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ENERGY EFFICIENT COMMUNICATION MODELS IN WIRELESS SENSOR AND ACTOR NETWORKS

by

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SUMMARY

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

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

A solution based on modelling a WSN as a small world network and then transmitting an initialisation message (IM) on network start-up to create multiple route paths from any sensor node to one or more sinks is proposed. The reason for modelling a WSN as a small world network is to reduce the number of nodes required to re-transmit a message from a source sensor node to a sink. The purpose of sending an IM at network start-up is to ensure that communication within the WSN is minimised.

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

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

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

OPSOMMING

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

deur

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

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

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

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

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

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

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

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

Dedication

To my family,

Raphael, