sensor nodes by involving them in multi-hop communication. This multi-hop relay networks will organize sensor nodes into clusters, and a cluster head is elected. In a single hierarchy, nodes are divided into clusters. This hierarchical cluster-based system is suitable for middle to large size wireless sensor networks. A multi-level hierarchy has nodes organized in a tree-like fashion with several levels of clusters which is suitable to deploy thousands of nodes in the network. The benefit of this hierarchical routing is that it can perform data aggregation and fusion in order to decrease the number of transmitted messages to the sink and less energy is consumed thus improving network performance.

The most well known hierarchical routing protocol is Low-Energy Adaptive Clustering Hierarchy (LEACH) [Heinzelman'00]. The cluster head, in LEACH protocol, is formed by neighbouring sensor nodes based on the received signal strength and uses local cluster heads as routers to the sink. The energy will be saved since the transmissions will only be completed by such cluster heads rather than all sensor nodes. The optimal number of cluster heads is estimated to be 5% of the total number of nodes. All the data processing such as data fusion and aggregation are local to the cluster. Cluster heads change randomly over time in order to balance the energy dissipation of nodes. This decision is made by the node choosing a random number between 0 and 1.

LEACH achieves more than a factor of 7 reduction in energy dissipation compared to direct communication and a factor of 4-8 compared to the minimum transmission energy routing protocol. The nodes die randomly and dynamic clustering increases the lifetime of the system. LEACH is completely distributed and requires no global knowledge of the network. However, LEACH uses single-hop routing where each node can transmit directly to the cluster-head and the sink. Therefore, it is not applicable to networks deployed in large regions. Furthermore, the idea of dynamic clustering brings extra overheads, e.g. head changes, advertisements etc., which may diminish the gain in energy consumption. The LEACH protocol inspired many hierarchical routing protocols such as PEGASIS [Lindsey'02], TEEN [Manjeshwar'01], APTEEN [Manjeshwar'02].

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [Lindsey'02] is an extension of the LEACH [Heinzelman'00] protocol. Rather than forming multiple clusters, the PEGASIS protocol forms chains from sensor nodes so that each node transmits and receives from a neighbour and only one node is selected from that chain to transmit to the base station (sink). The data is gathered and moves from node to node, aggregated and eventually sent to the base station. The chain construction is performed in a greedy way. As shown in Figure 2.10, node c0 passes its data to node c1. Node c1 aggregates node c0's data with its own and then transmits to the leader. In the meantime, node c4 transmits its data to node c3. Node c3 aggregates node c4's data with its own and then transmits to the leader. Node c2 waits to receive data from both neighbours and then aggregates its data with its neighbours' data. Finally, node c2 transmits one message to the base station.

c0→c1→c2←c3←c4

↓

Base Station

Figure 2.10 : Chaining in PEGASIS Routing Protocol

Threshold sensitive Energy Efficient Sensor Network protocol (TEEN) [Manjeshwar'01] is a hierarchical protocol designed for conditions such as sudden changes in the sensed attributes, such as temperature. Responsive issues are important for time-critical applications, in which the network is operated in a reactive mode. TEEN pursues a hierarchical approach along with the use of a data-centric mechanism. The sensor network architecture is based on a hierarchical grouping where closer nodes form clusters and this process goes on the second level until base station (sink) is reached.

After the clusters are formed, the cluster head broadcasts two thresholds to the nodes. These are hard and soft thresholds for sensed attributes. Hard threshold is the minimum possible value of an attribute to trigger a sensor node to switch on its transmitter and transmit to the cluster head. Thus, the hard threshold allows the nodes to transmit only when the sensed attribute is in the range of interest, thus reducing the number of transmissions significantly. Once a node senses a value at or beyond the hard threshold, it transmits data only when the values of that attribute change by an amount equal to or greater than the soft threshold. As a consequence, the soft threshold will further reduce the number of transmissions if there is little or no change in the value of sensed attribute. One can adjust both hard and soft threshold values in order to control the number of packet transmissions. However, TEEN is not good for applications where periodic reports are needed since the user may not get any data at all if the thresholds are not reached. The model is depicted in Figure 2.11.

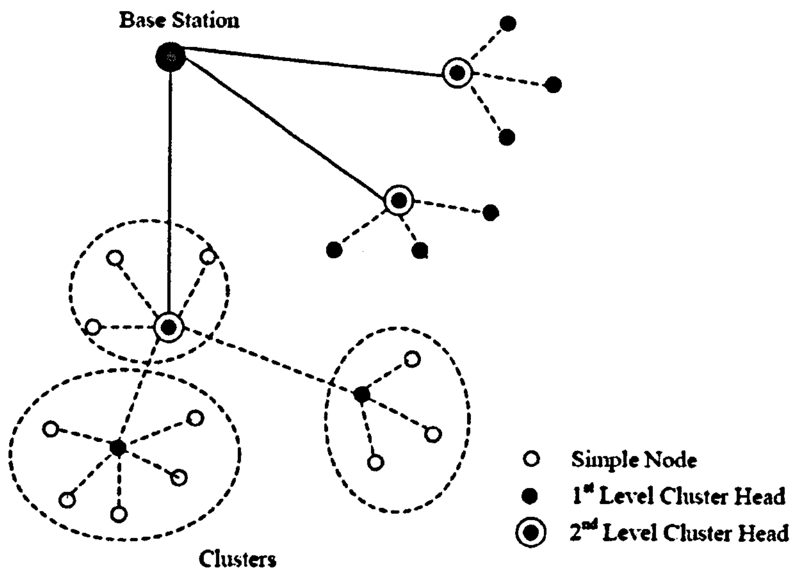

Figure 2.11 : Hierarchical Clustering in TEEN & APTEEN

The Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) [Manjeshwar'02] is an improvement to TEEN and aims at both capturing periodic data collections and reacting to time-critical events. The architecture is the same as in TEEN. When the base station forms the clusters, the cluster heads broadcast the attributes, the threshold values, and the transmission schedule to all nodes. Cluster heads also perform data aggregation in order to save energy.

Simulation of TEEN and APTEEN has shown them to outperform LEACH [Heinzelman'00]. The experiments have demonstrated that APTEEN's performance is between LEACH and TEEN in terms of energy dissipation and network lifetime. TEEN gives the best performance since it decreases the number of transmissions. The main drawbacks of the two approaches are the overhead and complexity of forming clusters in multiple levels, implementing threshold-based functions and dealing with attribute-based naming of queries.

2.6.3 Geographical Routing Protocols

Most of the routing protocols for sensor networks require location information for sensor nodes. Location information is needed to calculate the distance between two particular nodes so that energy consumption can be estimated. Since, there is no addressing scheme for sensor networks like IP-addresses and they are spatially deployed in a region, location information can be utilized in routing data in an energy efficient way.

The most well known geographical routing protocol in WSN is Geographic Adaptive Fidelity (GAF) [Xu'01]. GAF is an energy aware location based routing algorithm designed primarily for mobile ad hoc networks, but may be applicable to sensor networks as well. It forms a virtual grid for the covered area. Each node uses its GPS-indicated location to associate itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. Such similarity is exploited in keeping some nodes located in a particular grid area in a sleeping state in order to save energy. Due to this sleeping state, GAF can substantially increase the network lifetime without affecting the level of routing fidelity.

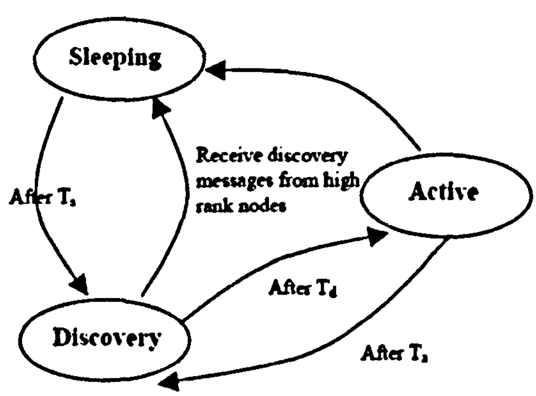

Figure 2.12 : State Transitions Diagram in GAF Routing Protocol

Nodes change state from sleeping to active in turn so that the load is balanced. There are three states defined in GAF. These states are discovery, for determining the neighbours in the grid, active, reflecting participation in routing and sleep, when the radio is turned off. The state transitions in GAF are depicted in Figure 2.12. Which node will sleep for how long is application dependent and the related parameters are tuned accordingly during the routing process. Although GAF is a location-based protocol, it may also be considered as a hierarchical protocol, where the clusters are based on geographic location. For each particular grid area, a representative node acts as the leader to transmit the data to other nodes. However, the leader node in the GAF protocol does not do any aggregation or fusion as other hierarchical protocols which may have redundant data when multiple sensors sense similar results from the network.

Alternatively, Geographic and Energy Aware Routing (GEAR) [Y.Yu'01] uses energy aware and geographically informed neighbour selection heuristics to route a packet towards the sink. In GEAR, each node keeps an estimated cost and a learning cost of reaching the destination through its neighbours. The estimated cost is a combination of residual energy and distance to destination. The learned cost is propagated one hop back every time a packet reaches the destination so that route setup for the next packet will be adjusted. There are two phases in the algorithm:

- Forwarding packets towards the target region: Upon receiving a packet, a node checks its neighbours to see if there is one neighbour, which is closer to the target region than itself. If there is more than one, the nearest neighbour to the target region is selected as the next hop. If they are all further than the node itself, this means there is a hole. In this case, one of the neighbours is picked to forward the packet based on the learning cost function. This choice can then be updated according to the convergence of the learned cost during the delivery of packets.
- Forwarding the packets within the region: If the packet has reached the region, it can be diffused in that region by either recursive geographic forwarding or restricted flooding. Restricted flooding is good when the sensors are not densely deployed. In high-density networks, recursive geographic flooding is more energy efficient than restricted flooding. In that case, the region is divided into four sub regions and four copies of the

packet are created. This splitting and forwarding process continues until the regions with only one node are left. An example is depicted in Figure 2.13.

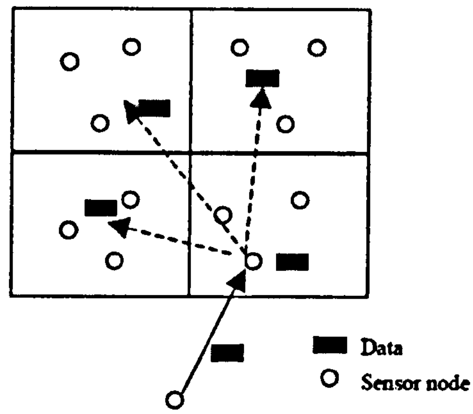

Figure 2.13 : Recursive Geographic Forwarding in GEAR Routing Protocol

SPEED [Tian He'03] is a geographic routing protocol designed for real-time communication in sensor networks. SPEED handles congestion and provides soft real-time communication by using feedback control and non-deterministic geographic forwarding. It also provides a different way to handle dead-ends similar to the way it handles congestion. However, in real-time sensor network applications, a routing protocol should guarantee the end-to-end delay, not only at each hop delay. So it may be possible that the packets are delivered through the link which may not satisfy the speed requirement.

A related routing approach to a QoS routing protocol for sensor networks and energy-efficient routing can be found in [Akkaya'05]. In [Akkaya'05], they find a least-cost, delay-constrained path for real-time requirements and taking into account the link cost, transmission energy and other communication parameters to achieve efficient routing with best-effort traffic. The research in [Draves'04] provides an effective metric for routing in distributed sensor networks by reducing the hop count. The approach in [Badia'07], considers adding QoS awareness to the routing protocols for heterogeneous networks. It uses a hop count together with link quality and node congestion metrics for ensuring QoS in routing.

To summarize, in data centric routing protocols, a user sends a query through the network in order to find nodes within a specific event area. Once nodes that satisfy the user query are found, these nodes start sending their information to the user sink. However, these approaches may suffer from resource constraints such as energy and bandwidth limitations.

In hierarchical clustering routing protocols, these approaches consider the data correlation that characterizes wireless sensor networks, by organizing the sensor nodes into clusters, where each group has a cluster head. This cluster head is responsible for gathering information from its group members, applying an aggregation operation on it and relaying the result to the sink. Current routing protocols based on hierarchical clustering achieve good resource saving and extend network life. This approach has several drawbacks, such as network latency and transmission delay.

Routing Protocol	Data-Centric	Hierarchical	Location-based	QoS	Data Aggregation
SPIN	√				√
Directed Diffusion	√				√
Rumor Routing	√				√
LEACH		√			√
TEEN & APTEEN	√	√			√
PEGASIS		√			√
GAF		√	√		
GEAR			√		
SPEED			√	√	

Table 2-2: Classification of Routing Protocols in Wireless Sensor Networks

In geographical routing protocols, they indicate whether the routing protocol uses geographic information (e.g., using GPS hardware) to build scalable and efficient routing protocols in this environment. Currently with trade-offs in cost, complexity, and energy consumption issues, it is not feasible to deploy all sensor nodes with GPS solutions. Nevertheless, it is found in [20] that algorithms based on triangulation can work quite well under conditions where only very few nodes know their positions. Therefore, it is favourable to have GPS-free solutions [21] for the location problems in WSN. Table 2-2 above summarizes the classification of the protocols covered in this section. The table shows whether the protocol is utilizing data aggregation or not, since it is an important consideration for routing protocols in terms of energy saving and traffic optimization.

It is hard to say which protocol is better than another because sensor networks are very application specific. Each approach has several advantages and disadvantages and achieves different trade-offs, mostly between energy dissipation and time efficiency. However, in traditional WSN a dense and static sensor node deployment is implicitly required. There arises a fundamental problem in traditional WSN with static topology. The non-uniformity of energy consumption among the sensor nodes closest to the static sink, this will drain their energy resources first, resulting in a shorter system life. Therefore, the major advantage of having a mobile sink is an increase in the lifetime of the system.

Moreover, the nodes near the static sink clearly forward a significantly greater volume of packets than nodes further away from the sink. Thus, a mobile sink moved closer to the nodes can help reduce network traffic since data is transmitted over fewer hops thus reducing the number of transmitted packets. Another advantage of having a mobile sink is to reduce the network traffic by moving closer to the sensor node. Additionally, since a mobile sink can move inside the area of the sensor network, it can navigate through or bypass problematic regions where sensor devices can't operate, such as small lakes, rocks that block the propagation path and other obstacles. Also, the sensor nodes can reduce their transmission range to the lowest energy required to reach the mobile sink. An additional advantage of having a mobile sink is that sparse and disconnected networks can be better handled.

In summary, routing protocols in traditional WSN will result in sensor nodes around a static sink consuming significant amounts of energy to relay the data from nodes that are further away, in addition to increased implementation complexity.

Moreover, the nodes near the sink clearly forward a significantly greater volume of packets than nodes further away from the sink. In case of sensor node failure or malfunctioning around the sink node, the network reliability may not be guaranteed. Finally, by travelling in the whole network area, the mobile sink is capable of collecting all the available data. The mobility assumption may be especially useful in particular applications. These applications include sink nodes attached to vehicles, animals or people that move around large geographic areas. Data exchange between sensors and mobile sinks will drive applications such as traffic and wild life monitoring, smart homes and hospitals and pollution control. Clearly, the traditional routing approach having a static sink is unable to operate efficiently in such scenarios.

2.7 Routing Protocols for Mobile Sinks Wireless Sensor Networks

As mentioned above, mobile sinks can be a viable solution to solve the problem that energy consumption is not balanced for all the sensor nodes in a WSN. This viable solution also removes the relaying overhead of nodes near the static sink which extends system life. However, despite these advances, mobile sinks also have some drawbacks such as frequent location updates which can result in increased packet collisions in wireless transmissions which will have a direct impact on network performance. Furthermore, it will lead to energy dissipation of the sensor nodes around the mobile sink. Hence, routing in MSWSN has different system requirements from traditional WSN which have to be considered; these are network performance, and communication reliability to adapt mobility of sinks in a wireless sensor networks environment.

A number of researchers have proposed several protocols or solutions to support sink mobility in a sensor network environment [Sohrabi'99] [Intanagonwiwat'00] [Xu'01] [Luo'02] [Kim'03][S. Gandham'03] [O'Hara'04] [Akkaya'04] [Kalva''05] [A.A. Somasundara'06]. However, we found "location awareness" is necessary for mobile sink wireless sensor networks. The reasons why location awareness is required are listed as below:

- Most MSWSN applications are based on military or disaster-relief scenarios. In these scenarios, routing with location information is more efficient and scalable than routing without location information.
- Most of surveyed geographic routing protocols use "Greedy Geographic Forwarding" as underlying protocol, which can out-perform those routing protocols without geographical information.
- Geographic routing protocols provide the optimum path length between two nodes and nodes only keep state information for their neighbour nodes which support energy efficiency for MSWSN.

Therefore, in this section, the issues related to geographic based routing protocols in MSWSN will be reviewed. These issues concern the routing problems related to the geographic based mechanisms and the routing coordinate issue and the non-geographic based routing mechanisms.

2.7.1 Geographic Based Routing Protocols for Mobile Sinks Wireless Sensor Networks

In wireless sensor networks, building efficient and scalable protocols is a very challenging task due to the limited resources and the high scale and dynamics. The geographic routing approach, that takes advantage of the location information of nodes, relies on greedy forwarding to route packets based on nodes' local information of the network topology. When in possession of location information, geographic routing provides the most efficient and natural way to route packets when compared to other routing protocols. The advantage of geographic routing protocols can be listed as:

- Nodes need to know only the location information of their direct neighbours, which requires little storage capacity, in order to forward packets.

- Such protocols conserve energy and bandwidth as they only need transmit a single hop.
- In mobile networks with frequent topology changes, geographic routing has a fast response and can find new routes quickly by using only local information.

Geographic routing protocols use geographic position knowledge of the network and greedy forwarding to achieve optimal routing schemes with high network performance and low energy consumption. This type of routing protocol allows a simple routing mechanism and with a formed network topology (e.g. grid based network topology) these goals are achieved. The first major question is how to provide efficient network topology construction mechanisms to the geographical based routing protocols.

A number of research efforts focus on routing protocols that aim to construct an efficient and load balancing network topology in MSWSN environments. A typical example as in the TTDD routing protocol [Luo'02], sensor nodes are stationary and location-aware which allows a source node to build a grid structure and form the network into cells while it detects a stimulus. They aim to provide efficient data dissemination in large scale WSN with sink mobility. However, it is not suitable for tracking applications where the source moves fast and changes location frequently since this incurs frequent changes of structure. The number of sources affects the overall performance. As the number of sources increases, the communication overhead to construct and manage the structure increases.

Efficient Data Dissemination and Aggregation (EDDA), was introduced in [J.Youn'04]. In EDDA, sources with the same data type share a single grid structure to disseminate their sensing data. This grid sharing also increases the chance of data aggregation. Furthermore, the local flooding is substituted by uni-casting messages. In EDDA, in order to obtain the immediate distribution node, the sink floods in the 1.3α range. In EDDA, a sink obtains the position of a nearby immediate broadcasting node by using a hash function. The hash function gives one output, (x, y), where location (x,

y) lies within 0, cell size (α). Then, it sends a uni-casting query to the point. However, EDDA still has high communication overheads for maintaining the grid structure. Especially in large-scale sensor networks, the grid construction and maintenance in a region that a mobile sink will never enter will waste considerable network resources.

To improve EDDA [J.Youn'04], On Demand Data Dissemination (ODDD) [Kalva''05] provides an efficient network maintenance mechanism in MSWSN. In ODDD, a source does not proactively construct a virtual grid. Instead, as shown in Figure 2.14, a source sends a data announce message along the X-axis only which means data announce message will only be send along horizontal axis in ODDD coordinate system. Therefore, ODDD reduces the amount of communication overhead for creating and maintaining virtual grid structures over the entire network including the areas where a data collector never roams. However, ODDD still uses hash functions to remember the location of the source or destination nodes which have the drawback that nodes associated with hashed locations will frequently serve the network over time. This may affect the network performance because the nodes associated with hashed locations will become a "hotspot".

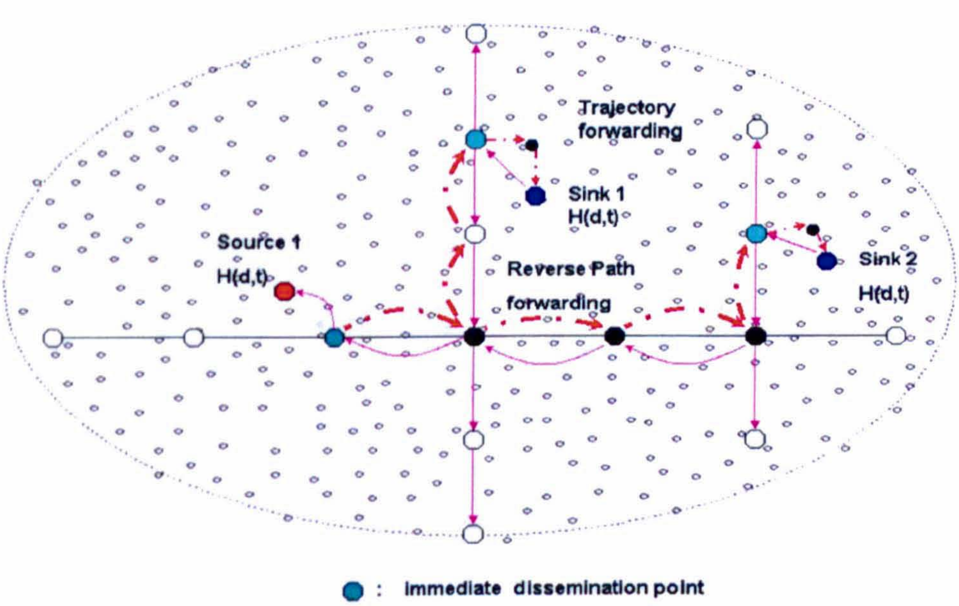

Figure 2.14 : A Diagram of Data Forwarding in ODDD Data Announcement

On the other hand, SEAD [Kim'03] is another routing mechanism for MSWSN. It is based upon constructing a minimum Steiner tree for the mobile sinks and designates some nodes on the tree as access points. Each mobile sink registers itself with the closest access node. When the mobile sink moves out of range of the access node, the route is extended through the inclusion of a new access node. However, such partial path extension is allowed only for a limited number of hops. This is not the case when multiple active sources generate data simultaneously which leads to network traffic congestion.

Another tree-based routing scheme is named Dynamic Proxy Tree-Based Data Dissemination Scheme [Wang'05]. This approach is aimed at the problem of frequent movement of sources and sinks which leads to sink node failure to receive data. They use two schemes, a shortest path-based (SP) scheme and a spanning range based scheme. Both of these schemes are designed to optimize the tree structure and enhance energy efficiency routing in MSWSN. However, they do not consider sensor node failure conditions or provide a maintenance algorithm, thus if a node fails they will pick the wrong nodes and lose information.

2.7.2 Non-Geographic Based Routing Protocols for Mobile Sinks Wireless Sensor Networks

A reinforced learning algorithm for mobile sinks in wireless sensor networks is Hybrid Learning-Enforced Time Domain Routing (HLETDR) [P. Baruah '04]. Each sensor node continuously learns the movement pattern of the mobile sink and statistically characterizes it as a probability distribution function. Thus, sensor nodes always know in which direction they have to route messages to the sink at a given time instant. The advantage of the solution is that nodes do not need time synchronization, since they make forwarding decisions in their local time-domain. The assumption is that the mobile sink comes within direct radio range of all the sensor nodes, which may not be true in practice.

Rumor Routing (RR) [Braginsky'02] is between event flooding and query flooding (a hybrid protocol) that attempts to balance event and query flooding in sensor networks. In rumor routing, as soon as an event occurs in a network region, sensing nodes create some agents as event agents and propagate them along the network. Each node of the network randomly forwards these agents to a neighbour. This information remains in each node visited by the event agent for a predefined time interval and helps to construct a routing table. Therefore, when a mobile sink sends a query, the idea is to route the query packets to the nodes that have observed a particular event rather than flooding the entire network to retrieve information about the occurring events. However, the actual path taken by an agent when it selects a random neighbour is not an efficient method for event discovery in mobile sinks wireless sensor networks.

Zonal Rumor Routing (ZRR) [T.Banka'05] is an extension to the Rumor Routing algorithm. ZRR algorithm enables the rumors to spread to a larger part of the network with high energy efficiency. This is achieved by partitioning the network into zones according to the zone leader's reception and updates of its neighbour list. Each node tries to relay the agents to neighbouring zones in a single transmission. In this way, in a few steps the agents are propagated deeply in the network and a greater region is covered. When mobile sinks generate a query, this query searches the event list of each intermediate node. If the node has a route to the event, it forwards the query in that direction. The objective of the ZRR algorithm is to spread the event as far as possible in the network with the minimum number of transmissions in order to increase the query delivery rate. However, while agents propagation zones become wider, density of visited nodes by the agents is decreased which leads to low network coverage and connectivity.

In summary, Table 2-3 shows the classification of the protocols covered in this section. Also included in the table is an indication as to whether the protocol is utilizing position awareness and power usage, since it is an important consideration for routing protocols in terms of energy saving and traffic optimization.

Routing Protocol	Mobility	Classification	Position Awareness	Salability	Query Based	Power Usage	QoS
TTDD	Yes	Hierarchical	Yes	Limited	Possible	Limited	No
EDDA	Yes	Hierarchical	Yes	Good	Yes	Maximum	No
ODDD	Yes	Hierarchical	Yes	Good	Yes	Maximum	No
SEAD	Yes	Tree-based	Yes	Limited	Possible	Limited	No
Dynamic Proxy Tree	Yes	Tree-based	Yes	Limited	Possible	Maximum	No
HLETDR	Yes	Flat-base	No	Limited	Yes	Limited	No
RR	Yes	Flat-base	No	Limited	Yes	Limited	No
ZRR	Yes	Flat-base	No	Limited	Yes	Limited	No

Table 2-3: Geographic Based and Non-Geographic Based Routing Protocols Comparison in Mobile Sinks Wireless Sensor Networks

2.8 Fault Tolerance in Wireless Sensor Networks

Fault tolerance becomes vitally important in WSN because a gracefully response to unexpected failure enables the system to operate continuously. Sensor networks made up of a number of such sensor nodes can be easily deployed in a wide variety of environments making them very attractive for large-scale applications such as habitat monitoring, security surveillance, and disaster relief. Sensor nodes in the wireless sensor networks are responsible for acquiring sensing information in their local environment. This can be achieved by self-observation or co-operation with neighbouring sensor nodes to maintain the up-to-date variation of the target. Wireless sensor networks consist of large numbers of sensor nodes possessing limited processing and power capabilities, unreliable communications and a low bandwidth environment. It is not uncommon for sensor nodes or communication links to become faulty and unreliable.

X.M. Huang [Huang'06], proposed a fault tolerant routing algorithm for wireless sensor grid networks. First, the levelling algorithm is proposed as an energy efficient method for route discovery and maintenance. Second, the use of an extended transmission range method is presented to overcome limited performance of the leveling algorithm on partitioned networks owing to the dead node. Lastly, a combination of these two techniques is investigated to reduce the probability of network partitioning. Extended transmission range will cause heavy loading on individual sensor nodes, but Huang does not propose the optimized duty sensor node to extend long term network lifetime.

Gunjan Khanna [Khanna'07], presents a protocol called Shortest Path Minded SPIN (SPMS). They use a metadata descriptor to check availability of data that can use multi-hop communication via the shortest path and they propose a Primary Originator Node (PRONE) and Secondary Originator Node (SCONE). The main function is to avoid unreachable PRONE that can be replace by SCONE via RQW messages. However, for the "Hole" affects networks operation, it cannot have the second route passing through the networks.

As mentioned above, due to low cost and the deployment of a large number of sensor nodes deployed in harsh environments, manual maintenance and debugging of the nodes becomes impractical. Moreover, these sensor nodes are powered by batteries, which are considered as limited resources. It is very expensive for the base station to collect information from every sensor and identify faulty sensors in a centralized manner. One of the most common approaches to provide fault tolerance in wireless sensor networks is applying redundant sensor nodes or communication links. However, this approach is not sufficient to fully meet the requirements of the users. For example, users are interested in a sense of reality when monitoring target objects. In this case, users require high quality and accuracy of target information more than high speed data delivery. Because these sensor nodes might be deployed in hostile environments, it is also difficult for operators to be on-site and diagnose faults and recover failed nodes. Thus, it is desirable that wireless sensor networks should have self-fault diagnosis capability and self-recovery functionality.

The development of theoretically attractive and realistic fault models is one of the key prerequisites for the development of real-life fault tolerance techniques for sensor networks. Apart from fault tolerance models for components such as computation, storage and communications, there is very little published in terms of fault models for sensors and actuators which are the most important for overall system fault tolerance. The development of fault models for sensors will be particularly difficult due to a great variety of their types, environments in which they will be deployed, and requirements in terms of fault tolerance of various applications.

Sensor nodes operate within constraining environments that make node components, system and even communications prone to failure. Once a major failure has occurred, sensor nodes will transmit the normal state to the failure state. Failure state is an incorrect state of node hardware or a software program as a consequence of a failure of a component. For instance, permanent faults are a kind of node failure that is continuous and stable in time. An intermittent fault is one that has only occasional manifestation due to unstable characteristic of the hardware, or as a consequence of a program being in a particular subset of space. Finally, a transient fault is one that is the consequence of temporary environmental impact on otherwise correct hardware. Therefore, the fault state can be inducing to the absolute cause and relative cause. The absolute cause represents the failure source or node constraints, such as a low power level, which directly impacts the target system; and relative cause represents ontology factors to the cause of the fault under consideration.

For example, consider a sensor node system that can be viewed as a set of components. The fault of the system can be represented by the causal chains of fault events which occur on each component. Figure 2.15 shows a diagram of relative cause. Suppose a node system consists of the three components, c1, c2, c3. Once an internal fault is propagated to the component c1 then c1 will produce an error action and a fault event on c1. Next, the fault event on c1 will influence a component fault to be propagated to c2. In this case, c2 will produce an abnormal action and a fault event on c2. Once again, the fault event on c2 will propagate a fault event on c3. In this diagram, the sensor system has three fault events and the three faulty components are c1, c2 and c3. Such influences represent factors external to the sensor system under consideration such as abnormality of the environment of the node system such as high temperature or humility environment to affect the sensor system operation. In the example, the absolute cause is the abnormal influence c1 component.

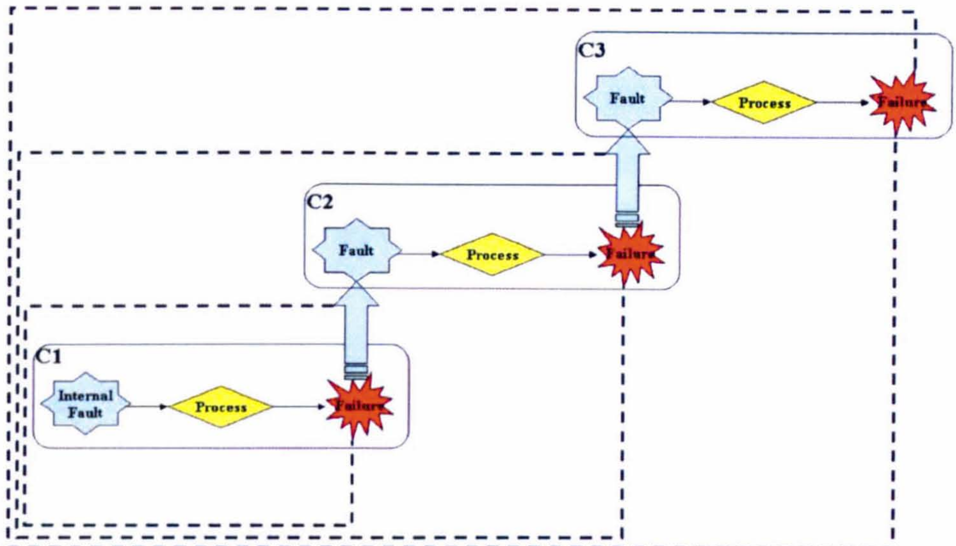

Figure 2.15 : An Example of a Causal Analysis of Fault Events

There are three main concerns with fault tolerance; fault detection and diagnosis, and recovery mechanisms. Fault detection is the first phase where it is recognized that an unexpected event has occurred. Traditionally, fault detection techniques are classified into active and inactive detections. Active detection targets real-time fault identification and is performed simultaneously with a real work load. In this approach, the system will normally produce false alerts triggered by interesting events. The common practice is to use event driven monitoring since it significantly reduces the traffic in the network. For inactive detection, it normally operates with regular fault checking programs or statistic fault quantity during various periods of time. The former type of monitoring collects multiple snapshots at certain times.

Diagnosis in the second stage is where the exact occurrence of a fault is attributed to a specific piece of hardware. Reconfiguration is the stage that is entered into after diagnosis and where the system is restructured in such a way that faults do not have an impact on the correct output. Gradual degradation is a reconfiguration technique where performance of the system is reduced, but the correct functionality is preserved. Several works for model-based fault diagnosis methods have been proposed [B. Horling'00][R. Jurdak'06][Kitamura'97]. Horling and Lesser [B. Horling'00] used a directed, acyclic graph (DAG) for organizing a set of diagnosis nodes. In the first stage, the nodes periodically perform simple comparison checks similar to the watchdog method to identify if a fault has occurred. Any deviation from the expected value of the characteristics triggers the diagnosis model to identify the exact source of the fault. This trigger-checking activity is a primary mechanism for initiating the diagnostic process.

Recovery is the final stage where an attempt to eliminate the effects of faults is conducted. Two most widely used recovery techniques are fault masking and retry. The fault masking approach is one where redundant correct information is used to eliminate the impact of incorrect information. In retry, after the fault is detected, a new attempt to execute a piece of a program is made in the hope that the fault is transient. Restart is the stage that is invoked after the recovery of correct undamaged information. In cold-restart, a complete resetting of the system is conducted.

The primary goal is to survey the field of fault tolerance in sensor networks. Fault tolerance is considered at four different levels of abstraction, starting from hardware and system software and going to the middleware and application layers. We consider fault tolerance at each level of six individual components of a node: computing engine, communication and storage subsystems, energy supply, sensors, and actuators. Also considered is fault tolerance at the level of the node itself, as well as the network level. Finally, resiliency against errors where wireless sensor networks are treated as embedded distributed systems is considered. In chapter 6, an explanation in more detail is given on how this node recovery scheme works, its benefits and which parameters affect its performances.

2.9 Summary

In this chapter the research efforts in the area of routing protocols and fault tolerant mechanism for efficient and reliable routing in mobile sinks wireless sensor networks were surveyed.

Evolving from Micro-Electro-Mechanical Systems (MEMS) technology development, sensor nodes are small, with limited processing, computing and wireless communication capabilities enable remote environmental surveillance and target tracking applications. However, applications that required fine-grain monitoring of physical environments subjected to critical conditions, such as fire, leaking of toxic gases and explosions, posed a greater challenge to network applications. Since sensor nodes have various energy and communication constraints because of their inexpensive nature and ad hoc deployment, it becomes imperative that research is carried out into sensor network survival on small, limited sources of energy and the ability to communicate through a wireless communication channel.

Although some existing communication solutions take into consideration energy efficiency or low-latency issues in sensor networks, these routing protocols may not consider sensor nodes closer to the static sink which will drain their energy resources first. This is because these sensor nodes are required to forward not only their own but also other sensor nodes packets with the result that system lifetime is reduced. Moreover, these routing protocols considering energy efficient or low-latency issues may neglect the user requirements such as network scalability and connectivity which result in inefficient routing and waste of limited resources. Finally, these sensor nodes are very vulnerable to failures. They may lose functionalities at any time because of energy depletion or harsh environment factors.

Therefore, the challenge is to design a new communication protocol set that provides high performance routing and reliable network infrastructure solutions for mobile users to retrieve sensed information from a remote region while consuming the minimum possible resources. In this thesis, new routing mechanisms for mobile sinks wireless sensor networks based on geographic based routing protocol are presented. These mechanisms take into consideration the following factors: system lifetime, efficient routing and fault tolerance relevancy to the user requirement thus achieving high performance, reliability and extended system life.

CHAPTER 3

3 HIGH PERFORMANCE COMMUNICATION FRAMEWORK FOR MOBILE SINKS WIRELESS SENSOR NETWORKS

The previous chapter gave an overview of the general characteristics and applications of WSN and MSWSN. As in the previous chapter, due to the sinks' mobility, MSWSN has different communication challenges such as dynamic topologies, dynamic network connectivity as compared to the WSN. Furthermore, in many cases, the sink will move continuously in a random fashion, thus making the whole network a very dynamic topology. This dynamic nature of MSWSN is reflected in the choice of other properties, such as routing and MAC level protocols and physical hardware. In most cases, it can be reasonably assumed that mobile sinks have infinite energy, computational and storage resources. The depleted batteries of mobile sinks can be recharged or changed with fresh ones and similarly the mobile sink has access to computational and storage devices.

MSWSN have been shown to improve overall performance and enhance data capacity over static WSN [Liu'05][W.Wang'05][Yarvis'05]. However, these protocols in use may not be high performance and energy-efficient in large scale networks due to increase in the number of nodes. Hence, in this chapter, we describe the difference between traditional WSN and MSWSN which leads to the fact that a new routing approach is required to address the challenges of developing a routing protocol for MSWSN. Then, we summarize and highlight the main issues and problems related to routing challenges based on non-location aware and location aware in MSWSN. This chapter also highlights fault tolerance requirements in

MSWSN. Some of the other advantages gained through MSWSN over traditional WSN are presented below:

- One major advantage of MSWSN over static WSN is its efficient energy usage. In static WSN, the nodes closer to the sink always lose their energy first, thus causing the overall network to "die". In the case of MSWSN, mobile sinks can move closer to the nodes which help energy dissipation efficiency. Moreover, since data is transmitted over fewer hops, the number of packets is reduced thus extending system life. Some work has already been done in this regard to building an optimum mobility pattern for maximum performance.
- Another advantage of having a mobile sink is it can support more channel capacity as compared to static WSN. By providing a number of mobile sinks, the channel capacity will increase linearly with the growth of sensor nodes. As in [C. Chen'06], they have calculated the channel capacity gains in the case of MSWSN and have calculated it to be 3-5 times more than static WSN. Moreover, in a sparse or disconnected network, mobile sinks can also help in better quality of communication between sensor nodes.
- The other advantage is that sink mobility can provide data fidelity. It is well known that the probability of errors increases with increasing number of hops that a data packet has to travel. If we reduce the number of hops, this immediately reduces the probability of error. This does not only increase the quality of data received but also further reduces the energy spent at the static nodes by reducing the retransmissions required due to errors. Moreover, the end-to-end communication range between mobile sinks and sensor nodes can be reduced. This feature can enhance network performance metrics.

However, the increased mobility in the case of mobile WSN imposes some restrictions on the already proposed routing and MAC level protocols for WSN. Most of the efficient protocols in static WSN perform poorly in cases of MSWSN. Namely, mobile sinks will introduce new challenges for WSN such as dynamic routing topology, network maintenance and reliability communication. Some of the design challenges as compared to traditional WSN are presented below:

- Reliable Link: Due to the dynamic topology of the MSWSN, communication links can often become unreliable. This is especially the case in hostile, remote areas where WSN application availability of constant communication channel, for minimum QoS, becomes a challenge. Therefore, a reliable routing mechanism to reflect the updating of the relay path from the mobile sink may be required.
- Dynamic Topology: Due to the mobility of the sinks, MSWSN has more dynamic topology as compared to the static sink WSN. It is often assumed that the sink will move continuously in a random fashion, thus making the whole network a very dynamic topology. Therefore, a dynamic routing topology should be used to improve network performance.
- Geographic Routing: Because of the frequent location updates from mobile sinks, location estimation plays an important role so as to have an accurate knowledge of the location of the sink or node. Therefore, a geographic-based routing mechanism to reflect the updating location of the mobile sink may be required.
- Logical Coordinate: The main drawback of geographic routing is that if the next hop node fails then communication failure will result. Fortunately, some logical coordinate algorithms [Rao'03] [Cao'04] [Caruso'05] can improve performance for geographic routing in WSN. Hence, a logical coordinate routing algorithm to improve network robustness may be required.
- Fault Tolerance: Sensor networks are expected to operate in hostile environments; hence, a reliable and efficient fault tolerance mechanism becomes vitally important to provide a robust operational system and network for MSWSN.

In section 3.1 we summarize and highlight the main issues and problems related to routing and the fault tolerance challenges while designing routing protocols in MSWSN. In section 3.2 we present our new communication mechanisms. The simulation environment used in our work is described in section 3.3. Finally, a summary of this chapter is provided in section 3.4. This chapter provides a road map for the following chapters.

3.1 Motivation and Design Challenges

To motivate our research, let us consider a forest fire rescue application as an example. After a forest management department gets a fire alarm call, it will send a fire rescue team to the forest fire field. Normally, a fire rescue team consists of one incident commander vehicle, multiple fire engine vehicles, and the most important role, a set of fire fighters, who are grouped as squads associated with one of the above vehicles. During the process of fire rescue, the incident commander is in charge of the whole fire rescue situation, including monitoring the fire field and making a real-time schedule for fire fighter assignment. The fire fighters are organized into different squads based on their specialty and work together to eliminate the forest fire.

Let us assume that the fire fighters can collect the wind direction information, temperature, and weather conditions from WSN deployed in the forest fire location using PDA devices. These PDA device functionalities are similar to mobile sinks carried by fire fighters that collect the sensed information to monitor the current situation, reduce the damage of the wildfires strike and maintain sensor networks communication. However, this mobile sinks solution for forest fire rescue operation also has several challenges.

- First of all, the sensing information collected at the sensor nodes close to the source of forest fire should be reliably communicated to neighbouring sensor nodes which may be pre-processed by mobile sinks and relayed to the incident commander.

- Second, mobility of the sinks and various adverse factors including wireless communication phenomena, the routing protocol should be very scalable and efficient to work well in most cases.
- Third, for the mobile sinks (fire fighters) to keep randomly moving according to the fire situation during the process of fire rescue and real time monitoring requirement of the forest fire, sensor nodes may need to have the geographic location information of the mobile sink to reflect the updating location of the mobile sink.
- Fourth, in some cases, such as in the existence of obstacles, routing with geographic location information can not reflect the connectivity of the network environment. Routing mechanism requirements having the logical coordinate algorithm to improve the performance in MSWSN.
- Finally, due to the hostile environment of the WSN, sensor nodes are prone to failures. Both sensor node and routing mechanism are required to have fault tolerant capability and robust communication features to elegantly respond to the failure without affecting current network operation.

This section will review the issues related to routing mechanisms in MSWSN resulted from the previous chapter. First, we will consider the problems related to routing mechanisms in MSWSN. Then, we will consider the fault tolerance algorithms to node-level and the self-fault diagnosis issue in sensor nodes of WSN. Our design criteria can be described as follows:

3.1.1 Routing in Non-Geographic Aware Mobile Sinks Wireless Sensor Networks

As described in chapter 2, we found in the literature many works that treat the problem of routing protocols in non-geographic aware based MSWSN. The main drawback we found in these routing protocols is that the network topologies may vary in time which causes heavy communication overheads in the network layer. Moreover, most of these works fail to propose energy efficiency with a reliable communication solution to the problem and few of them use the flooding technique as the routing approach [Intanagonwiwat'00] [Kim'03]. Nevertheless, these flooding based protocols also present some drawbacks, the most important ones are:

- Since frequent location updates from a mobile sink in a non-geographic aware based network topology will lead to large amounts of computing and traffic overheads caused by network routing information changes, frequent route computing and network state updates respectively. We know that large amounts of communication overload is not suitable for sensor networks because sensor networks suffer from resource constraints such as energy and bandwidth. Hence, it is necessary to design an energy efficient routing topology to eliminate redundant communication overheads to prolong system lifetime in non-geographic based MSWSN.
- Second, the network scalability is a fundamental design objective in MSWSN. The number of sensor nodes deployed in the sensing area may be in the order of a few nodes to hundreds or thousands, or more. We know that zone based routing protocols [Z.J.Hass'97] [M.Gerla'00] [C.C.Yang'07] provide extended zones which improve scalability and performance in MANET. Therefore, the main concept of this new routing protocol is to design a zone based routing topology which improves scalability without geographic information on the sensor nodes. Moreover, the routing protocol should also be scalable enough to both the number of

data sources and the mobile sinks population, and allow a diversity of user requests in terms of desired update rates and service durations.

- Third, the network connectivity between the sensor nodes and mobile sinks might vary all the time as frequent topology changes, unreliability and asymmetric links which directly impact the data dependability of MSWSN. Hence, routing mechanisms in MSWSN are required to support efficient and reliable data transmission between sensor nodes and mobiles sinks to achieve high data reliability in the presence of network dynamics.

These issues emphasize the necessity for a new routing protocol for non-geographic aware based MSWSN. This new routing mechanism must be able to provide scalability, performance and reliability to support large scale sensor nodes and multiple data sources deployed in WSN, while respecting the resources constraints of the mobile sinks wireless sensor network

3.1.2 Routing in Geographic Aware Mobile Sinks Wireless Sensor Networks

Following our literature review on geographical based communication protocols in MSWSN presented in the chapter 2 [J.Youn'04] [Kalva"05], we found the current geographic based routing does not only rely on geographic knowledge but on logical coordinate topology to provide simple, scalable, and satisfactory performance. However, most of these works fail to propose fault tolerance solutions when grid node failure or malfunctions occur. Moreover, these coordinated routing protocols also present some drawbacks, the most important ones are:

- Unlike traditional geographic based routing protocols in wireless sensor networks, geographic coordinate-based routing systems can provide routing efficiently and has comparable performance to previous works [J.Youn'04] [Kalva"05]. However, when a power node failure such as in a grid point node in coordinated based routing protocols, it can result in network congestion or communication data loss between source and destination. Therefore, to provide network reliability, a communication level of fault tolerance mechanisms are required to be implemented in the coordinated based routing protocols.

- On the other hand, current routing protocols which have a fault tolerance capability will require either repartitioning of the network or extending the transmission range to support routing path recovery [Gunjan Khanna'04] [X. M. Huang'06]. However, while partitioned, the network performance will be degraded and the extended transmission range scheme can cause heavy loading on individual sensor nodes. Therefore, to provide good performance in geographic coordinate-based routing mechanisms we will need to take into account the system lifetime issues in MSWSN.
- System lifetime is an important design challenge in WSN because sensor nodes are autonomous devices that usually derive their power from a battery mounted on each node. The existing works might have a heavy load when constructing a grid network by letting every potential data source keep flooding their measurement before any explicit user requests. Therefore, the designed routing mechanisms should be able to satisfy them with lower energy dissipation and a considerably extended system lifetime.

These issues emphasize the necessity for a new geographical coordinated based routing protocol to provide fault tolerance and good performance in MSWSN. This new geographical coordinated based routing approach must support energy efficiency without degrading performance of data communication, while respecting the resources constraints of the MSWSN.

3.1.3 Component Level Fault Tolerance Mechanisms in Wireless Sensor Networks

Following our literature review on fault tolerance mechanisms in MSWSN presented in chapter 2, we found that fault-tolerance mechanisms are vitally important for wireless sensor networks because they respond gracefully while the node or communication fails in sensor networks. However, most of these mechanisms fail to propose component level fault tolerance solutions when sensor nodes fail or malfunction. Nevertheless, these fault tolerance mechanisms also present some drawbacks, the most important ones are:

- Sensor nodes are autonomous devices that usually derive their power from a battery mounted on each node; however, most of the fault tolerance mechanisms are required to construct a synchronization environment over the wireless channel that will consume considerable resources, hence, these mechanisms are not appropriate for implementation in the wireless sensor networks. To provide energy saving issues for fault tolerance mechanisms in wireless sensor networks, knowledge based self-diagnosis systems can be the optimized solution for energy constrained wireless sensor networks.
- However, one of the main drawbacks of the knowledge based self-diagnosis mechanisms is: it will consume large computing resources while high analyzing complexity algorithms are implemented. Therefore, reducing the analyzing complexity is the key issue for fault tolerance mechanism in WSN.

These issues emphasize the necessity for new fault tolerance mechanism in wireless sensor networks to reach two objectives which are: energy efficiency and low complexity. This new fault tolerance mechanism must be energy efficient and highly reliable to support node-level sensor nodes self-diagnosis system; while respecting how to reduce the analyzing complexity, the key issue for this kind of fault tolerance mechanism.

3.2 Mobile Sinks Routing Mechanisms for Communication

Our solution to address the mentioned challenges is for new communication protocols and mechanisms for MSWSN. These mechanisms consist of three novel schemes that aim to support high performance and high reliability routing framework for mobile sinks wireless sensor networks:

a) A new routing protocol for non-geographic based routing in MSWSN [Chang'06-a] [Chang'07-a]

b) A fault-tolerant coordinate based routing protocol for geographic based routing protocol in MSWSN [Chang'07-c] [Chang'07-d]

c) A causal model based fault-diagnosis algorithm in wireless sensor networks [Chang'09]

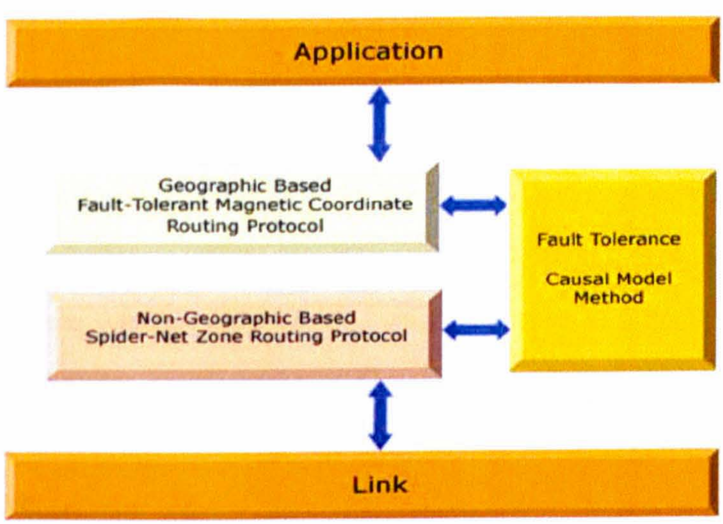

Figure 3.1: Proposed Routing Framework

In order to explain our routing framework better, Figure 3.1 shows our proposed routing framework. It consists of three sub-components on the basis of the functionality it provides. All these components may run on different devices depending on user/application requirements. The reasons for illustrating the framework is to understand how different components can be integrated together and to demonstrate flexibility of our routing framework, as well as fault tolerance capability while remaining robust to one or more service failures. In this section, we describe these novel contributions in details.

3.2.1 Scalable Routing Topology for Non-Geographic Based Mobile Sinks Wireless Sensor Networks

We develop a new routing topology utilizing spider web topology inspired by the way spiders hunt prey in their web. This routing topology can provide high scalability and good performance data communication for non-geographic based MSWSN. Also, this scheme utilizes routing redirect between the mole nodes (the cluster heads near mobile sink) which aims to achieve reliable communication for MSWSN.

- ❖ The spider-net zone based routing protocol forms its network topology by partitioning the whole network area into different zones. Each zone has their membership nodes; they are named core, intermediate and gateway cluster heads. This spider-net zone routing algorithm supports the network scalability, improves the network performance and provides robust data transmission for non-geographic based MSWSN.
- ❖ The protocol uses an intra-spider-net zone routing mechanism to update the data dissemination between the mobile sink and a spider-net topology network. This scheme supports redundant routing paths to provide better reliability of communications in MSWSN. The protocol uses an inter-spider-net zone routing mechanism extending a spider-net zone to multiple spider-net zones. This scheme also supports network scalability for mobile sinks in wireless sensor networks.
- ❖ The protocol also uses a routing redirect mechanism to update the current mobile sink location which allows event messages to be quickly forwarded. This scheme helps to deliver event messages efficiently with continuous forwarding to the mobile sink, while it is moving.

Details of this protocol are presented in chapter 4 of this thesis.

3.2.2 A Fault-Tolerant Magnetic Coordinate Routing Protocol for Geographic Based Mobile Sinks Wireless Sensor Networks

We will present a new fault tolerant routing protocol for data dissemination in a geographic based MSWSN. This routing algorithm uses a logical coordinate routing mechanism to eliminate communication overheads of data dissemination and applies the consensus-based fault tolerance scheme to provide reliable network communication for MSWSN. In addition, this scheme utilizes collision avoidance mechanisms between the mole nodes (the cluster heads near mobile sink) which aims to achieve reliable communication for MSWSN.

- The protocol uses coordinate based routing approach to form a grid-based network topology and applied magnetic routing concepts to build an efficient data communication protocol in MSWSN. Unlike traditional geographic based routing mechanism, this coordinate based routing protocol utilizes sensor nodes' logical coordinate information and magnetic based data dissemination algorithm to improve performance and reliability issues for MSWSN.
- The consensus-based fault tolerance scheme can detect malicious nodes in the sensor networks from multiple experts decisions based on consensus-based fault tolerance scheme. This scheme aims to support data source accuracy and reliability by applying both consensus-checking and consensus-detection schemes which help to achieve quick discovery and replacement of any faulty grid node in the network.
- The protocol also provides a simple random calculation period to reduce collisions, assist efficient data dissemination and can be incorporated into existing MAC layer protocols.

In chapter 5, we will explain in more detail how this scheme works, its benefits and which parameters affect network performances.

3.2.3 A Causal Model Based Fault-Diagnosis Algorithm in Wireless Sensor Networks

We present a new algorithm based on Causal Model Method (CMM) which applies fault sources analyzer for component-level fault diagnosis in wireless sensor networks. This scheme consists of three phases to define the node failure sources as "collect, classify, and correct". Once the fault source has been classified, our CMM mechanism will reconfigure the network or execute a recovery scheme to compensate for the erroneous sensor nodes impact. The proposed algorithm will be able to "deep understand" the fault cause and conforming to "light weight" while analysing the fault causes in the WSN.

- ❖ It uses a reputation checker scheme based on the notation of a thread-based checkpoint to detect the abnormal behaviour of a sensor node which is a very light-weight checking scheme to support sensor node reliability.
- ❖ It uses an ontology manager scheme based on the ontology notation which is useful for developing knowledge based systems, analysing domain knowledge and the knowledge reuse. This scheme aims to pinpoint the special characteristics of sensor faults and limited analyzing complexity to categories fault taxonomy as a fault tree in wireless sensor networks.
- ❖ It uses an action planner scheme to reduce the risk of a range of node failures that impacts the whole wireless sensor networks operation. This scheme will enable a local reconfigure process to avoid failure expending effect by wireless sensor networks operation.

A complete description of this framework is presented in chapter 6.

3.3 Simulation Environment

In many cases, it is not feasible to develop theoretical and analytical models of the target WSN since such models often fail to capture many important aspects of sensor networks. Due to these reasons, simulation becomes the only viable alternative to test, validate, evaluate, and choose among design approaches, network protocols, and design parameters. Among existing WSN simulators, GTSNetS [6], is a sensor network extension to the GTNetS simulator, which aims to provide a scalable, highly extensible and customizable, model-centric simulator to WSN researchers, and also enables the simulation of sensor control networks. Besides its key feature of scalability, the design of the GTSNetS closely matches the design of real network protocol stacks and is best characterized by its adaptability and extensibility. The adaptability comes from the different methods included in the baseline implementations. The extensibility comes from the modular implementations using the C++ object-oriented programming language.

Our simulation environment consists of ($240 \leq N \leq 600$) sensor nodes including cluster heads in a 1200m × 1200m grid and each node has a radio range of 50m. The simulation network also consists of ($30 \leq N < 40$) cluster heads which any of them could be a mole node (the cluster head node close to the mobile sink). The energy consumptions of transmitting and receiving of the sensor node are 0.66W and 0.395W. The reason for us setting these network parameters is to maximize the lifetime of a sensor network, while keeping an acceptable performance and energy efficient level. In fact, these network parameters required to be customised by designer. The designer might need to choose among different network protocols, collaboration strategies or decide on other design parameters. In our simulation environment, we follow the design parameters with compared routing protocols as ZRR [T.Banka'05] and ODDD [R.R. Kalva'05].

However, it is not always possible to deploy sensor networks of realistic sizes to test and validate these new routing protocols. In fact, sensor networks often consist of several thousands if not hundreds of thousands of elements and it is not always possible to deploy such a large network for testing. For this reason, simulation becomes the only viable alternative to validate new design approaches for sensor networks. Several sensor networks simulators are available and in widespread use by the research community such as NS-2, OPNET. SensorSim, SWAN, TOSSIM. Most of these simulators do not scale well with the size of the network and can simulate only networks of up to several tens of thousands of nodes. To the best of our knowledge, GTSNetS is the only sensor network simulator capable of handling networks of several hundred thousand nodes.

GTSNetS is built as an extension of GTNetS as simulation framework for sensor networks which is written entirely in the C++ language using an object-oriented methodology. Therefore, we can choose and modify from various implemented functions: different energy models, network protocols and tracing options. As GTSNetS is an event-driven simulator, therefore, it has advance in simulation time and executes the code associated to a given event when the event time is reached. Moreover, GTSNetS provides packet tracing function which tracing occurs every time a message is sent or received by a sensor node. However, due to GTSNetS has default one sink limitations; therefore we only use one sink to compare with other existing algorithms.

In addition of our simulation environment, the power consumption of the communication unit depends on several factors. These include the modulation scheme, the data rate, the transmission distance and the operation mode. A communication unit can operate in several modes: active, idle and sleep. The last two modes imply constant power consumption. Therefore, we set source nodes sends data every 10 seconds, and the hello message is periodically broadcast by mobile sink every 30 seconds. Our main concern is how to reduce the mole nodes competition for energy saving by considering the time limited to decide the mole nodes. We therefore mainly focus on average energy consumption, average packet success ratio and average end-to-end delay. An example of simulation environment is presented in Figure 3.2.

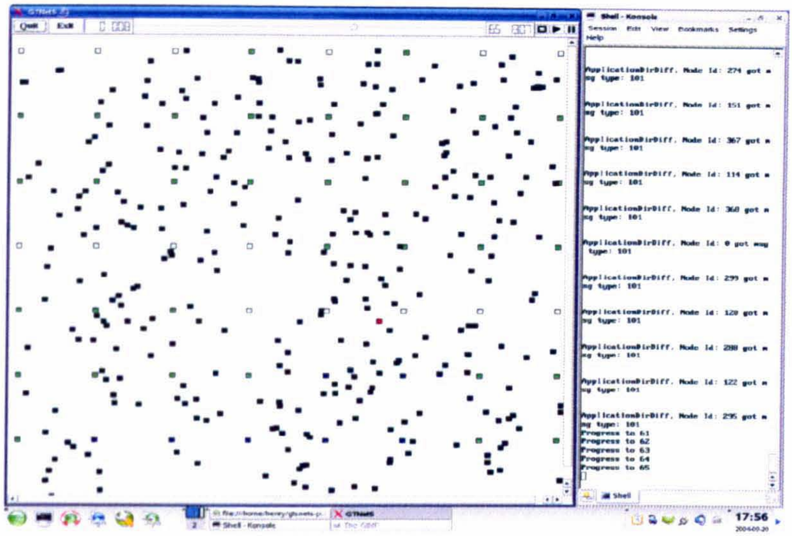

Figure 3.2: GTSNetS Simulation Environment

3.4 Summary

In the past few years, researchers have shown great interest in wireless sensor networks and have focused on the issues involved in the development of energy efficient, high performance, reliable and scalable routing solutions in wireless sensor networks. However, since sensor nodes closer to the sink will drain their energy resources first because of the nodes near the sink clearly forward a significantly greater volume of packets than other nodes further away from the sink. Hence, in the same manner, the data transmission delay will be increased which will leads to a reduction in network reliability. Among all the proposed approaches to solve these problems in WSN, mobile sink seems to provide the optimized solution. However, the influence of the velocity of mobile sinks also brings different challenges to wireless sensor networks, and impact on network performance and communication reliability has not been fully investigated. Therefore, in this chapter, we clearly define the challenges that need to be considered in order to achieve both high performance and reliability in MSWSN.

First, data dissemination mechanisms need to be re-designed to fit mobile sinks in wireless sensor network. Due to the network connectivity between the sensor nodes and mobile sinks variations might very at different time; hence, this data dissemination mechanism should be considering the trade-off between the energy efficiency and network reliability.

Second, the number of sensor nodes deployed in the sensing area may be in the order from a few nodes to hundreds, thousands, or more. Therefore, an efficient routing topology to support scalability is required. This routing topology will be able to support good performance with reliable data communication in MSWSN, while considering that the sensor nodes do not have geographical information knowledge.

On the other hand, we consider the sensor nodes taking advantage of the geographic information knowledge in the network. However, these sensor nodes are very easily prone to failure or malfunction because of complicated system design. Therefore, we propose a robust routing protocol to protect against malfunction and support network reliability. We design a fault tolerance coordinate based data communication solution for user / application to improve network reliability and performance issues in geographic based MSWSN.

Finally, we design a fault tolerance mechanism for component-level in sensor node. However, currently with tradeoffs in cost, complexity, and energy consumption issues in the sensor node, it is not feasible to deploy complex fault tolerance solution in sensor node, but should be able to provide basic fault cause analysis and support reconfiguration capability to recover failure node and keep the energy efficiency in mind when implementing this fault tolerance algorithm.

CHAPTER 4

4 SPIDER-NET ZONE ROUTING PROTOCOL FOR MOBILE SINKS WIRELESS SENSOR NETWORKS

MSWSN are expected to enable real-time and reliable information from the remote sensing areas to mobile sinks. This sink mobility solution has the potential to enhance performance, extend network lifetime and reduce energy consumption and latency by routing data to a nearby mobile sink. In this chapter, we consider MSWSN applications where a mobile sink is a PDA carried by user. We assume that the mobile sink can perform a random walk through the sensor networks field to receive and process the sensed events from sensor nodes. Moreover, these sensor nodes in MSWSN are not aware of their geographic location or their sensing environment. We will address research challenges such as the high communication overhead and packet loss problems while transmit event messages to mobile sinks.

For instance in forest rescue applications, the fire department will get a fire alarm call from control centre. Normally, a fire fight team consists of one incident commander vehicle, a number of fire engines, and a set of firefighters who cooperate to eliminate fire in the fire field. First of all, the incident commander could not have a clear view of the status of the fire field. Hence, the incident commander may need to inquire the environment information of the field such as "What is the wind direction and temperature of the fire field". As a result, each sensor receiving this query checks first if its readings related to the information satisfy the incident commander query, before firefighters enter the fire field. Once sensor nodes meet the condition of the query, they start sending their temperature readings to the fire fighter team. However, while the sensors reply to the user query, it will result in a huge volume of correlated data transmitted to the mobile user thus wasting the sensor resources. The challenge is to design an efficient communication solution that achieves high performance and energy efficient communication for MSWSN. Therefore, in this work, we address this challenge by proposing a new routing protocol for data dissemination in non-geographic aware MSWSN. This is called the Spider-Net Zone Routing (SNZR) protocol.

The novel contribution of this chapter is a new routing protocol that provides an efficient data dissemination algorithm in non geographic aware based MSWSN. It is inspired by a spider building a web topology [Xiaohui Gu'04] [S.S. Kao'05] that can provide high performance, energy efficiency and reliability to routing protocols in MSWSN. Our algorithm provides a spider-net zone topology to improve energy efficiency in MSWSN [Chang'07-a] [Chang'07-b]. Instead of flooding the whole network to send sensing event to a mobile sink while it is moving, this routing mechanism will build an efficient routing path to forward sensed events to the new location of the mobile sink. Moreover, as sensor networks are prone to node failure by hardware, software or environmental issues, this mechanism also has connection link redundancy designed to increase reliability.

We organize this chapter as follows. In Section 4-1, we describe the research challenges and an overview of related works. In section 4-2, we organize the randomly deployed sensor network to form a spider-net topology and present our SNZR routing topology. In section 4-3, we evaluate our protocol analytically while in section 4-4 we evaluate it by simulations. Finally, in section 4-5 we present a summary of this chapter.

4.1 Problems and Limitations

In this section we provide problems and limitations overview of a selection of protocols that have been developed in MSWSN. We will focus on routing protocols, path planning and reliable data transfer mechanisms. To the best of our knowledge, so far only limited researches have tried to address high performance issues in MSWSN.

The cluster-based routing protocols (CBRP) such as LEACH [W.B. Heinzelman'00], PEGASIS [S. Lindsey'02], and BCDCP [S. D. Muruganathan'05] are well-known routing protocols in ad hoc and sensor networks. The main strategy of the CBRP is to use a clustering approach and cluster heads (CHs) [Y.C.Chen'89] [M.Chen'06] [C.S.Nam'08], to enhance scalability and efficiency of the routing protocol. Clustering is particularly useful for applications that require scalability to hundreds or thousands of nodes and provide better solution for load balancing, efficient resource utilization, and data aggregation functionality. However, to select or reconfigure a cluster head in WSN, higher processing and control packet overhead will be result. The cluster head selection scheme will also increase communication overhead utilization and produce longer delays.

Zone Routing Protocol (ZRP) for wireless networks [Z.J.Hass'97] is a hybrid routing scheme that contains both reactive and proactive components. As mentioned in the background chapter, ZRP uses proactive routing to enhance routing discovery capability and reduces the topology maintenance costs to a limited zone. On the other hand, Fisheye Zone Routing Protocol (FZRP) is an extension of ZRP adopting the concept of Fisheye State Routing (FSR) [M.Gerla'00]. FZRP uses the ZRP concept to update routing information in its defined basic zone and uses the "fisheye" technique to reduce the frequency of transmission updates in the extended zone. However, when the network size increases, routes become stale quickly and delays to nodes afar tend to grow large. Moreover, routing table size grows linearly with network size.

A number of research efforts focus on routing protocols in MSWSN aimed at achieving power efficiency, load balancing and extended system lifetime in non-geographic aware wireless sensor networks. The Rumor Routing (RR) [Braginsky'02] aims to achieve lower energy consumption than algorithms that flood the whole network with query or event messages. The algorithm is configurable depending on how well the parameters are set for the particular event and query distribution in the network. However, the actual path taken by an agent when it selects a random neighbour is not an efficient method for reliability in mobile sinks wireless sensor networks. Zonal Rumor Routing (ZRR) [T.Banka'05] is an extension to the Rumor Routing algorithm. ZRR algorithm enables the rumors to spread to a larger part of the network with high energy efficiency. This is achieved by partitioning the network into optimal number of zones by calculate the communication range of the sensor node and the uniform network node density. However, while agents propagation zones become wider, density of visited nodes by the agents is decreased which leads to low network coverage and connectivity.

In this work, we propose a different routing topology for non-geographic aware MSWSN based on spider-net zone. The proposed hybrid network topology provides energy efficiency and network scalability in non geographic aware MSWSN. Moreover, this network topology can also provide parallel link redundancy to ensure that node failure will not impact the data dissemination process, thus improve network reliability.

4.2 Spider-Net Zone Routing Protocol

Spider-net zone routing protocol (SNZR) [Chang'07-a, Chang'07-b] is a hierarchical hybrid scheme for event based data dissemination for MSWSN. SNZR uses hybrid network topology, which is a radial-ring network topologies. This spider-net network topology contains 3 classes of nodes; central star with *m* branch nodes named Core Cluster Heads (CCHs), intermediate branch nodes on *n* inner rings named Intermediate Cluster Heads (ICHs), and peripheral ring nodes named Gateway Cluster Heads (GCHs), as shown in Figure 4.1. In this section, we first describe the assumptions and environmental requirements. Then we divide the SNZR in two parts: first the spider-net topology mechanism and second the spider-net data dissemination mechanism.

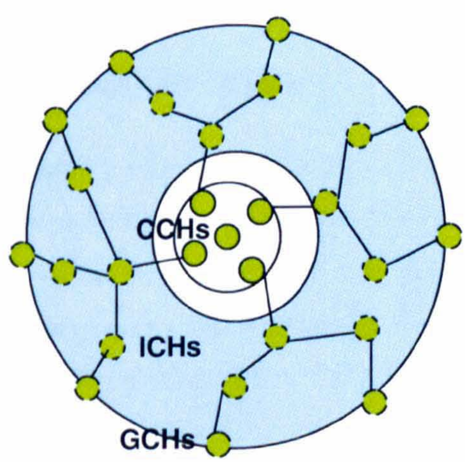

Figure 4.1 : Spider-Net Radial-Ring Network Topology

4.2.1 Concepts and Assumptions

We consider the specific case while a mobile sink moves through the sensor field with a random route. The network model for SNZR makes the following basic assumptions:

- The sensor nodes and cluster-heads are knowledgeable about their neighbour nodes direction but are not aware of their geographical location.
- The sensor nodes and cluster heads are randomly deployed over the entire sensing region. The sensor nodes and cluster heads are homogenous with constrained energy resources. Their wireless communication channels are bidirectional.
- After deployment these sensor nodes and cluster heads will all remain stationary at their initial location in a flat two dimensional space.
- Each mobile sink only broadcasts the beacon message (hello message) to its neighbouring cluster-heads and concentrates on listening to reply messages around it.
- The sensor nodes will send aggregate sensed data using multi-hop communication across vicinity cluster-heads, and forward to mobile sinks. That is to say, sources and mobile sinks are typically much further apart than a single radio radius (multi-hop).

4.2.2 Spider-Net Zone Topology Mechanism

We use the spider-net zone topology mechanism to form the dynamic network in randomly deployed sensor networks. As mentioned above, this spider-net network topology contains 3 classes of nodes; CCHs, ICHs and GCHs. Our spider-net network topology applied this concept to compose those powerful sensor nodes (name cluster heads) to spider-web network topology. The CCHs are inner cluster heads of the spider-web, similar as the most inner intersection nodes of a spider-web which connects the entire radii web in the network. These CCHs are used as a rendezvous place for sensor nodes and mobile sink, once there is an event detected by sensor nodes, the event message will be forwarded to CCHs first. Another class of cluster heads named GCHs, GCHs are the cluster heads around the peripheral area of the spider-web, which provide bridge functions between the different spider-net topology networks. These GCHs are able to extend one spider-web to multiple spider-web network topologies. The other class of branch cluster heads named ICHs; ICHs are the intermediate cluster heads of the web that provide junction between CCHs and GCHs.

The idea of the spider-net zone construction is based on using CCHs, GCHs and ICHs to build a logical spider-net zone. For the construction of a spider-net zone, the network requires three steps during formation in order to determine which sensor nodes in the network should become CCHs, GCHs and ICHs. Step 1 provides CCH selection. Step 2 provides ICH and GCH formation. Step 3 provides Multilayer Ring topology construction.

CCH formation: In the algorithm a predefined initial sensor node is selected to establish the network topology. An initiate sensor node is the key to establish network topology construction; it will implement minimum response time node selection (MRTNS) as will be mentioned in next section. Initially, it will broadcast a *Cluster_Head_Candidate_Msg* to its 1-hop away neighbouring sensor nodes and wait for their response. When the sensor nodes get this message, they will send out *Cluster_Head_Select_Msg*. When initial node receives this message, it will extract node id, response time t and store in its Cluster Head Candidate List (CHCL). Then the initial node will sort out these cluster head candidates by response time order at each direction. If these candidates get a response time less than a predefined threshold T, the initial node will send out *Candidate_Select_Msg* to that particular sensor node and it will become one of CCHs.

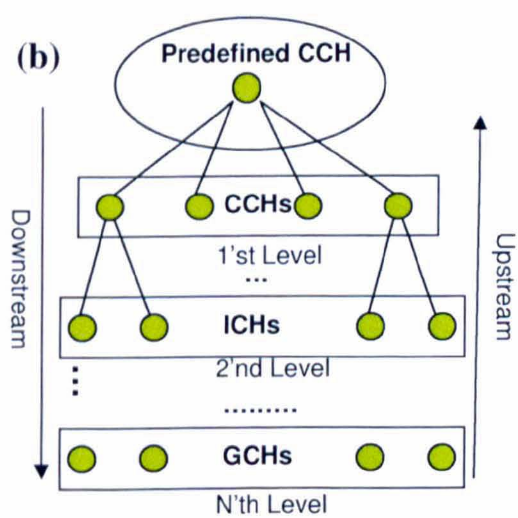

Figure 4.2 : Spider-Net Zone Topology Construction

ICH and GCH formation: As same as CCH formation, after the CCHs have been selected, these CCHs will broadcast *Cluster_Head_Candidate_Msg* to its 1-hop away neighbouring sensor nodes to find downstream ICHs. This radial-ring network topology construction is the start of a tree-based network topology. Any sensor node which is 1-hop away from CCHs and with a response time less than the predefined threshold T will be selected first level ICHs. In the same way, by implementing the MRTNS mechanism, first level ICHs will be able to connect with second level ICHs and so on until the *N'th* level. The number of level N can be defined by user or application to scale the monitoring area or ICHs aware that there is no response when they want to exchange this construction message with downstream sensor nodes. When the *N'th* level ICHs have been elected, these ICHs are the GCHs. This is shown in Figure 4.2 above. Once GCHs have been elected, they will relay their node ID to the CCHs by sending back the construction complete message. When CCHs receive this construction complete message, CCHs will have their routing table and will know the N hops distance to their GCHs. Once the routing table has been decided, these CCHs will share their routing information to other CCHs in the spider-net.

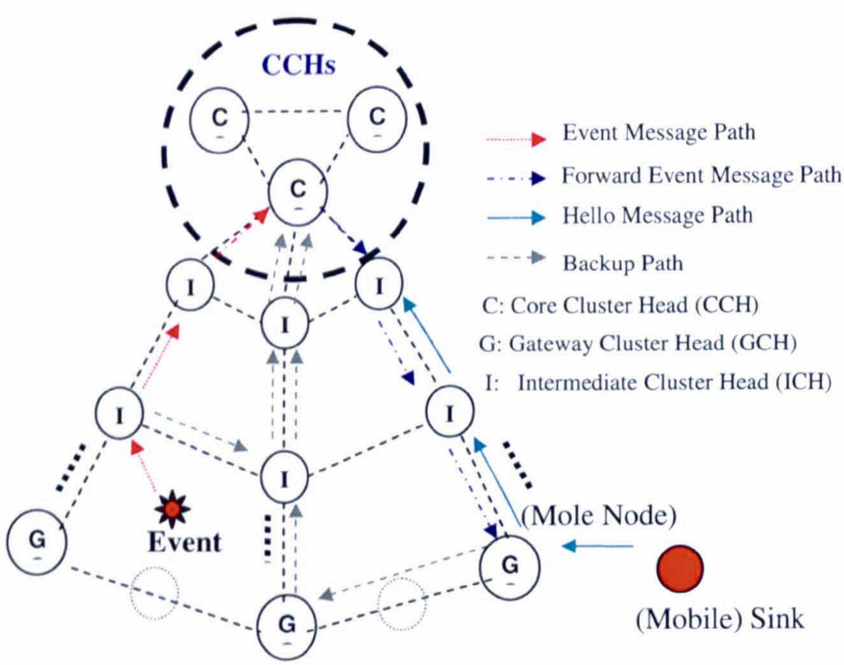

Figure 4.3 : Intra-Spider-Net Zone Routing Diagram

The spider-net zone provides many benefits in terms of efficient data dissemination and reliable communication. As shown in Figure 4.3 above, the bold circle reduces the complexity for data disseminate to mobile destinations. When a sensor senses an event, it will forward the event to its neighbouring ICH; this ICH will forward a copy of this event with its node ID to its CCH. Once the CCH receives this event message, CCHs can know the event source ICH. When the mobile sink arrives at the network, it will also send a hello message to its neighbouring ICH/GCH. This ICH/GCH will forward this hello message to CCHs and the CCHs can respond with source information to the mobile sinks. This spider-net zone topology can reduce energy consumption and decrease end-to-end delay for data dissemination in non-geographic aware MSWSN.

4.2.3 Minimum Response Time Node Selection (MRTNS)

This node selection mechanism is based on the simple idea that an initial node will select 1-hop away cluster heads with a response time lower than a predefined threshold *T*, which represents the minimum distance to the initial node. Considering that cluster head candidates for the initial node are selected randomly, some cases may occur where an initial node can not find a cluster head candidate whose response time to the initial node is shorter than predefined threshold *T*. The pseudo code for minimum response time node selection is outlined as shown in Figure 4.4.

Minimum Response Time Node Selection

```
∀ s ∈ S I
1. u = rand(1)
2. If u ≤ p
3. State='Cluster_Head_Candidate'
4. Broadcast Cluster_Head
   _Candidate_Msg
5. Wait for Cluster_Head_Select Msg
   from cluster head
6. If (msg received)
7.     State = 'Cluster_Head_Node
8.  Else
9.     State='Plain_Sensor_Node'
10. End If

∀ I ch ∈ CH
12. Receive Cluster_Head_Candidate_Msg
13. Extract id, response time duration
    to initial node, store information in
    the Cluster_Head_Candidate_List (CHCL)
14. Sort the CHCL in increasing order by
     response time to initial node
15. If chc.rt_to_ initial node < T
16.     add cluster head -> chc.id
17.     send Msg Candidate_Select
18. Else
19.     remove  cluster head
20. End If
```

Figure 4.4 : Minimum Response Time Node Selection Mechanism

In such a scenario, finding a cluster head candidate may violate our energy conservation objective. An intuitive solution is to relax the condition of finding the cluster head candidate in case a cluster head candidate with lesser cost does not exist. In other words, if an initial node cannot find a cluster head candidate that has a response time shorter than a predefined threshold T, it will extend the threshold, T, until one is reached.

4.2.4 Spider-Net Data Dissemination Mechanism

In this section, we will introduce a simple routing path setup with a data dissemination mechanism for spider-nets in MSWSN. After the network topology has been formed, the routing paths will be set up before the sinks reach the spider-net network. In our network topology, each small square of the spider-net is similar to an isosceles quadrangle. When an event happens in the spider-net, event messages are only sent to the vicinity cluster heads. The cluster heads that receive these event messages will forward them to the next ICH until they reach the CCHs. Then the cluster heads in the CCHs belonging to the event message zones will save the event messages and keep them memory resident until the mobile sink's hello message arrives. These sinks can broadcast hello messages to vicinity cluster heads in the network. These neighbouring cluster heads, called moles [Urgaonkar'04], can provide the current mobile sink's location and maintain routing paths according to their movements.

A. Intra-spider-net zone routing algorithm and maintenance

We now consider how the event messages are transmitted to the sinks. When a sensor in the network sends an event message to the vicinity cluster heads (ICHs or GCHs), these cluster heads will look up their routing table and forward event messages to the CCHs. When these event messages reach the CCHs, these events will be saved in the CCHs' memory until they receive a hello message from the mobile sink. In intra-spider-net zone routing, the mobile sink will send a short hello message which only queries one spider-net zone. Once the CCHs receive this short hello message they will check any event messages in their memory. If they have any such messages, they will forward them to the mobile sink. Otherwise, they will remain calm. If the time tag in an event message has expired, the CCH will remove this event from its memory.

The event message will be sent to any neighbouring intermediate cluster heads (ICHs). This cluster head will forward the event message to its next hop cluster heads until it reaches the CCHs. These CCHs will share this event message between each other since they are inside the reference node radio range. When the mobile sink arrives, it will forward its short hello message to the moles. The moles provide the current mobile sink location by adding this location information to the short hello message. Once the CCHs receive the short hello message, they will send the current event message to the mobile sink. Therefore, when the mobile sink receives this event message from CCHs, it can decide either to move towards the source node(s) location or still perform the random walk through the sensor networks. If mobile sink performs the random walk, its neibhouring moles will continuously forward the event message following the current location of mobile sink.

In addition, as shown in Figure 4.3 above, each ICH/GCH will have its one-hop away neibhouring ICHs/GCHs. Once the ICH gets an event message from a neighbouring sensor node, it will forward the redundant event message to its one-hop away neighbours. The number of this redundant event message can be defined by user or application. Therefore, if there is a ICHs/GCHs failure between the source and destination, the neighbouring ICH/GCH will be able to forward redundant event message using backup path to provide reliable and efficient data dissemination.

B. Inter-spider-net zone routing algorithm & maintenance

In this section we discuss the possibility of extending a spider-net zone to multiple spider-net zones. The benefit of multiple spider-net zones is to provide better network coverage of the monitoring field, for example if one spider-net zone cannot cover the whole area of the monitoring field. This extended multiple spider-net zones can provide extendable coverage of the monitoring field. Therefore, we extend the intra-spider-net zone routing algorithm to inter-spider-net zone routing algorithm.

We suppose different spider-net zones will have different CCHs groups. Each group of CCHs will have a group ID. If a GCH receives different peer group IDs from the network, it will respond as a gateway node between the different spider-net zones. As we mentioned in the intra-spider-net zone routing algorithm, the mobile sink can broadcast a short hello message to moles that can notify CCHs to forward data to a mobile sink in this spider-net zone. In the inter-spider-net zone routing algorithm, the mobile sink can broadcast a long hello message to moles that can notify different spider-net zones to forward data following the current mobile sink location.

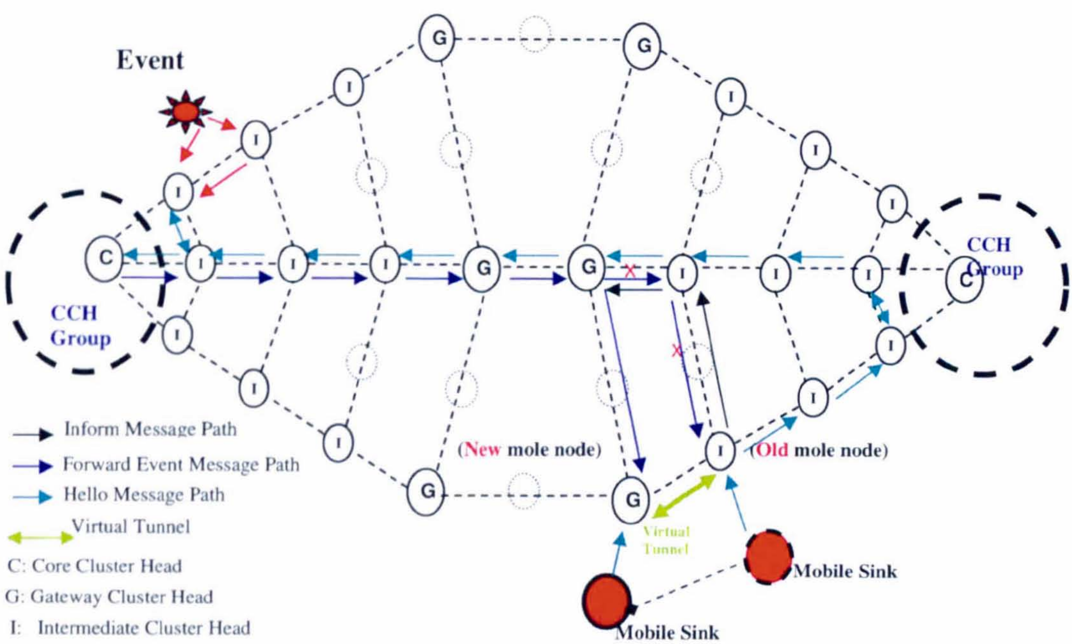

Figure 4.5 : Inter-Spider-Net Zone Routing Diagram

Each long hello message will include sink ID, mole node ID, extended zone flag and a Time-To-Live (TTL) value. Suppose there is an event message in the neighbouring CCHs. The mobile sink will send this long hello message to current CCHs. When the CCHs receive this long hello message, they will check the extended zone flag and TTL values. If both parameters allow access to different spider-net zones, then the CCHs will forward the long hello message to their GCHs. Once the GCHs have received this long hello message, it will have the same checking function as the CCHs. If these two parameters allow access to different spider-net zones, these GCHs will forward it on to neighbouring spider-net-zones. When the long hello message arrives at neighbouring CCHs, these CCHs will forward the event message following the original route of the long hello message back to the current mobile sink location. An example diagram is shown in Figure 4.5 above.

C. Data collection & redirect tunnel

Due to the mobile sink random movement can cause broken links between these sinks and the neighbouring cluster heads (named mole nodes). Therefore, spider-net provides a redirect tunnel, which provides a redirect link to the new mole node locations. One of the best ways is to build a link between new mole nodes with the previous mole nodes before the old link fails.

When the mobile sink moves, it will periodically broadcast hello messages to the mole nodes. These mole nodes receive this message and determine the signal strength from the mobile sink. When the communication signal with the vicinity cluster heads rises over a threshold, these cluster heads can become new mole nodes. A new mole node will broadcast an update link message including its ID to the old mole nodes. On the other hand, when the old mole nodes receive such a broadcast message from a new mole node, they inform the previous cluster heads to redirect messages to the new mole node. The following are the steps to build the redirect tunnel, as shown in Figure 4.5 above.

a) A new mole node detecting hello message from a mobile sink will broadcast its mole node ID to the vicinity mobile sinks.

b) The mobile sink will receive the new mole node ID and forward this new mole node ID to the current mole nodes.

c) When an old mole node suffers a high transmission delay with the mobile sink, it will inform the new mole node to handover to become the new mole node.

d) The old mole node will build a temporary communication tunnel to the new mole nodes and inject data along this new route. At this moment the new mole node will also broadcast a new hello message to the vicinity network.

e) The cluster heads receiving the new mole node's hello message will send this event message to follow the new mole node.

f) The old mole nodes will tear down the communication with the mobile sinks and remove the state of the old route. In addition, this redirect tunnel could be pre-configured with adjacent cluster heads to support efficient inter-cluster head handovers.

4.3 Discussion

While the end-to-end network connection between the source sensor nodes and mobile sink have been established, the mole nodes will continuously forward the event message following the current location of mobile sink. Moreover, by analyzing the proposed clustering protocol we can see that:

- The SNZR utilizes zone based routing mechanism which reduces the energy consumption and decrease bandwidth utilization while construction network topology.
- The network scalability can be achieved by expanding the radial-ring network topology and perform inter-spider-net zone routing which allows the number of data sources and the data sink populations to be rendezvous.
- SNZR provides redundant path to ensure that node failure will not impact the data dissemination process, thus achieve high data reliability and fault tolerance capability in the presence of network dynamics.
- Due to the lack of the node position information, SNZR is difficult to maintain the cluster structure. These CCHs, ICHs and GCHs clustering structure introduce additional overhead and complexity in the formation and maintenance of clusters.

All these analytical results will be verified and investigated in more details in the following section.

4.4 Evaluation

We evaluate our routing framework through simulation using the same simulator and with the same parameters presented in the chapter 3. Our goal through these simulations is to assess the efficiency of our solution and evaluate its performance in terms of energy saving and transmission average delay, and the impact of the sink mobility on the packet success ratio. Compared to routing protocols in MSWSN, several routing approaches have been considered to address effectively power consumption, low network maintenance cost, and fault tolerance problem. One of these protocols is Zonal Rumor Routing (ZRR) which is an extension to the Rumor Routing (RR) designed for routing in MSWSN. In, ZRR, the network is partitioned in to different zones using k-clustering approach or even pre-configuration to improve the percentage query delivery and requires fewer transmissions. Because of the similarity between our algorithm and ZRR, we will compare the SNZR to it. However, as mentioned in previous chapter, GTSNetS has a default one sink limitation. Hence, if we add more than one mobile sinks in GTSNetS simulation environment, it will direct impact on simulation stability but will not affect our current simulation result. As energy consumption is affected by multiple issues such as dissemination path and sinks mobility, our SNZR main concern is how to reduce the energy consumption for long distance communication by considering a time limited dissemination path election procedure first. Then, we therefore can focus on energy consumption for sink mobility.

4.4.1 Average Energy Consumption

In this experiment, we investigate the average energy consumption and we set the number of sensor nodes to vary from 500 to 600 and one sink moving with different speeds (0, 5, 10, 15, 20 m/sec). Both average sink refresh rate and average source update rate are set to 10 seconds and the interests are updated periodically every 20 seconds. The node density has little influence on the energy per node in ZRR and SNZR although more neighbours overhear data from a sender at high density. In ZRR, the routing path is similar to the traditional RR algorithm to minimize the energy cost by minimize hop distance between source and mobile sink. However, ZRR do not distribute energy consumption fairly. This is because the agent node utilises more energy cost to maintain the routing paths and the network connectivity between stationary sensor nodes. Figure 4.6 shows the better energy consumption in SNZR.

Both ZRR and SNZR are based on zone routing schemes, mobile sink uses unicasting for communication with neighbouring sensor nodes. In ZRR, the objective is to spread the rumor of the event as far as possible in the network with minimum number of transmissions in order to increase the query delivery rate. However, this will increase the communication distance between any two agent node that increases the power consumption in communication duty cycle time and decrease network lifetime. The reason that SNZR achieves lower energy consumption is because SNZR has shorter radio duty cycle time than ZRR. SNZR reduce the communication cost across longer distances from source node to relay nodes and mobile sink, which decease energy consumption in MSWSN.

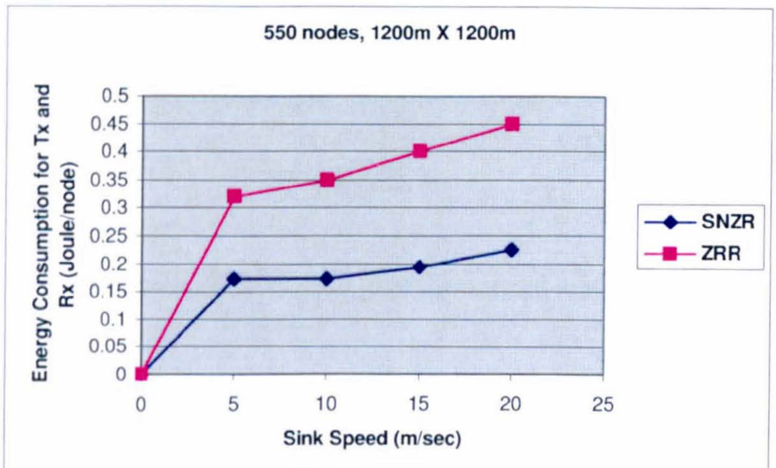

Figure 4.6 : Spider-Net Zone Routing Average Energy Consumption

4.4.2 Average Delay

In the following experiment, we investigate the average delay as a function of the number of mobile sinks and their speed. The second experiment is to measure the average delay for different speeds of mobile sink movement. In this experiment, the number of sensor nodes, including cluster heads, is varied from 500 to 600. The speed of the mobile sink varies (0, 5, 10, 15, 20 m/sec). Figure 4.7 shows that average delay increases when mobile sink movement speed increases. In ZRR, the sink speed has influence on the average delay. The slope of the curve increases with sink speed increase because ZRR does not consider the connectivity between the mole node and mobile sink while mobile sink movement speed increases. ZRR attribute a short delay when the sink moves at low speed. However, different from ZRR, SNZR consider the redirect channel while mobile sink moves at higher speed thus SNZR performs competitively with ZRR. As shown in Figure 4.7, SNZR has a shorter average delay than the ZRR routing approach.

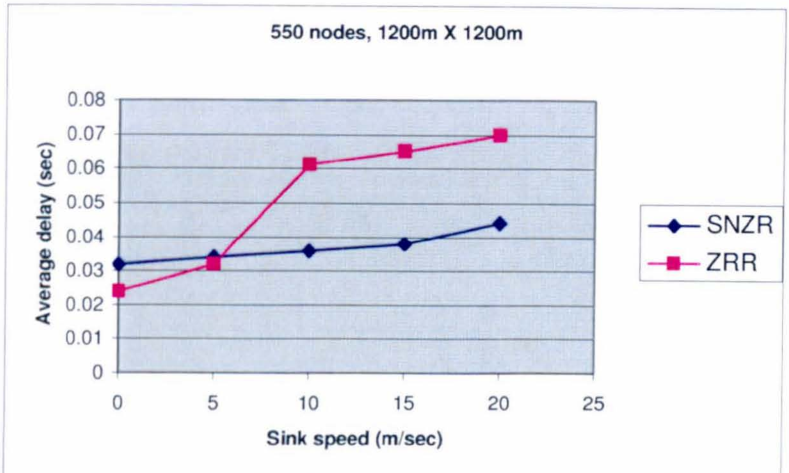

Figure 4.7 : Spider-Net Zone Routing Average Delay

The ZRR routing approach generates more routing path update packets when sink speed increases, which leads to an increase in the network traffic and data retransmission in the network. So, it will directly impact the network average delay in ZRR approach. However, in SNZR, we separate data communication into two parts. The first part is only forwarding an event message from source to CCHs and the second part is forwarding the same event from the CCHs to the mobile sink. This eliminates network congestion and data retransmission probability when sink speed increases, which reduces network transmission delay in MSWSN.

4.4.3 Average Packet Success Ratio

The success ratio is the ratio of the number of successfully delivered data messages that have been received by the sink. The third experiment is to measure average success ratios for the different speeds of mobile sink movement. In order to study the impact of node failures to packet success ratio setup, we randomly selected nodes to up to a maximum of 10% out of 500 to 600 nodes. All other simulation parameters are as specified in the default simulation scenario. The average success ratio experiment are shown in Figure 4.8, we observe that SNZR maintains a high success ratio of around 94%. The average success ratio slightly decreases when the number of node failures increases. Our results show that our scheme achieves better success rates than the ZRR scheme and obtains a better success ratio than the ZRR approach.

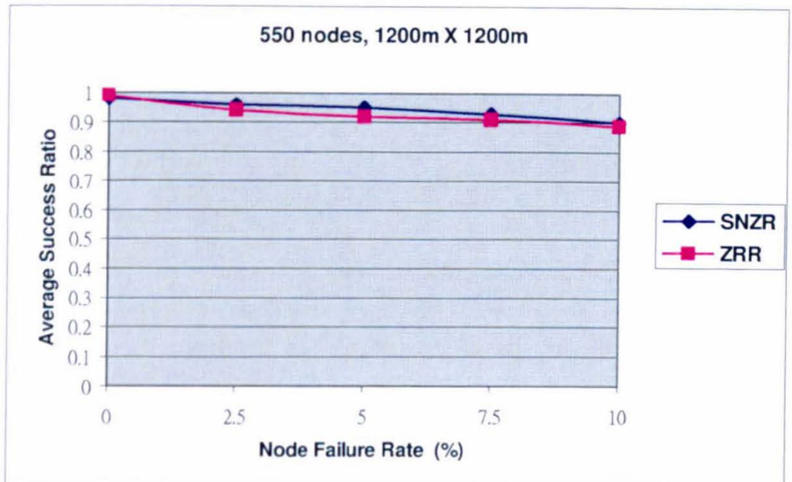

Figure 4.8 : Spider-Net Zone Routing Average Packet Success Ratio

In ZRR, if the agent fails to find any node that is in a different zone, then it randomly selects a neighboring node similar to Rumor Routing algorithm. However, when the node failure rate increased, this randomly selects a neighboring node stops downstream data delivery, and so the success ratio drops. However, compared to ZRR, SNZR has better fault tolerance capability by its routing mechanism. SNZR will disseminate sensed data to redundant routing path when dissemination nodes fail. Hence, SNZR provides better network reliability than ZRR.

4.5 Summary

In this chapter, we proposed and evaluated an energy efficient and reliable routing protocol in MSWSN. Instead of changing the whole routing path when the mobile sink moves, Spider-Net Zone Routing (SNZR) mechanism has the potential as an efficient routing mechanism that can provide mobile sinks gathering sensing data with high-speed movement. It also uses a spider-net network topology to provide efficient routing and data collision avoidance in MSWSN. We addressed this new routing mechanism which applied radial-ring network topologies to provide an energy efficient and reliable routing protocol in MSWSN. The simulation results show that our scheme achieves less energy consumption, less average delay and better packet success ratio than compared protocol.

CHAPTER 5

5 FAULT TOLERANCE MAGNETIC COORDINATE ROUTING FOR MOBILE SINKS WIRELESS SENSOR NETWORKS

In the previous chapter, we discussed our routing topology we named SNZR in non-geographic aware MSWSN. In this chapter, we discuss a new fault tolerant coordinate routing protocol in a geographic aware MSWSN; this routing algorithm we named Fault Tolerance Magnetic Coordinate (FTMC) [Chang'07-c, Chang'07-d]. The previous chapter discussed a novel routing topology named SNZR, which provides an efficient data dissemination algorithm in a non-geographic aware based MSWSN. SNZR utilizes its network topology, intra-spider-net zone, inter-spider-net zone routing and in case of mobile sink movement provides a redirect link to keep a network connection. In this chapter, we discuss a coordinate based routing scheme with a fault tolerance mechanism for MSWSN, aiming at achieving the robustness and energy efficiency in MSWSN application scenarios.

Recently, virtual coordinate based routing protocols have been proposed for data dissemination in WSN. The coordinate node is selected as a next hop according to the applied routing strategy e.g., distance-based or energy-level strategy. These virtual coordinate based routing protocols are utilizing geographical greedy forwarding routing algorithms to forward packets based on the coordinate positions of nodes. As geographic-based routing protocols aim to find a small number of intermediate (hop) nodes and utilize greedy forwarding routing algorithms, so that the path length (number of hops) between the source and destination can be reduced. However, because of the mobile sink characteristics, intermediate nodes between source and mobile sink will change frequently. This contributes to the communication overhead and quick depletion of the energy for some nodes.

The challenge is to discover a power-efficient routing path with high performance routing algorithm that sends the query message as well as route the data. Moreover, since sensor networks are prone to failure because of hardware, software, and environment issues, our solution provides a fault tolerance mechanism to increase reliability. The main idea of this fault tolerance mechanism is to ensure that faulty cluster heads are not sharing the data dissemination process, thus guaranteeing that mobile sinks gather "correct" data from proper cluster heads only. FTMC is a new routing algorithm combining coordinate routing and consensus-based fault tolerance to provide an efficient and reliable routing protocol in MSWSN. Therefore, important issues to design a coordinate-based routing algorithm for MSWSN are:

- Eliminate communication overhead of data dissemination while implement a coordinate-based sensor network.
- Apply efficient fault tolerance solutions to provide reliable network communication.

The novel contribution of this chapter is a new routing protocol that eliminates communication overhead of data dissemination through a grid-based sensor network and supports a fault tolerance mechanism to ensure the reliability of a routing path. We organize this chapter as follows. In Section 5-1, we give the research challenges and overview of related works. In section 5-2, we describe the coordinate magnetic routing mechanisms. In section 5-3, we will assess our protocol analytically while in section 5-4 we will evaluate it by simulation. Finally, in section 5-5 we will present a summary of this chapter.

5.1 Background

In this section, we provide an overview of a selection of related protocols and mechanisms that have been developed to improve the performance and reliability in MSWSNs. We will focus on routing protocols; path planning, and reliable data transfer mechanisms. To the best of our knowledge so far, limited routing protocol has tried to address high performance and reliability issues jointly in WSNs. A number of research efforts focus on routing protocols in MSWSNs that aim at achieving power efficiency, load balancing and extended system lifetime in hostile environments.

The TTDD [H.Luo'02] is a well-known grid-based routing protocol to provide query and data dissemination for multiple mobile sinks. Upon detection of an event, the source node creates a virtual grid structure and divides the network into cells with several grid cross nodes. The grid cross nodes, named dissemination nodes, are responsible for relaying the query and data to and from the proper sources. In TTDD, a mobile sink floods its query within the lower tier until it reaches the closest dissemination node. Once this closest dissemination node receives this query, it will request a data download to the source node along the reverse grid path direction back to the sink. TTDD solves the sink mobility problem using a grid structure. However, if the number of source nodes is increased, data dissemination point management can considerably increase the communication and storage overhead of the system.

Efficient Data Dissemination and Aggregation (EDDA), was introduced in [J. Youn'04]. In EDDA, sources and relay nodes share the same single grid structure to disseminate their sensing data. In EDDA, the sink finds the immediate dissemination node using a hash function. This hash function gives the location information for the immediate dissemination node such as a coordinates output (x, y) and cell size (α). Based on this output, nodes can send a unicast query to the location. However, this uniform grid maintenance over the entire network wastes energy resources because sinks only stay in a small part of the entire network. Therefore, to improve EDDA, ODDD [R.R. Kalva'05] proposes a new data dissemination scheme to reduce battery energy usage in the creation and maintenance of virtual grid structures. Different from TTDD, a source does not proactively create a virtual grid. Instead, ODDD forwards data announcement messages horizontally without building a virtual grid over the entire network, and a query is propagated vertically. The delivery of data is guaranteed because there is at least one intersection between query and data announcement. Therefore, ODDD reduces the amount of communication overhead for creating and maintaining virtual grid. However, in ODDD scheme, a grid point node failure may lead to communication congestion or data lost between source and destination.

Previous research considered fault tolerance and reliability schemes in MSWSNs. We suggest that Byzantine faulty behaviour [L. Lamport'83] is suitable to describe dynamic senor network environment, thus we apply it to the cluster heads in our algorithm because of their critical role. A Byzantine fault is described in [D. Mogilevsky'06] as "one in which a component of some system not only behaves erroneously, but also fails to behave consistently when interacting with multiple other components." Byzantine faulty nodes will send arbitrary values to other neighbouring components during collaboration. The data sent from a neighbouring component is possibly inaccurate and may affect the correct data available with the valid component.

Currently Byzantine tolerance solutions cause redundancy in computation and retrofitting protection campaign. Lamport [L. Lamport'83] offers an elegant solution to this problem by detection of up to m traitors given 3m + 1 or more generals. However, Lamport proved using a complicated construction, this fault preventing algorithm requires network synchronization and using a complicated construction which is hard to implement in sensor networks. In [R. Rajagopalan'05], two approaches have been proposed to combat the Byzantine faulty nodes for data gathering in MSWSNs: randomized censored averaging (RCA) and randomized median filtering (RMF). These approaches suggest a different methodology to provide fault tolerance in mobile sinks routing. However, they do not provide adaptable fault detection and identify (FDI) function to identify the faulty nodes. In the next section, we present the different mechanisms that constitute our fault tolerant routing algorithm. Our approach aims at providing energy efficiency, fault tolerance and high performance data dissemination for MSWSNs.

5.2 Fault Tolerance Magnetic Coordinate

In this section we describe our proposed routing framework: Fault Tolerance Magnetic Coordinate (FTMC). This protocol uses magnetic coordinate conception to provide efficient data dissemination. It also has fault tolerance capabilities. One of the major problems of routing in MSWSNs is the movement of the sink. Existing schemes like TTDD [H.Luo'02], EDDA [J. Youn'04], and ODDD [R.R. Kalva'05] use one or more of the following three solutions to cope with such movements: increase the radio range of the mole node, or include more nodes in the path between the mole and sink (tunneling), or change the routing path completely. Different from them, we suggest a partial update of the routing path according to the sink movement, thus providing more energy savings. This can be achieved by representing the network as a virtual grid and routing according to magnetic coordinates of the nodes. To achieve reliability, FTMC has a consensus-based fault tolerance mechanism. Thus our framework consists of three main parts: virtual grid zone construction, magnetic coordinate data dissemination and consensus-based fault tolerance algorithm. The proposed algorithm is based on the following assumptions:

5.2.1 Assumptions:

- The sensor nodes and cluster-heads are location aware and knowledgeable about their neighbouring nodes. Several algorithms exist [O. Younis'04] to estimate the locations of the individual nodes and to route messages towards these geographic locations.

- The distribution of sensor nodes and cluster-heads over the entire sensing region is almost regular with equal probabilities.
- After having been deployed, sensor nodes and the cluster-heads all remain stationary at their initial locations.
- The sensor nodes and cluster-heads are heterogeneous and the wireless channels are bidirectional. Both sensor nodes and cluster-heads have a constrained energy source (battery).
- The sink broadcasts hello messages to the neighbouring cluster-heads to notify its location and concentrates on listening to the reply messages around it.

5.2.2 Virtual Grid Zone Construction

The idea of the virtual grid zone construction is based on using reference points and coordinate conception to build a logical grid. These specific reference points will have their coordinate information before network deployment. Each reference point will broadcast a grid construction message to its 1-hop neighbouring nodes. This message is used to initialize the grid construction and also to query the neighbouring node about their specific coordinate information. This specific query semantic is similar as – "Does any node is located near (5, 0)…". Any cluster head or sensor node which receives this message will check its coordinate information, and if they satisfy the query it will reply to the construction message. For the purpose of building this logical grid network, we need to define the node radio communication range for broadcasting construction messages.

We define our nominal radio range R, the farthest possible distance between two adjacent grid points (because they must be able to communicate). If a virtual grid consists of squares with α length, then the longest possible distance between two adjacent grid nodes is the long diagonal connecting the two grids, therefore, $R \leq 2\sqrt{2}\alpha$. Thus, any node inside the range α can be picked up as the next grid point node. As our assumption, every node is aware of its 1-hop away neighbouring nodes inside the radio range α. The first reference node will start to broadcast a grid construction message using greedy forwarding. The cluster heads or sensor nodes satisfying the condition of this construction message will reply by sending their coordinates and node IDs to the reference node. After the reference point receives the reply messages, it will decide which node will become its next grid node. Then, it will send a confirmation message to these new grid nodes and add these nodes to its routing table. The grid nodes which receive this confirm message will use the same construction message to find the next grid nodes. The node which receives this grid construction message will check its neighbour ID then reply its coordinate message if they are the "right" nodes. Therefore, there should only few nodes will become the next grid points and these nodes will add 1 in X or Y axis coordinates and continuously forward to the next grid node. An example of a virtual grid zone with four reference points is shown in Figure 5.1.

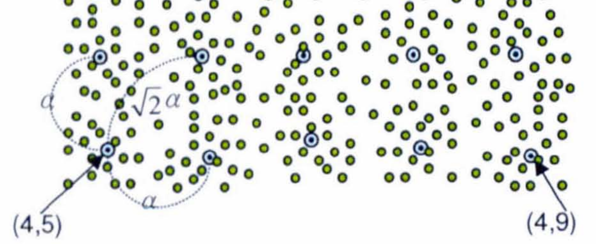

Figure 5.1 : Virtual Grid Zone Construction Diagram

When the reference points broadcast grid construction message, the nodes which receive this message will check its locations and calculate the distance between the required location and its location by:

$$d_{i-j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{5–1}$$

If d_{i-j} <= defined range d_r, then the nodes inside d_r will reply to this grid construction message with its node ID and coordinate (x_j, y_j). If two or more nodes reply to this message within the similar coordinate information, the reference node will choose the node that replied first as the next grid node before the time reference tr times out. On the other hand, if there is no node reply message, it will extend the defined range d_r to α and send the message again. If still no node replies, it will send back the construction complete message to reference points using greedy forwarding. Once the reference node receives construction complete message, the grid node in the network should have its' own unique coordinate. That is *(xi+ n, yi) or (xi−n, yi) or (xi, yi+n)* or *(xi, yi-n)*, where (x_i, y_i) is the reference point's coordinate.

Once the grid nodes have their coordinates, the initial virtual grid zone construction is complete. The main purpose of this algorithm is to transform a target space from a physical plane to a virtual grid. In addition, if any intermediate grid node fails; neighbouring grid nodes can pick up a new grid node by running this grid construction independently to avoid grid node failure to cause traffic congestion.

5.2.3 Magnetic Coordinate Data Dissemination

The magnetic polarity concept comes from magnetism [S.J. Hegland'09]. In WSN, it has been used before in [H.J. Huang'05] to represent the propagation of the magnetic charges to set up the magnetic field. Here we use it in a different context. In our scheme, mobile sinks are viewed as magnetic nodes that attract aggregated data from networks. While mobile sinks move around the sensor network, they will periodically send hello messages to their moles (vicinity CHs). This hello message is mainly to notify its location so that it can collect data from the network. Therefore, mobile sinks are similar to a magnet which has "negative (-)" polarity to indicate that they request data [H.J. Huang'05]. On the other hand, the sensor nodes which have the sensing data will have "positive (+)" polarity. This positive polarity means they can supply data. Once a mobile sink or a CH node starts to forward notifying messages to the network, these messages, called query or event messages will be have polarity characteristics. Furthermore, the nodes that receive these polarity messages will change their polarity depending on message's polarity characteristics. In other words the node which knows the location of the mobile sink will have a negative polarity, and the node that knows the location of the source data node will have a positive polarity. These polarities will be useful for defining the routing path between the source and the sink.

Another important feature of our protocol is providing a coordinate forwarding capability. Once the virtual grid has been constructed as described in the previous section, each grid node will have its coordinate information. We use this coordination information to provide coordinate forwarding, which means the message will be forwarded only to specific nodes based on their virtual coordinates according to the rules of forwarding. The magnetic coordinate applies magnetic polarity and coordinate information to accelerate data dissemination in virtual grid zone networks. According to our magnetic coordinate routing algorithm an event message with positive polarity will only forward along two parallel Y axes grid nodes. When an intermediate grid node receives this positive event message, it will keep a copy of this message; calculate coordinate information and only forward in the Y axis direction to neighbouring grid nodes.

Different from existing grid-based data dissemination algorithms TTDD [H.Luo'02], EDDA [J. Youn'04], and ODDD [R.R. Kalva'05], we provide two parallel lines and magnetic polarity message forwarding in wireless sensor network. The main advantage of using two parallel lines for magnetic event message forwarding is to provide a reliable transmission capability by redundant paths to prevent network failure. As shown in Figure 5.2, if any burst failure occurs, FTMC can provide reliable event message delivery.

In order to notify the data source node about its location, the mobile sink will periodically broadcast a hello message to its neighbouring CHs (called moles). This hello message will have negative polarity and a Time-To-Live (TTL) parameter that depends on the mobile sink speed. The mole which receives this hello message will have negative polarity until the TTL timeout then it will forward the message to X axis intermediate grid nodes. Once an intermediate grid node receives this hello message, it will first check if it has a positive polarity (i.e. it knows the location of the data source) then it will become a redirection node. Otherwise, it will change its polarity to negative and continuously forward to X axis direction neighbours. In addition, when the TTL times out, each node that has negative polarity will change back to the non-polarity state.

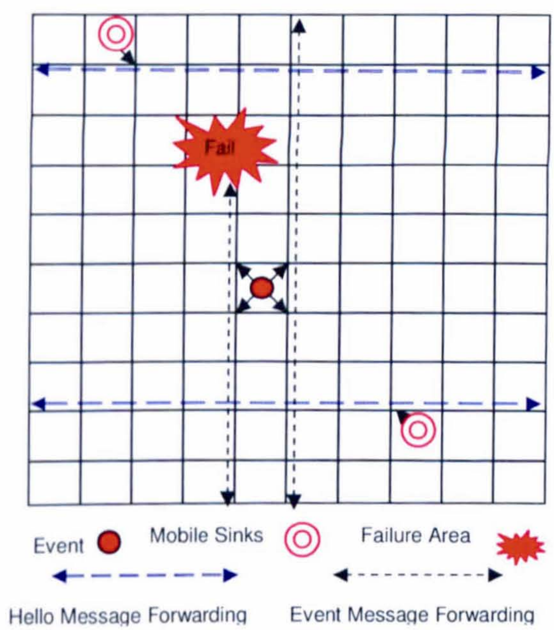

Figure 5.2 : Magnetic Coordinate Data Dissemination Scheme

Once the grid node becomes a redirection node, it will send the source coordinate information to the mobile sink using greedy forwarding and send another message to source data node to notify it about mobile sink location. The source data node will start sending packets alone the same path to a mobile sink. However, the mobile sink location could have changed and there would be a new mole node. In this situation, the intermediate grid nodes play an important role to partially update the path to the new mole and the mobile sink' new location by checking the neighbouring grid nodes magnetic polarity and/or TTL lifetime. Intermediate grid nodes will be continuously listening to any new hello message from neighbouring grid nodes and update their information about the "newest" mole node coordinate. Once the newest mole receives the reply message or the data packets, it will redirect the source coordinate information to the mobile sink. Once the mobile sink receives this reply message, it can decide either to move towards source location using the same routing path thus receiving all sent data packets and reducing communication energy, or stop in its current location and receive all required information, or if not possible, to continue moving while updating the path continuously by hello messages.

This query message will include the source's coordinate information, then the data will back the same way as hello message routing algorithm. As shown in Figure 5.3, the intermediate grid nodes have the responsibility to forward event or data messages back to mobile sinks based on the magnetic coordinate algorithm. This phenomenon is similar to magnets attract each other by their magnetic lines of force.

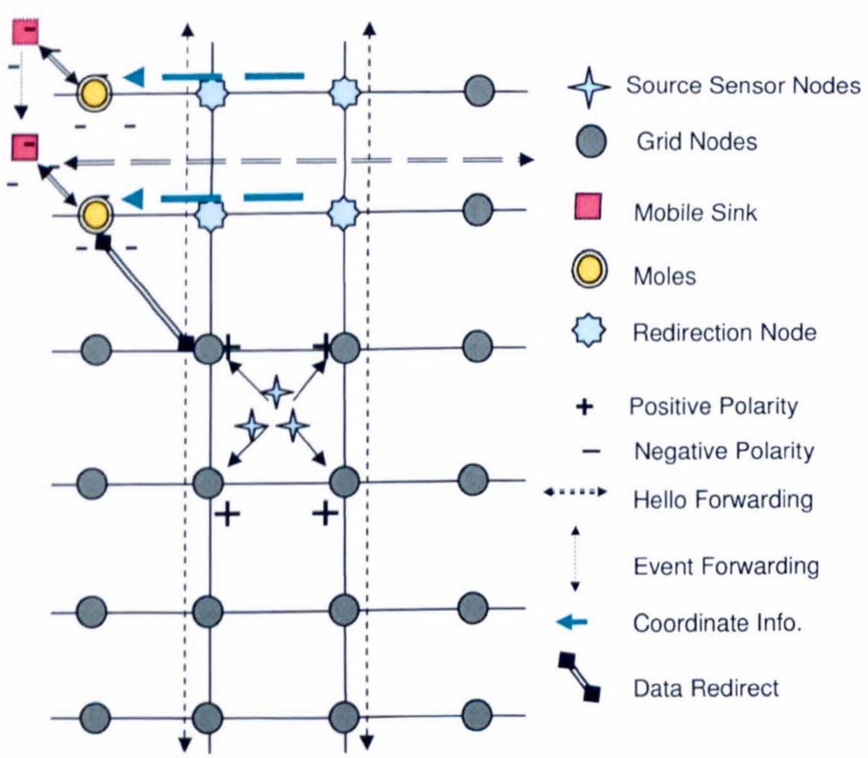

Figure 5.3 : Reverse Data Path Diagram

5.2.4 Consensus-based Fault Tolerance Algorithm

Generally sensor nodes are very prone to failure. In dynamic and hostile environments the rate of failure increases because of environmental issues. This failure of nodes may cause malicious faults [L. Lamport'83]. A malicious fault occurs when a faulty node delivers inconsistent data to non–faulty nodes which results in what is called Byzantine faults [L. Lamport'83]. Byzantine faults are described as a node in a network behaveing erroneously, and also failing to behave consistently when interacting with multiple other nodes. As described in [L. Lamport'83], Byzantine faults can be reasoned from the Byzantine Generals Problem which is expressed in terms of generals deciding on a war mission of attack or retreat. The generals can communicate with one another only by messengers. After observing the enemy, they must decide upon a common plan of action. Generally it is very difficult to overcome Byzantine faults and most existing solutions address only some specific Byzantine failure.

To achieve high performance, and to overcome Byzantine faults in MSWSNs, we suggest a fault tolerant algorithm that combines two consensus-based fault tolerance schemes. The first part of our algorithm is to adapt a simple error-detection scheme called consensus-checking. This consensus-checking scheme has been implemented in parallel programming systems in ByzwATCh [D. Mogilevsky'06]. As described in [D. Mogilevsky'06], the cluster heads implementing consensus-checking are called initiators. The initiator will implement challenge-response, consensus-checking to local cluster heads. These healthy nodes would respond by sending the checking results back to the initiator. Once the initiator receives the reply message, it will have a list of the cluster heads software and hardware status. According to this list, the initiator can use this status information and a grade parameter 'κ' to each cluster head. The node which has a higher κ means it has better health situation. This scheme can be used to prevent the faulty nodes of reporting inaccurate data by hardware and / or software checking algorithm. This scheme can assist our consensus-based decision scheme to find the "healthy" nodes in the networks.

The second part of our consensus decision algorithm comes from consensus theory [J.A. Benediktsson'99]. This consensus theory involves general procedures, which summarize estimates from multiple experts based on Bayesian decision theory. This theory has a combination formula obtained by the consensus rules. Several consensus rules have been proposed. Probably the most commonly used consensus rule is the linear opinion pool (LOP) which has the following (group probability) form for the user specified information (land cover) class if data sources are used:

$$C_j(Z) = \sum_{i=1}^{n} \lambda_i p(\omega_j \mid x_j) \tag{5–2}$$

Where C_j is consensus rules, j is indicate information classes, Z = [Z1, Z2,..., Zn] is an input vector, p $(\omega_j \mid x_j)$ is a source-specific posterior probability and λ_i 's (i=1,2,…,n) are source-specific weights.

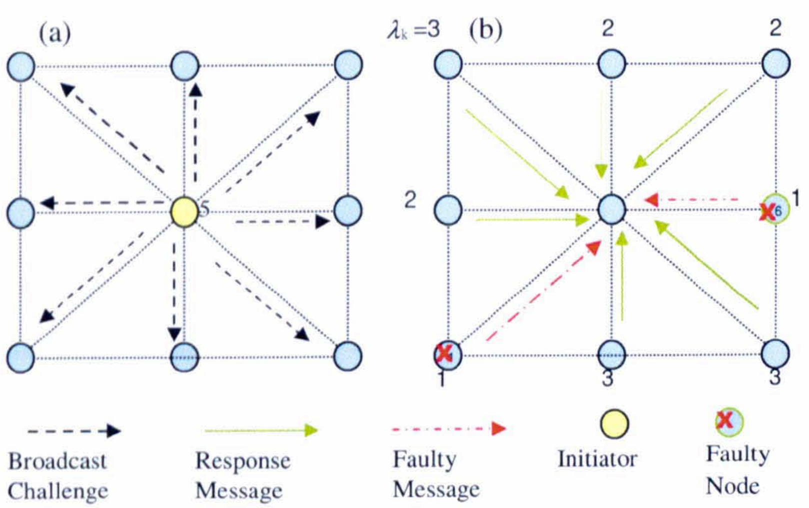

Figure 5.4 (a) (b): Challenge Message & Response Message Routing Diagram

The main contribution of our fault tolerance algorithm is to replace the λ_i by the κ parameters which we mention previously. The healthy parameter κ is to express quantitatively the goodness of data which is controlled by the source nodes. To clarify our algorithm we provide the following example as shown in diagrams Figure 5.4(a) and Figure 5.4(b).

a.) After deployment the network will start to organize as a virtual grid as described before. Each nine CHs will be organized as a small grid for consensus checking. Each one of these nodes will be the initiator for a certain period of time and then its role changes periodically. The first node can be chosen according to its ID so the first initiator is the node with the lowest ID then the next one, and so on. The initiator is responsible for challenging the other eight neighboring nodes to collect their health status. This is shown in Figure 5.4 (a) where CH with ID = 5 becomes an initiator.

b.) The initiator CH will generate challenge data and broadcast it to the vicinity grid nodes. The neighbouring nodes, upon receiving this challenge message, will execute consensus-checking, which uses the challenge list as an input to a computational checking algorithm that performs a series of checks to generate an output message. This checking list can have hardware and / or software checking items. These checking items can be designed according to user requirements.

c.) Each vicinity grid CH node performs consensus-checking to assess if any of the nodes returned a result that differs from the expected result. After these grid nodes complete this consensus-checking, they will respond back to the initiator by sending a response message. The initiator will aggregate the response messages and register the node health status results in its memory.

d.) Based upon the results of this test, the initiator can select healthy grid nodes accordingly. The results can be quantified as parameter κ for each CH. The higher value means better healthy condition and vice versa. Once the healthy grid nodes have been listed, the initiator can run the consensus-based decision scheme using equation (5-2) after replacing λ_i for each grid head by its κ, then the LOP will be executed to get the results $C_j(Z)$. The initiator will send back these results to each grid node. In this algorithm, each node will have a threshold value T, which can be defined by the user or sensor application. If the grid node's result λ_k is higher than T, it will have high priority to forward the data or event through the network. On the other hand, if the result is lower than T, it will become a standby node or only assist in message forwarding.

e.) To maintain this small region grid network operation, our consensus-based algorithm also has a simple replacement scheme to reselect a new grid node. When a grid node fails or becomes a standby node, its neighbouring grid node will be aware of that in the short term, thus it will broadcast grid construction messages. The first CH node that replies to this message will become the new grid node to replace the failed one. The diagram shown in Figure 5.5 illustrates our fault tolerance algorithm.

Our consensus-based fault tolerance algorithm aims to support data source accuracy and reliability by applying both consensus-checking and consensus-detection schemes. It will help quickly discover and replace any faulty CH node. As this detection and replacement of failure nodes is performed locally, the algorithm achieves energy-efficiency while not affecting the network communication. However, it increases communication reliability when it works with our magnetic coordinate routing protocol that aims to support data communication reliability and energy efficiency by using both parallel lines and magnetic polarity message forwarding schemes. An example to show how the two schemes interoperate is shown in Figure 5.4 (b). When the initiator receives the reply messages from the CHs, it will be aware which grid node is prone to failure or already in a fault status. During that time, our magnetic-coordination routing will be using the redundant parallel routing capabilities, therefore, one failure node will not influence network operation. When the two schemes work together, the network will achieve high reliable and efficient data dissemination.

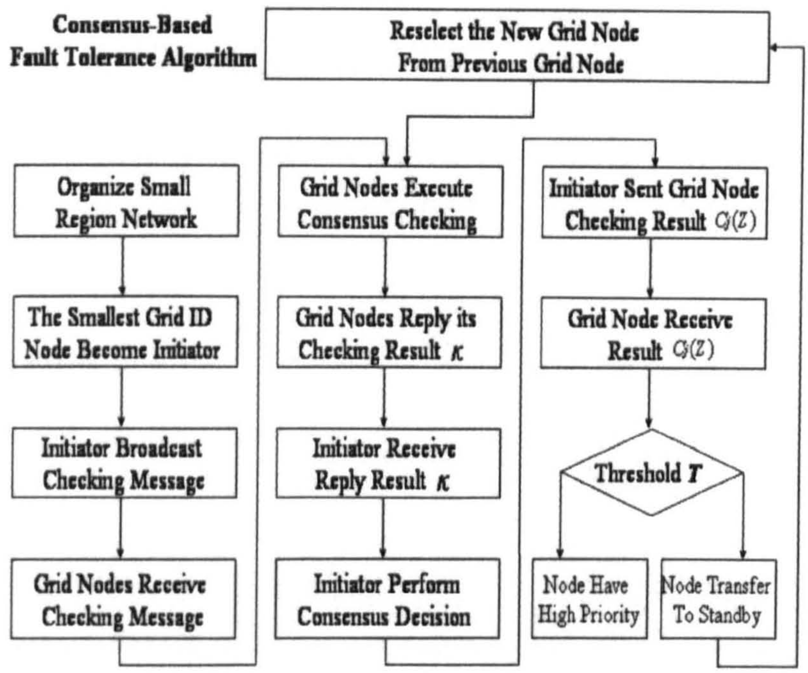

Figure 5.5 : Consensus-Based Fault Tolerance Algorithm Diagram

5.3 Discussion

While the end-to-end network connection between the source sensor nodes and mobile sink have been established, the mole nodes will continuously forward the event message to the current location of the mobile sink. Moreover, by analyzing the proposed clustering protocol we can see that:

- FTMC routing mechanism can eliminate communication redundancy in grid-based network topology by utilizing a coordinate-based routing approach which reduces the amount of hop distance of data dissemination.

- FTMC supports reliable data communication by utilizing a consensus-based fault tolerance approach which would deal with cluster head malfunction or network failure conditions based on challenge-response method.

- Because sensor networks have limited energy resources; a consensus-based fault tolerance approach would cause redundancy communication overhead and consume computing resources in sensor network. However, the most energy resource is consumed by communication. Therefore, how to efficiently reduce communication overhead is a major issue in WSN.

All these analytical results will be verified and investigated in more details in the following section.

5.4 Evaluation

We evaluate our coordination framework through simulation using the same simulator and with the same parameters presented in the chapter 3. Our goal through these simulations is to assess the efficiency of our solution and evaluate its performance in terms of energy saving and transmission average delay, and the impact of the sink mobility on the packet success ratio. Compared to routing protocols in MSWSN, several routing approaches have been considered to address effectively power consumption, low network maintenance cost, and the fault tolerance problem. However, most of the existing studies are not based on virtual grid-based approach and the ODDD [R.R. Kalva'05] algorithm has a virtual grid-based topology. We therefore compare our routing protocol to the ODDD algorithm because they also build a similarity virtual-grid based network topology. Energy consumption includes that of mole node competition, data dissemination and sinks mobility. Our main concern is how to reduce the mole node competition for energy saving by considering a time limited mole node decision procedure. We therefore mainly focus on energy consumption for data dissemination and sink mobility management.

5.4.1 Average Energy Consumption

In this experiment, we investigate the average energy consumption as the number of sensor nodes is varied from 380 to 400 and one sink moves by different speeds (0, 5, 10, 15, 20 m/sec). Both average sink refresh rate and average source update rate are set to 10 seconds. The node density has little influence on the energy per node in FTMC although more neighbours overhear data from a sender at high density. This is because there are more chances that better energy cost paths can be found in a higher density network. As shown in Figure 5.6, FTMC shows the better performance in energy consumption. The reason that FTMC can have less energy consumption is because the source can direct transmissions to a mobile sink when a redirection node sends the coordination data to both source and mobile sink. This eliminates an event route through longer distance which consumes energy in sensor nodes and grid nodes in the network.

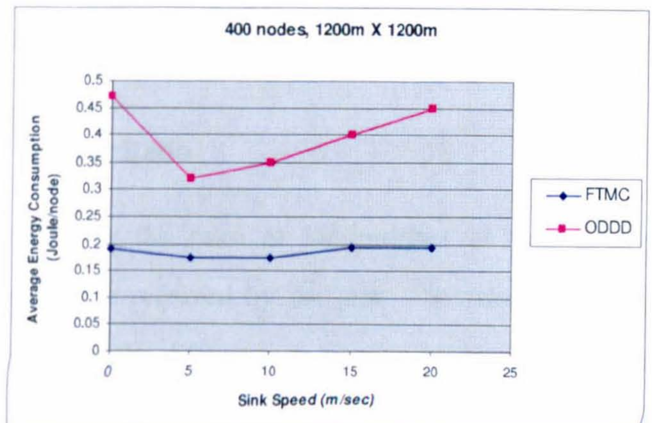

Figure 5.6 : Fault Tolerance Magnetic Coordinate Average Energy Consumption Diagram

5.4.2 End-to-End Delay

In the following experiment, we investigate the average end-to-end delay. The second experiment is to measure the end-to-end delay for different speeds of mobile sink movement. Figure 5-7 shows that end-to-end delay increases when mobile sink movement speed increases. In this experiment, the number of sensor nodes including cluster heads is varied from 380 to 400. Speed of mobile sink movement differs (0, 5, 10, 15, 20 m/sec). The sink speed has little influence on the end-to-end delay per node in FTMC although dynamic route change from a sender want to send message to sink when it is in different speed. As shown in Figure 5.7, FTMC has a shorter delay than ODDD [R.R. Kalva'05]. FTMC achieves lower average delay than the ODDD approach because of shortest routing paths and consumes less energy than the ODDD approach.

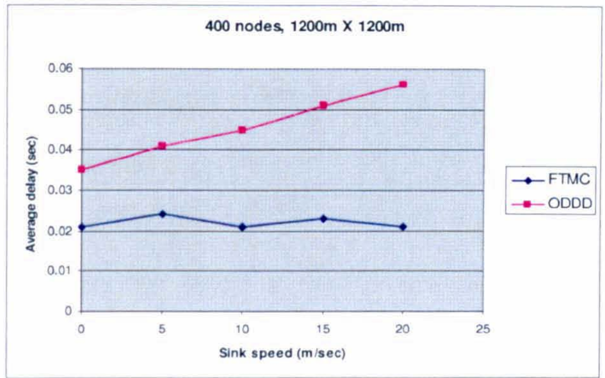

Figure 5.7 : Fault Tolerance Magnetic Coordinate Average End-to-End Delay Diagram

5.4.3 Average Success Ratio

The success ratio is the ratio of the number of successfully delivered data messages that have been received by the sink. The third experiment is to measure average success ratio for the different speed of mobile sink movement. As the default simulation setup, we have different speeds of the mobile sink from 0, 5, 10, 15, 20 m/sec. All other simulation parameters are as specified as the default simulation scenario. As shown in Figure 5.8, we observe that FTMC maintains a high success ratio of around 90%. The average success ratio has a little bit decrease when mobile sinks movement speed increase. Our result shows that our scheme achieves better success rate than the ODDD scheme and obtains comparable success ratio with much less energy cost than the ODDD approach.

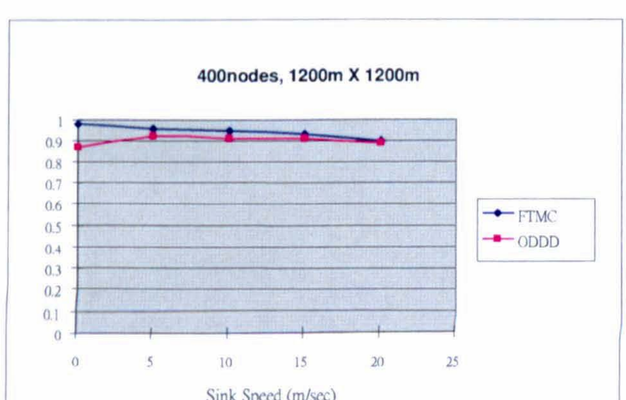

Figure 5.8 : Fault Tolerance Magnetic Coordinate Average Success Ratio Diagram

5.4.4 Fault-Tolerance Evaluation

In this fault tolerance experiment, we place 64 grid nodes randomly over the entire network, and divide the entire network region into 8x8 grids. We deploy 320 nodes randomly over the region and one sink moves by different speeds (0, 5, 10, 15, 20 m/sec). We then consider the effect of faulty nodes on the performance of our networks. Once we setup the network environment, then we vary the number of grid node failing from 5 to 20. These faulty grid nodes are randomly distributed in these 64 grid nodes that alternate the node failure rate from 0.078 to 0.31. Figure 5.9, Figure 5.10, Figure 5.11, Figure 5.12 depicts the numbers of grid failed nodes and mobile sink speed effect on packet success ratio of FTMC algorithm. The success ratio is around 90% with the original FTMC network fault tolerance algorithm. As the grid failed nodes rate continues to increase, the success ratio starts to fall down. However, comparing to the same environment without fault tolerance algorithm it increases 54% packet success ratio with 20 grid failed nodes as shown in Figure 5.12. FTMC provides parallel event dissemination for communication link fault tolerance in sensor network. This feature increases our average packet success ratio but also increases the communication overhead for event transmission.

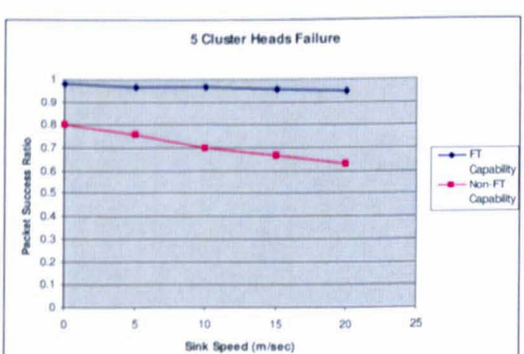

Figure 5.9 : Fault Tolerance Comparison with 5 Faulty Grid Nodes

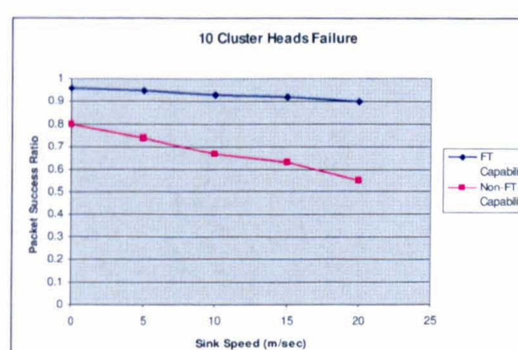

Figure 5.10 : Fault Tolerance Comparison with 10 Faulty Grid Nodes

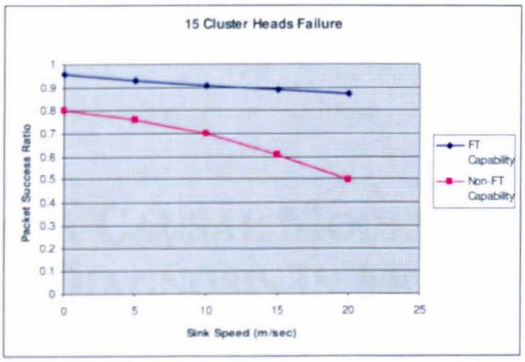

Figure 5.11 : Fault Tolerance Comparison with 15 Faulty Grid Nodes

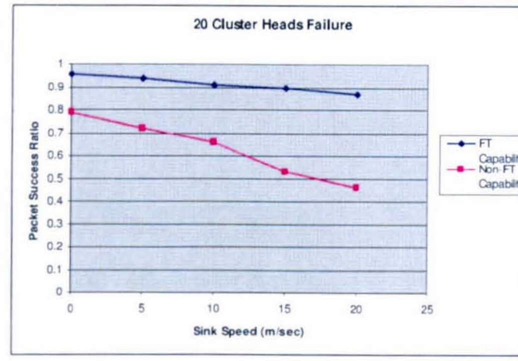

Figure 5.12: Fault Tolerance Comparison with 20 Faulty Grid Nodes

5.5 Summary

In this chapter, we described our Fault Tolerance Magnetic Coordinate Routing Protocol (FTMC) for MSWSNs. FTMC is an efficient routing mechanism that is very suitable for MSWSNs. FTMC uses magnetic coordinate query mechanism with consensus-based fault tolerance scheme to provide efficient routing, high reliable algorithm in WSNs. In our simulation works, we have shown its effectiveness by comparing it to similar existing schemes like ODDD [R.R. Kalva'05]. The simulation results show that our scheme achieves less energy consumption and provides a desirable end-to-end delay and a better packet success rate than ODDD. The result of simulation shows that FTMC can achieve high performance and high reliable data transmission in MSWSNs.

CHAPTER 6

6 A CAUSAL MODEL METHOD FOR FAULT DIAGNOSIS IN MOBILE SINKS WIRELESS SENSOR NETWORKS

Wireless sensor networks are deployed either randomly or according to some predefined distribution, over a geographic region to perform tracking or monitoring according to user requirements. These features make wireless sensor networks very attractive for large-scale applications like environment monitoring, military surveillance, medical sensing, and disaster relief. It provides a promising solution of gateway between the digital and physical worlds. However, a number of formidable challenges must be solved before these exciting applications become reality. Typically, a wireless sensor network consists of a large number of sensor nodes that can cooperate with neighbouring nodes to maintain the up-to-date information. These wireless sensor nodes are small in size and deployed in harsh environments and share a number of challenges such as hardware/software failure, unreliable communication, energy constraints and bandwidth limitation. Due to these fundamental limitations and the environment of wireless sensor networks, it is not uncommon for sensor nodes or communication links to cause fault behaviours.

Since these sensor nodes are typically operated with limited energy, computing and communication capabilities and usually deployed in harsh environment, they suffer from numerous attackers. These limitation and attackers render wireless sensor networks more prone to failure than other wireless networks. Therefore, fault tolerance becomes vitally important for wireless sensor networks so that they can gracefully respond to unexpected failure thus enabling the system to continually operate. The most common approach to providing fault tolerance in wireless sensor networks is applying redundant sensors to re-collect sensor readings and re-transmit them to target objects or destinations. However, this approach is not sufficient to fully meet the requirements of the users. Many applications require a continual stream of accurate information and extensive network lifetime with specific performance requirements when monitoring the safety parameters of target objects. In this chapter, we are concerned with the node level fault tolerance in wireless sensor networks. To achieve this goal, we identify the following key requirements for fault-tolerance in wireless sensor networks:

- Awareness of the system operation and the status of the system resources.
- Ability of deeply understand the fault reasons and provide self-diagnosis strategy.
- Adaptability to the fault conditions and changing the functionality of the node itself based upon that.

Very limited research has been proposed for fault tolerance and diagnosis in wireless sensor networks. The main contribution of this chapter is to propose a generic fault tolerance framework named the Causal Model Method [Chang'09]. This Causal Model Method approach will collect failure information from the sensor components, classify the sensor node failure causes and provide simple methodologies to recover these faulty behaviours. This Causal Model Method applies fault checkpoint conception and ontology tree diagnosis functions in order to "deeply understand" the sensor node condition. Moreover, it utilises an ontological tree diagnosis function to uncover the internal schemes in sensor node system and adapts by adjusting the influencing factors that would affect the normal network operation.

The remainder of this chapter is organized as follows. A brief review of background and related work in section 6-1. The causal model method framework and its main components: reputation checker, ontological manager and action planner schemes to support software fault diagnosis and recovery are described in section 6-2. A test case will be studied in section 6-3. Our evaluation will be presented in section 6-4. Finally, our conclusions and future work are explored in section 6-5.

6.1 Background

In this section, we provide a brief survey of existing fault tolerance techniques. The primary goal is to classify the existing fault tolerance techniques and find out the strengths and weaknesses of these researches. To deal with component failures in a sensor node, it is important to identify failure patterns. These failure patterns can be uncovered by an analytic algorithm and the causal model method. The main objective of an analytic algorithm is for formal specifications of failures to forecast the failure trend following the analytical model. It involves periodically gathering dynamic failure information from a target system and identifying the failure symptoms with these fault patterns. From the analytic aspect, Farinaz Koushanfar [F. Koushanfar'05] developed a family of Markov chain-based models for identification of faulty data readings for widely used MICA2 sensor motes. This work adapted a class of Markov chain models called semi-Markov chain models that ensured the correct lagged autocorrelation statistical properties, while keeping the size of models very compact. This model provides better protocols for collecting data in the presence of faulty and missing samples. However, there are many limitations for the semi-Markov chain models of the failure environment as the model only deals with partial statement of faulty situations and diagnosis mechanisms.

Moreover, concurrent analytic algorithms focus on the passive analytic models which have a Markov chain or Bayesian algorithm to find the problem domain. An example in Bayesian networks can be found in [A. Davison'02]. This work focuses on diagnosing system-level problem domains such as network and communication protocols. The goal of this Bayesian networks is to make a reputation network so that each node will check its neighbouring node to insure the networks reputation.

However, such Bayesian networks are not suitable for large scale WSNs as they result in complex computing and it will be hard to maintain a large number of network failure behaviours. Different from previous passive model, Byzantine Fault Tolerance (BFT) [L. Lamport'83] has been proposed as an active analytic model. As described in Lamport [L. Lamport'83], Byzantine Fault (BF) can be described as "one in which a component of some system not only behaves erroneously, but also fails to behave consistently when interacting with multiple other components."

For the purpose of reducing communication resource consumption, an ontology-based fault tolerance method has been introduced in [Nicola Guarino'94] [M. Eid'06]. Ontology comes from the philosophy field which is to describe "an explicit formal specification of a shared conceptualization". It is the name given to the study of the nature of existence; describe the conceptualization behind the knowledge represented in a knowledge base. An ontology comprises three components: (1) classes or concepts that may have subclasses to represent more specific concepts than in super-classes, (2) properties or relationships that describe various features and properties of the concepts, also named slots or roles, and (3) restrictions on slots (facets) that are superimposed on the defined classes and/or properties to define allowed values (domain and range). In this way, we use ontology conception to construct "languages" for communicating the contents and structure of the fault patent databases. Ontology based mechanisms are useful to develop knowledge based systems, analyse domain knowledge and knowledge reuse. However, one of the main drawbacks of those knowledge based systems is that they will consume large computing resources if high complexities of ontology are used. Therefore, how to reduce the complexity of analysis is the key issue for fault tolerance mechanism in WSNs.

To improve the ontology-based mechanism, we propose the use of the Causal Model Method as a flexible solution for fault detection and diagnosis in WSNs. Causal Models represents causal relations between fault and symptoms which can be represented in causal relations: fault → events → symptoms. Causal Model Method uses a model-based approach that predefines a decision graph for detecting and diagnosing problems that occur during system operation. Several model-based fault diagnosis methods have been proposed [Y.Kitamura'97] [B. Horling'00] [R. Jurdak'06]. Horling and Lesser [B. Horling'00] proposed a directed, acyclic graph (DAG) used for organizing a set of diagnosis nodes. In the first stage, the nodes periodically perform simple comparison checks using a watchdog method to identify if a fault has occurred. Any deviation from the expected value of the characteristics triggers the diagnosis model to identify the exact source of the fault. This trigger-checking activity is a primary mechanism for initiating the diagnostic process. In the second stage, the Causal Model Method provides a casual analysis process to identify the reasons why a fault occurs. In other words, causal model method analysis constructs a wider process to investigate fault. Most of the causal analysis techniques like [Y.Kitamura'97] [R. Jurdak'06] consider limited extent of possible causal factors so that they gather an appropriate range of evidence about the fault sources. The advantage of Causal Model Method is tightly integrated into the relationship of fault and symptoms. This method can express the relations among the failure behaviors and node system components through causal relations. This technique is essentially suitable for diagnosing a component level in sensor nodes because it has led to only diagnose specific failed source that may cause the system malfunction.

6.2 A Generic Fault Tolerance Architecture

Due to the harsh environment and small size, low cost and high density of sensor nodes, they may suffer from several faults such as system, resource, and communication faults which result in sensor nodes abnormal behaviour. Therefore, it is desirable that sensor nodes can have a fault tolerance capability. In other words, the key objective of any fault tolerance mechanism is to provide fault self-diagnosis and self-recovery mechanisms to adapt to this harsh environment and constraints. Hence, we proposed a generic based causal model method (CMM) framework to provide sensor nodes with self-diagnosis and self-healing capabilities in wireless sensor networks. This CMM has been widely used in fault classification algorithms which are based on knowledge-based conceptions [Y.Kitamura'97] [R. Jurdak'06] [Nicola Guarino'94] [M. Eid'06]. In our vision, it appears to be the most feasible approach to be implemented for a hierarchical sensor nodes environment. Unlike traditional fault tolerance methodologies, the CMM framework provides a simple fault diagnosis mechanism to specify the limited scope of detectable faults. We proposed a system that is based on CMM mechanism. This is shows in Figure 6.1.

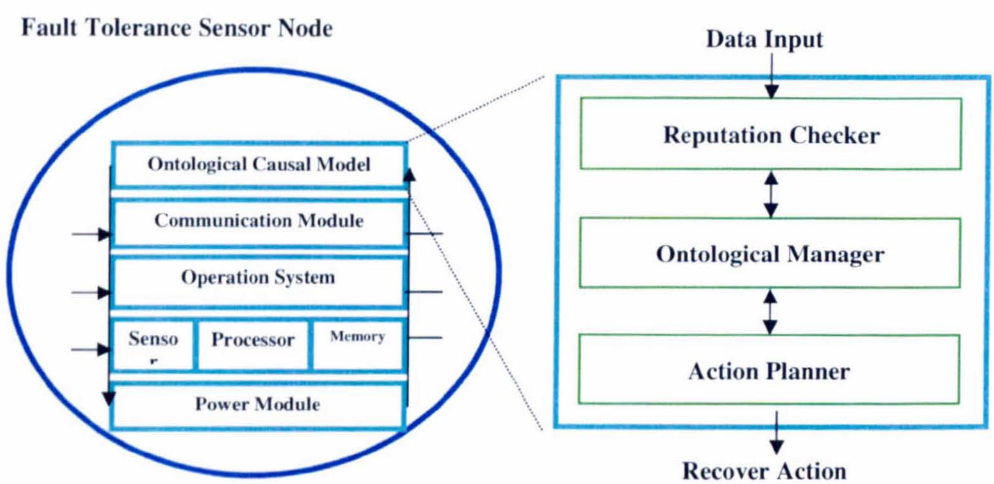

Figure 6.1: The Sensor Node Hardware Architecture

Our Causal Model Method system is a fault-tolerant model for sensor node systems which consists of three components and interfaces. The first component is named reputation checker whose function is to preliminary identify the failure event message of the sensor node. The second component is named Ontological Manager whose function is to classify and analyse the fault causes and the third component is named Action Planner whose function is to recover the fault causes depending on the previous fault analysis. In the following sections, we will describe the constitution of this CMM system and explain how it can provide fault tolerance for node level in hierarchical WSNs.

6.2.1 Reputation Checker

The characteristics of the reputation checker mechanism are similar to watchdog function. This mechanism will regularly check to maintain system reputation and use an adaptive threshold to evaluate system trustworthiness. It uses a sensor node embedded application programming interface (API) for failure detection in system components. When a failure of system components such as the node's radio, an API, LinkState(), returns the current communication link state to achieve preliminary fault identification. Once the monitored system components operation exceeds a threshold range, the node's API will generate a notification event message to the reputation checker. Then it can identify this event message according to the source API function. Once the fault has been preliminary identified, it will enable an ontological manager to further process the failure components.

The idea of our reputation checker introduces the notation of a thread-based checkpoint to detect the abnormal behaviour of a node communication. Similar to the watchdog implementation method, the reputation checker will regularly check the system condition to decide whether the node is normally working or has an abnormal phenomenon. It will set multiple checkpoint threads to monitor sensor node behaviour. This thread-based reputation checker will be embedded as part of the system operation process running on the sensor node. If the reputation checker does not detect any fault on the sensor node, it returns "no fault found". Otherwise, it will save the error information as a specified syntax. This specified syntax can be designed by the program designer for conform to further fault analysis demand.

Rather than only identify failure information, the reputation checker manages node failure information to specify fault event syntax. This fault event syntax consists of <object, attribute, state, value>. The first parameter, named object, represents system, resource, communication, or environment. The system can match any the component in the sensor system. The resource represents the sensor power, communication bandwidth, etc. The second parameter, named attribute, represents the event information attribute related to object tag. The third parameter, named state, represents what is the current state of the fault. The last attribute, named value, represents the obtained record or value from the target components. After the reputation checker stores this syntax information in its error log file, it will trigger ontology manager to further analysis of the failure reason.

6.2.2 Ontological Manager

Once the ontological manager has been triggered by the reputation checker, it will subdivide different types of fault causes based on its fault taxonomy tree as we will describe later. The ontological manager is responsible for relative the failure event message with this fault taxonomy tree. An example is link failure, where the ontological manager will check AntennaFactor(), NoiseBandwidth() and use IF, ELSE statements to diagnose the fault cause of the sensor node. When the fault cause has been identified, the ontological manager will send fault causes result to activate action planner.

As mentioned above, ontology is a useful notion to develop knowledge based systems, analyse domain knowledge and knowledge reuse. Therefore, it is very helpful to find out an explicit reason for sensor failure. Although we realize faults in sensor networks are potentially open-ended, and an ontology mechanism can consume large computing resources if high complexity of analysis. Different from previous methodologies, our ontology manger aims at pinpointing the special characteristics of sensor faults with limited analyzing complexity to provide fault diagnosis in wireless sensor networks. For these reasons, we divide the fault causes into the following categories; system, resource, and communication failure.

In system aspect, system failure in sensor networks is defined as node hardware or software malfunction. Hence, we separate the system faults into hardware and software fault aspects. In the hardware part, hardware faults are mainly from component level faults such as antenna circuit, sensing device malfunction. Because sensor nodes are usually densely deployed in an open field environments, managing hardware failure is typically replaced by redundancy nodes and scheduled periodic data backup. However, if a great number of nodes experience hardware failure, it would be better to have a reorganisation procedure to manipulate data dissemination paths and prevent its expiry by the hardware failure.

In the software part, software failure results in data being corrupted or malfunctioning. These faults may occur due to poor code or incorrect program procedures. For example, adjusting sensing power to a lower value which may directly affect data accuracy in the sensor node. In this point of view, software itself should have fault tolerance design. Even though the program procedure meets the failure situation, it should not have direct impact on sensor node operation. Moreover, sensing data should have a regular check procedure such as cyclic redundancy check (CRC) to ensure data accuracy and integrity. Figure 6.2 presents our proposed sensor network fault taxonomy fault tree to classify the fault causes in sensor networks.

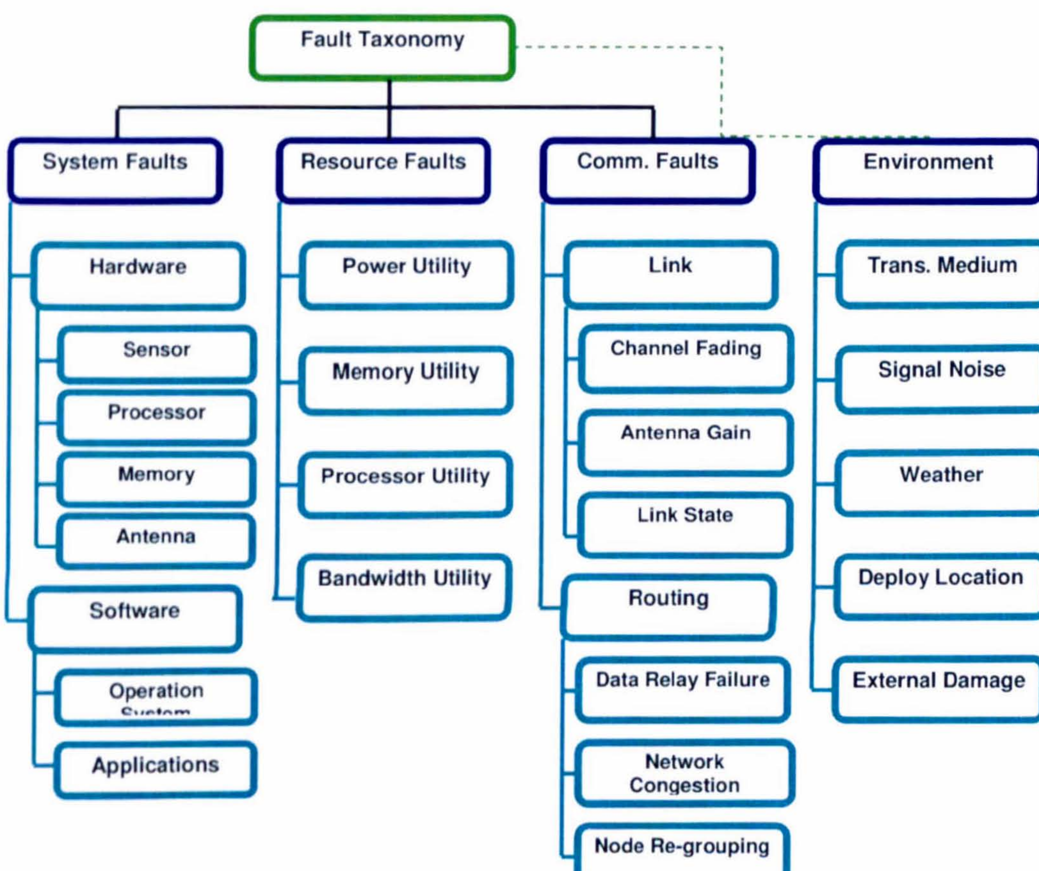

Figure 6.2 : Illustration of Fault Taxonomy Tree

In resource terms, the most precious resource in the sensors networks is power. Power consumption needs to be carefully designed to adapt to user/application requirements before sensor networks applications are deployed. Hence, in hierarchical sensor networks [H. Luo'02][J. Youn'04][M. Chen'06][R.R.Kalva'05][S.H. Chang'07], cluster heads will aggregate neighbouring sensor nodes data and relay this aggregated data to cluster heads until reaching the destination sink node. As well as other resources (such as memory, processor, and bandwidth) in the networks, application designers need to keep in mind the resource constrain in the sensor networks, for instance, decreasing the resource consumption and increasing the network lifetime in the wireless sensor networks.

Because wireless sensor nodes are normally deployed in harsh and complex environments, communication in wireless sensor networks is more prone to failure than in traditional wired networks. The purpose of sensor networks is often to obtain the sensed data from the remote area according to application/user requirements. Therefore, communication failure in sensor network can be defined as route for link failure during data transmission. The link failure means the communication channels between the sender and receiver nodes inside the same radio range cannot be set up. The routing path failure means the communication link between the source and destination nodes in the same networks cannot be established. Therefore, how to support link stability and maintain route lifetime become key issues in communication fault tolerance.

Moreover, in the environmental aspect, considering wireless sensor networks deployed in a hardly feasible environment (such as under water, forest, fire, or harsh desert) that causes communication failure in wireless sensor networks. This harsh environment may cause transmission loss, signal spreading, multi-path propagation, background noise and interference, etc,. In this case, sensor networks may suffer a high packet drop rate when deployed in this kind of environment.

6.2.3 Action Planner

When the action planner receives the final fault causes from the ontological manager, the action planner will take appropriate fault recovery actions to maintain sensor node system, communication, or energy levels. If the sensor node failure can be recovered by reset attenuation factor or entering the power saving mode, the action planner will update the sensor node or even restart the node system immediately to maintain the wireless sensor networks operation. In the following sections, we will cover causal model method mechanisms and ontological tree construction.

The purpose of our action planner is to reduce the risk of a range of nodes failure that impacts the whole WSNs operation. Actually, a local reconfiguration process is a useful method to avoid the failure expending effect. Hence, the design goal of this action planner should be simple and offer low resource consumption. The main function of the action planner is to use explicit failure location information from an ontology manager and fault reconfigure API from sensor system to achieve local repair. Currently, this fault reconfigure API is very simple. Once the ontology manager reports the fault location information, it will use this information to call the most related sensor API and this sensor API will reset the parameters related to this fault. For example, when a sensor node transfers its working state to sleeping state because of software malfunction, our action planner will receive a failure information from the ontology manger that indicate power mode is incorrect. Therefore, our action planner will enable the sensor API to reconfigure the sensor power mode into working mode to solve this failure. It is also possible for our action planer to be incorrectly set up. Once the failure cannot be eliminated by reconfiguring the sensor node, our action planer will reboot the node system by using cold-restart. Cold-restart is a simple system reboot method that make the node went back to its previous state. This method conducts a complete resetting of the system to eliminating execute incorrect procedure in the node. This reboot method in WSNs is an open issue that has been proposed by a number of excellent surveys papers and methods. The most two widely used recovery methods are fault masking and retry [P.Jalote'94] [F.Koushanfar'02].

In [P.Jalote'94] [F.Koushanfar'02], they apply the fault masking approach which uses the redundant correct information to eliminate the impact of incorrect information while system reboot.

Imagine that we have a communication failure scenario between node x and node y because the transmission power value in node x is incorrect. This incorrect transmission power value causes the communication channels to fade and raises the packet drop ratio. Once the packet drop ratio is over the threshold defined by the reputation checker, it will trigger the checkpoint threads to examine the communication state to collect the fault event information. If the communication state and examined data do not corresponded to the reputation checker's predefined parameters, then the reputation checker will save this event information syntax <communication, channel phenomenon, fading, N/A> and enable the ontology manger to further analyse the explicit failure information. As the diagram shows in Figure 6.3, the reputation checker classified the communication failure from the node x.

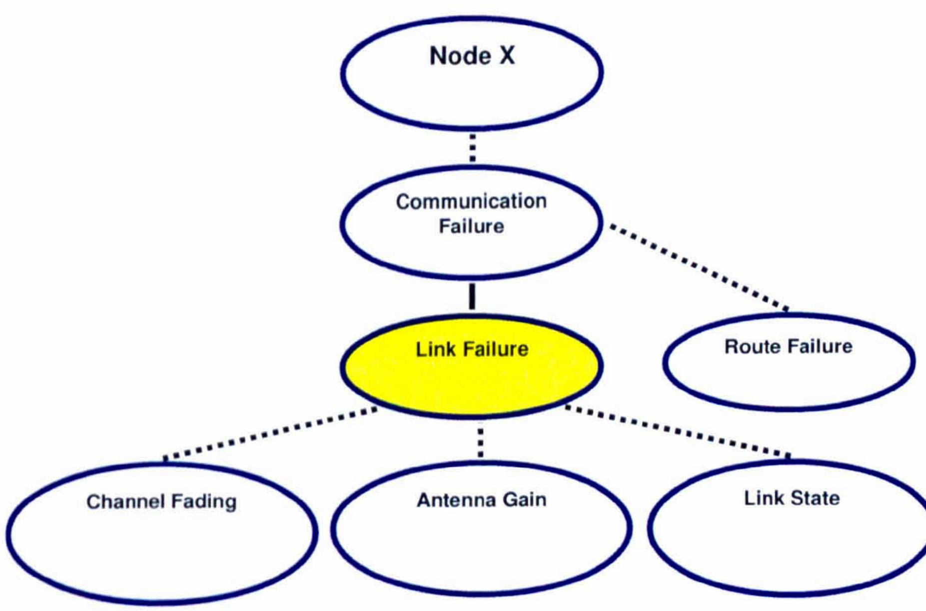

Figure 6.3: Illustration of Casual Model Method (CMM) Fault Diagnosis

When the ontology manager has been activated by the reputation trigger, it will reference to the event syntax values and check out the lower layer parameters. First, the ontology manage does not receive any event message related to data relay failure, regroups network or network congestion. Second, the ontology manager finds out that the channel fading is related to link failure. Then, it will indicate this failure event is related to the link failure. Therefore, it will only check link related parameters (such as link state and Antenna Gain and channel fading, etc) and compare to the node's original setting. Sooner or later, it will find out the transmission power is different from the original setting. Once it has found out the explicit failure cause, it will trigger the action planer to reconfigure transmission power to its original value. Once it has been done, our reputation check will periodically check any further event from the sensor node.

6.4 Evaluation

We evaluate our Causal Model Method framework through simulation using the same simulator and with the same parameters presented in the chapter 3. Our goal through these simulations is to assess the efficiency of our solution and evaluate its performance in terms of packet success ratio and transmission average delay, and the impact of the faulty cluster heads and sink mobility on the energy consuming. Energy consumption includes that of mole node competition, data dissemination and sinks mobility. In this experiment, our main concern is energy dissipated and the time for the CMM mechanism to find the faulty cluster heads. Therefore, we highlight on energy consumption for data dissemination and sink mobility management in our simulation works. In addition, because of GTNetS has default one sink limitations; therefore we only use one sink node to evaluate this algorithm.

6.4.1 Fault Injection

For the reason of detecting the malfunction cluster heads, we inject interference packets in the wireless link and lower down the receiving power which attempts to disable packet receiving capability of these cluster heads. Once the fault injection has been done in couple of cluster heads in the network, we assume these faulty cluster heads are not able to receive packets over the network which reduces the packet success ratio and increase end-to-end delay. Then we implement our CMM fault tolerance mechanism in a schedule to recover the malfunction of the cluster heads. An example of pseudo code as shown in Figure 6.4, This event-driven CMM mechanism can leads to regularly execute segments of code to provide energy efficiency within a while() block.

```
for (int i = No_Sink; i<=Faulty Nodes; i++)
{
  //Set faulty node resource parameters
  static_cast<NodeSN*> (n[i])-
>setComputing
  Energy(100);
  static_cast<NodeSN*> (n[i])-
>setComputOver
  headEnergy(100);
  static_cast<NodeSN*> (n[i])-
>SetDataRelaying
  Energy(100);
  ...
  //Set faulty node sense parameters
  static_cast<NodeSN*> (snsr[i]-
>SetSensSize
  (100));
  static_cast<NodeSN*> (snsr[i]-
>SetSensRange
  (100));
  static_cast<NodeSN*> (snsr[i]-
>SetResolution
  (100));
  ...
  //Set faulty node network interface
parameters
  static_cast<NodeSN*> (iface[i]-
>SetRxPower
  (0)); // Set Rx Power Equal 0
  static_cast<NodeSN*> (iface[i]-
>setTxPower
  (100));
  static_cast<NodeSN*> (iface[i]-
>SetLinkState
  (InterfaceWireless::RX_ZZ)); // inject
interfere
  packets in the wireless link.
}
```

```
while(1)
{
    debug_checkpoint (&mycheckpoint_t);
    if(mycheckpoint == identified fault source)
{
      cout << "Failure: Identified Failure
Occur" ;
     // format the failure message as the specific
syntax
     String s = formatter.format(x);
     // restoring the formatted failure message in
a error log file
      outfile.write(event s);
     fault_handler();
     } else {
      cout << "Great! No Failure Occur");
     }
    thread_sleep(deadline);
}

fault_handler()
{
  // read failure message from the error log file
  infile.read(event s);
  if(this.fault s.object == system fault) {
     static_cast<NodeSN*> (n[i])-
>reconfigure();...}
  else if(this.fault s.object == sense fault) {
     static_cast<NodeSN*> (snsr[i]-
>reconfigure();...}
  ......
  else if(this.fault s.object == interface fault) {
     static_cast<NodeSN*> (iface[i]-
>reconfigure();...}
}
```

Figure 6.4 : Pseudo Code for CMM Fault Tolerance Mechanism

6.4.2 Average Success Ratio

This experiment is mainly to measure average success ratio under a number of cluster heads failure in the networks. The average success ratio is the ratio of successfully delivered packets which reach the mobile sink. Hence, in this experiment, we set up a mobile sink to move at different speeds (0, 5, 10, 15, 20 m/sec) and we choice regular number of cluster heads failure from 0 to 12 (0, 3, 6, 9, 12 nodes). Due to these regular numbers of cluster heads have been set up failure randomly; the average success ratio will be different depend on the failure cluster heads locations. In fact, the closer of failure cluster heads to the mobile sink, the lower of average success ratio will be made. As the diagram shows in Figure 6.5(a), the cluster heads failure has an impact on the average success ratio although mobile sink can collect data from a sender by moving around in the network. The average success ratio has dramatically decreased when failed cluster heads increases. On the other hand, as shows in Figure 6.5(b), we observe that CMM mechanism is able to maintain high success ratios above 82%. Once the node has been recovered from the faulty state, the average packet success ratio will increase to a higher value comparing to the non-maintenance situation.

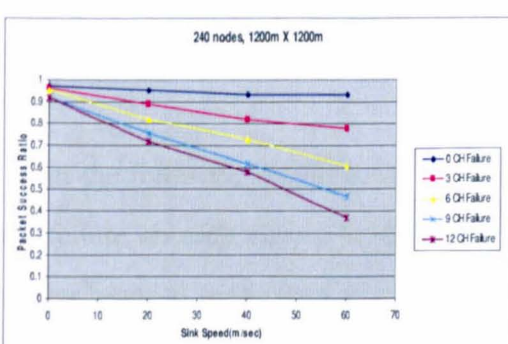

Figure 6.5 (a) – Average Success Ratio without CMM

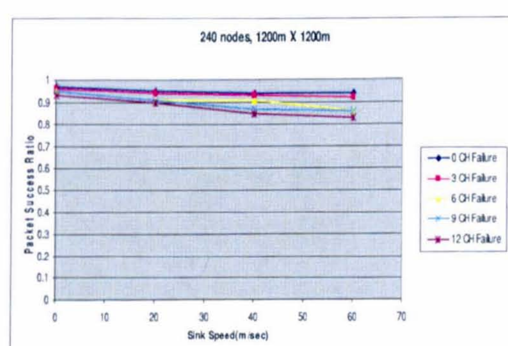

Figure 6.5 (b): Average Success Ratio with CMM Average Ends-to-End Delay

In the following experiment, we investigate average end-to-end delay as a function of the number of failure cluster heads and mobile sink speeds. This experiment is to measure the average end-to-end delay for a number of cluster heads failure in the networks. Figure 6.6(a) shows that end-to-end delay increases when several failed cluster heads increase. In this experiment, the number of failure cluster heads is varied from 0 to 12. Mobile sink moves by different speeds (0, 20, 40, 60 m/sec). The failure cluster heads have an impact on the end-to-end delay without the CMM mechanism although mobile sinks can receive from a sender whose routing path does not pass through the failure cluster heads. As shown in Figure 6.6(b), once the CMM mechanism starts to work, it will support shorter delay than non-maintenance network. CMM achieves lower average delay than non-maintenance network because cluster heads are recovered after CMM mechanism implemented.

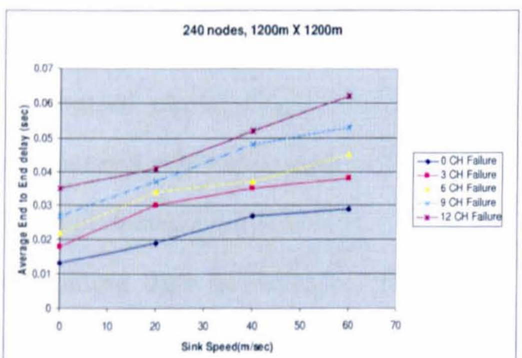

Figure 6.6 (a): End-to-End Delay without CMM

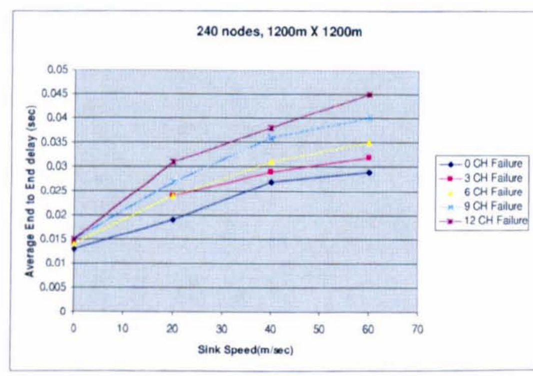

Figure 6.6 (b): End-to-End Delay with CMM Average Energy Dissipation

In the following experiment, we investigate the average energy dissipation after the failure on each cluster head has been recovered. We set the number of failure cluster heads to verify from 0 to 12 and one sink moves by different speeds (0, 20, 40, 60 m/sec). This experiment is to measure the average energy dissipated on each cluster heads in the networks. Figure 6.7 shows that average energy consumption on each cluster heads without CMM mechanism implemented. The node energy consumption has decreased. As exhibited in Figure 6.7, the reason for higher energy dissipation is because each cluster head will execute fault examine and reconfigure tasks in the wireless sensor networks.

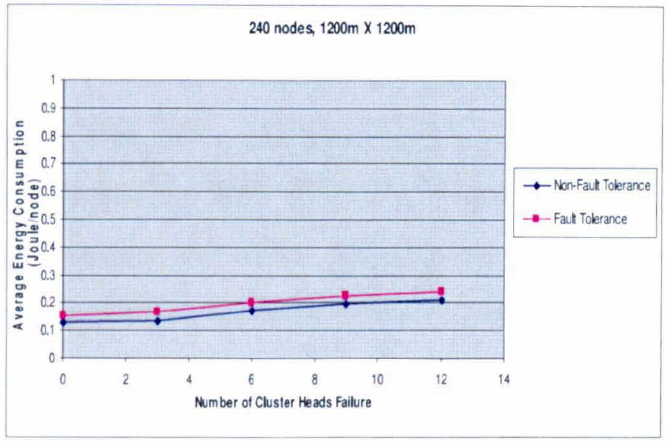

Figure 6.7: Energy Dissipated Comparison

Since the number of failure cluster heads varies from 0 to 12 reputation checker will check periodically for every 50 seconds (50, 100, 150, 200, 250 seconds). A number of cluster heads will have failed during the simulation. Once the CMM mechanism starts execution at the examining time points, the CMM mechanism will be implemented until the end of recovery procedure. As exhibited in Figure 6.8, the examining time is between 0.0279 and 0.0329 seconds. The reason for this time variation may depend on node processing speed and complexity of implement of CMM mechanism. In this experiment, we understand that the complexity of CMM mechanism will influence the node examine time.

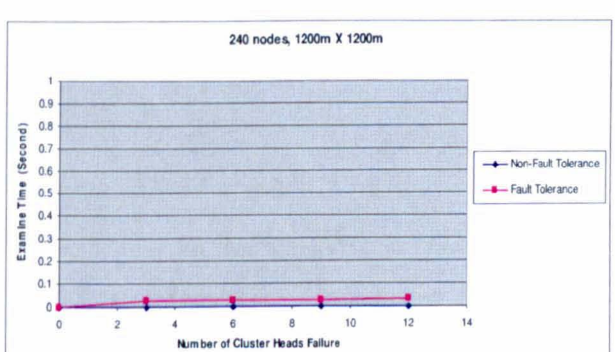

Figure 6.8 : Examine Time Comparison

6.3 Summary

In this chapter, we described our Causal Model Method (CMM) Fault Tolerance Model for WSN. CMM Fault Tolerance Model is an explicit fault tolerance mechanism that is suitable for WSN. CMM Fault Tolerance Model uses reputation checker, ontology manager, and action planner schemes to provide efficient fault tolerance algorithm in WSN. In our simulation work, we have shown its effectiveness by comparing it to the same scenario but without fault tolerance mechanism. The simulation results show that our scheme expense little bit higher energy and examine time to achieve better average end to end delay and packet success ratio when a number of cluster heads fail in the wireless sensor networks. The result of simulation shows that CMM Mechanism can provide more reliable network in WSN.

CHAPTER 7

7 Conclusion And Future Work

This thesis has presented new routing protocols for geographic and non-geographic aware based mobile sinks wireless sensor networks. This chapter is organized as follows: Section 7.1 presents a summary of the thesis. Our main contributions, the high performance routing protocols for geographic and non-geographic based mobile sinks wireless sensor networks and a new node-level fault tolerance approach are presented in section 7.2. In section 7.3, we discuss and compare to the existing works in these fields. Future work is investigated and proposed in section 7.4, and conclusions are provided in section 7.5.

7.1 Thesis Summary

In wireless sensor networks, all nodes in a network communicate with each other via multi-hop wireless links, where the communication cost is much higher than the computational cost. Most of the proposed deployment applications do not allow the sensor nodes to recharge their batteries. Consequently, the route of each sensed data destined for the sink is really crucial in terms of network life. Different from wireless sensor networks, mobile sinks wireless sensor networks are composed of resource constrained sensor nodes and multiple mobile devices called sinks. Since mobile sinks can remit the effects of the hotspot problem in wireless sensor networks and improve network performance, it has attracted much research interest in recent years. However, mobile sinks wireless sensor networks also introduce many challenges such as scalability, performance, power consumption and network reliability. Therefore, our work focuses on the design of communication protocols that can provide network scalability, high performance, and fault tolerance capability of the monitored environment, and take into account the resource constraints of the wireless sensor network. To achieve this goal we have developed several schemes in the area of routing and data dissemination in wireless sensor networks.

Chapter 1 outlined the main characteristics of wireless sensor networks as:

1) Limitation of resources such as energy, bandwidth, memory and computation power.
2) A dense deployment of sensor nodes and a high correlation of the retrieved data.
3) A lack of global identification and a random deployment of sensor nodes

These characteristics make the design of a routing protocol for this kind of network difficult. On one hand, the routing protocol must satisfy the user requirement and deliver a high level descriptive information to the user, and on the other hand this protocol must be the most resource efficient possible.

Chapter 2 presented a survey of the actual wireless communication and research efforts on wireless sensor networks as well as a state of the art on routing protocols for mobile sinks wireless sensor networks and fault tolerant mechanism found in the literature. This chapter pointed out the main drawbacks of existing works and the issues that needed to be addressed as:

- Existing routing protocols are focused excessively on the energy efficiency or low-latency issues and only consider the static sink communication pattern, but may neglect the user requirements such as network scalability and connectivity resulting in inefficient routing and wasted limited resources.
- Major works on routing in mobile sink routing approach are not energy efficient and it is necessary to emphasize high performance and reliable network infrastructure for mobile users to retrieve sensed information from

the current sensing region.

- Sensor nodes are very vulnerable to failures in wireless sensor networks; however, the node level fault tolerance mechanism has not been addressed yet even though it is a crucial element to the reliability of sensor networks.

Chapter 3 discussed in more detail the routing topology impact on network performance and reliability issues in wireless sensor networks and presented our approach to tackle these important challenges by describing the novel contributions that comprise our work. Our novel contributions were explained in detail in chapters 4, 5, and 6. We presented the analysis of the problem, the design and the evaluation of the suggested schemes in each chapter.

Chapter 4 presented our Spider-Net Zone Routing protocol addressing energy efficient and reliable routing in non-geographic aware based mobile sinks wireless sensor networks. We described in detail the different elements of this routing mechanism. This protocol has been evaluated through simulations and compared to existing routing protocols.

In chapter 5, we presented our Fault Tolerance Magnetic Coordinate routing protocol which addressed high performance and reliability issues in geographic aware based mobile sinks wireless sensor networks. We described in detail the different elements of this routing mechanism and evaluated our Fault Tolerance Magnetic Coordinate routing protocol through simulations and outlined its advantages over existing schemes.

In chapter 6, we addressed the component-level failure problem in WSN and presented our Causal Model Method fault tolerance approach. In this chapter, we presented a fault taxonomy tree and used a causal model for fault tolerance method in WSN. We described in detail the different elements of this fault tolerance approach and proved that it achieves better average end to end delay and packet success ratio than the same routing algorithm but without Causal Model Method fault tolerance approach.

7.2 Research Contributions

It is a challenge to design and analyse communication protocols for mobile sinks wireless sensor networks and fault-tolerant realizations of non-conventional networks. These enable the designer to make good tradeoffs in the different system parameters to best support mobile sinks wireless sensor networks applications. Based on the design constraints, we developed a routing framework [Chang'07-a, Chang'07-b, Chang'07-c, Chang'07-d] and a fault tolerance mechanism [Chang'09] for mobile sinks wireless sensor networks. The contributions of this work are summarised as follows:

- We have proposed a new spider-net topology [Chang'07-a, Chang'07-b] for routing in mobile sinks wireless sensor networks. This routing topology can provide high scalability and high performance data dissemination for non-geographic based mobile sinks wireless sensor networks. The protocol uses both zone-based and tree-based network topology by partitioning the whole network area into different zones. Each zone has its membership nodes and utilizes spider-net zone routing algorithm to support the network scalability, improve the network performance and provide robust data transmission for non-geographic based mobile sinks wireless sensor networks. The protocol also uses a routing redirect mechanism to update the current mobile sink location which allows event messages to be quickly forwarded to it. This scheme helps to deliver event messages efficiently and continuously to mobile sink, while it is moving.

- We have proposed a new fault tolerant routing protocol [Chang'07-c, Chang'07-d] for data dissemination in a geographic based mobile sinks wireless sensor networks. This proposed routing protocol uses nodes' logical coordinate information to form a grid-based network topology. To improve performance and reliability issues for mobile sinks wireless sensor networks, this scheme uses a coordinate based routing mechanism with a path update mechanism. The advantage of this coordinate based routing mechanism is to improve network performance and thus save more energy and extend the network life. Moreover, this routing protocol utilizes consensus analysis scheme to support fault tolerance and network reliability issues that allows the faulty or malfunctioning node to be detected and replaced in the network.
- We presented a new fault tolerance framework named Causal Model Method [Chang'09] which utilizes a light-weight and thread-based checkpoint to detect the abnormal behaviour of a sensor node. Once the fault source has been detected, CMM uses an ontology manager scheme which is based on the ontology notation to "deeply understand" the fault cause. This ontology manager aims to pinpoint the special characteristics of sensor faults and classify the fault according to our taxonomy allowing each sensor node to reconfigure itself or execute a recovery scheme to compensate for the erroneous impacts on the sensor node. This scheme consists of three phases to define the node failure sources as "collect, classify, and correct". To avoid failure impact to sensor networks operation.

7.3 Comparison to Existing Work

As mentioned before, the main objective of our communication mechanisms is to provide a set of routing protocols and communication schemes that allow the user to collect the desired information from the sensor field at minimum energy cost and with the shortest time delay. The problem of routing in wireless sensor networks has been addressed by many research groups, and many routing protocols have been proposed. Our work shares some similarities with prior works carried out in other projects. In this section we compare our mechanisms with these works.

The protocol Directed Diffusion proposed in [Intanagonwiwat'03] is a data centric routing developed to look for sensor nodes satisfying a user query. Once found these sensor nodes start sending information to the user through different paths. However, the routing framework we proposed is not only in non-geographic aware routing as in Directed Diffusion, but also proposed completed solutions in geographic aware routing and fault tolerance mechanism. Indeed, the simulations performed in this work show that the query dissemination proposed in our non-geographic aware routing protocol is more energy efficient as it avoids flooding and reduces the scope of the interest propagation. Moreover, our non-geographic aware routing protocol reduces the number of data messages by grouping nodes in a cluster and aggregating their data and thus saves more energy.

The TTDD [H.Luo'02] is a well-known grid-based routing protocol to provide query and data dissemination for multiple mobile sinks. Upon detection of an event, the source node creates a virtual grid structure and divides the network into cells with several grid cross nodes. The grid cross nodes, named dissemination nodes, are responsible for relaying the query and data to and from the proper sources. In TTDD, mobile sink floods its query within the lower tier until it reaches the closest dissemination node. Once this closest dissemination node receives this query, it will request a data download to the source node along the reverse grid path direction back to the sink. TTDD solves the sink mobility problem using a grid structure. However, if the number of source nodes is increased, data dissemination point management can considerably increase the communication and storage overhead of the system.

The ODDD [R.R. Kalva'05] forwards data announcement messages horizontally without building a virtual grid over the entire network and a query is propagated vertically. The delivery of data is guaranteed because there is at least one intersection between query and data announcement. Hence, this data delivery mechanism reduces the amount of communication overhead for creating and maintaining a virtual grid. However, in the ODDD scheme, a grid point node failure may lead to communication congestion or data lost between source and destination. Furthermore, the routing framework we proposed is not only in geographic aware routing as in ODDD, but also proposed completed solutions in non-geographic aware routing and fault tolerance mechanism. Specifically, the fault tolerance mechanism in our routing protocol that avoids grid failed nodes impact on network performance and data reliability.

Considering the problem of fault tolerance in wireless sensor networks, our work presents also some advantages over existing schemes like [R. Rajagopalan'05], which proposed two approaches to combat the Byzantine faulty nodes for data gathering in mobile sinks wireless sensor networks: randomized censored averaging (RCA) and randomized median filtering (RMF). These approaches suggest a different methodology to provide fault tolerance in mobile sinks routing. However, they do not provide adaptable fault detection and identification (FDI) function to identify the faulty nodes. Simulations show that the node recovery scheme presented in our work maintains the network connectivity and extends the system lifetime much longer than non-fault tolerance scheme. Moreover, our scheme maintains the network connectivity much longer than multi-path based approaches while performing better energy saving and network lifetime extension.

The mechanisms proposed in this thesis contribute to our understanding of the benefits of designing communication protocols that consider the application profile, the user requirements, and the network constraints. We have developed and evaluated these communication mechanisms for mobile sinks wireless sensor networks based on non-location awareness and location awareness. These mechanisms are able to better support mobile sinks wireless sensor networks applications than other communication approaches and protocols for wireless sensor networks.

7.4 Future Work

So far in this chapter we have reiterated this thesis aims, findings, main results and considered the novel contributions of our work. While several contributions have been achieved, they raise, some interesting questions. This section deals with, in our view, the most significant of these challenges.

- **Multiple Sinks Mobility Support:** In time-critical applications such as those enabled by large military surveillance applications, there existed a critical need to have multiple sinks mobility support. However, in these multiple mobile sinks applications, frequent locations updates can generate excessive communication overheads that deplete power of sensors. Moreover, the impact of multiple sinks moving at different speeds in wireless sensor networks will influence data reliability. Therefore, solutions to such a problem should address many issues including the network configuration, compatibility and performance issues. In particular, this effective mobility management scheme should support empower sensor nodes to make better decisions regarding mobile sinks positions and network coordination to benefit in multiple mobile sinks wireless sensor networks applications. It is clear that a lot of work needs to be carried in the field to supports the functionality by the architecture.
- **Optimal Sink Mobility Model for Wireless Sensor Networks:** An extension to our current routing framework is already being carried out by other researches that focus on optimal sink mobile model. Since sink mobility will have direct impact on the network performance and lifetime of the wireless sensor networks, the design of optimal sink mobility model for scheduling data collection in wireless sensor networks will need to be concerned. However, the problem is very challenging as individual applications and protocols at different layers will have different requirements to configure the current sink mobility model. Therefore, a next challenge of our routing framework is to provide an adaptable sink mobility model which is able to

obtain the current application requirement on sink mobility and provide flexibly configuration to achieve optimal sink mobility demands of the current network topology and application requirement.

- **Fault Tolerance System Extension:** In our implementation we used a Causal Model Method algorithm as detailed in Chapter 6. However, the existence of sensor system failure that caused by hostile environment, especially in contained environments such as military and disaster relieve where a more complete fault tolerance system needs to be implemented to insure the reliability of the network. Due to the failures occurring in practice, the current Causal Model Method that we proposed in chapter 6 may not able to deal with all types of failure nodes in a complex application. Instead, a much more robust and complete solution would be required to adapt and extend the current Causal Model Method on the basis of experience. Hence, our next challenge is to extend and implement the current Causal Model Method including fault taxonomy tree and action planner to make better fault tolerance system in realistic wireless sensor networks application.

7.5 Concluding Remarks

Wireless sensor networks is one kind of wireless network which consists of multiple sensor nodes and sink nodes. Harvesting advances in the past decade in microelectronics, sensing, analogue and digital signal processing, each sensor node is normally compact in size with low-cost, low-power, multifunctional capabilities. Each sensor node is powered by battery and networked via low power wireless communications to cooperate and coordinate with neighbouring sensor nodes to enable multiple applications. However, for battery-operated sensors, energy conservation is one of the most important design goals, since replacing batteries may be difficult or impossible in many applications. In order to achieve it, many recent solutions use mobile sinks that move either randomly or along a predefined path. This type of wireless sensor network is named mobile sinks wireless sensor networks which provide an optimal solution for the complementary problem.

Typical applications of mobile sinks wireless sensor networks include military surveillance, medical treatments, environmental protection, disaster assistance, rescue scenarios, etc. In such scenarios, mobile sink can be adapted to the current events in the network or send the query to the network. Different from fundamental WSN, mobile sinks wireless sensor networks introduce new challenges for WSN such as dynamic routing topology, network maintenance and reliability communication. Therefore, new communication protocols and fault tolerance mechanism are required to satisfy the user requirements. In this thesis, we highlighted the main problems and challenges to design communication protocols and fault tolerance mechanism for mobile sinks wireless sensor networks, and then we presented our approach for dealing with these problems.

Our routing framework is composed of non-geographic and geographic aware routing protocols that consist of fault tolerance mechanism, designed to support mobile sinks wireless sensor networks: (1) a new Spider-Net Zone Routing protocol for non-geographic aware mobile sinks wireless sensor networks [Chang'07-a, Chang'07-b], (2) a new grid-based fault tolerance magnetic coordinate routing protocol for geographic aware mobile sinks wireless sensor networks [Chang'07-c, Chang'07-d] , and (3) a Causal Model Method for fault diagnosis in wireless sensor networks [Bouhafs'06-e].

We analyzed and evaluated the proposed schemes analytically and by simulation techniques. Our evaluation was focused on the three important network performance parameters of mobile sinks wireless sensor networks, namely, end-to-end delay, success ratio and energy consumption. By comparing our results to those of other mechanisms available in literature, we showed that our solution can improve network performance and is more energy efficient than other approaches. We showed also that our routing framework supports both non-position and position based sensor nodes deployed in wireless sensor networks. Our solution also provides sensor nodes with self-classification and self-diagnosis of faults in wireless sensor networks. The experiments showed that our solution achieves better end-to-end delay and packet success ratio when compared to the same scenario but without fault tolerance mechanism.

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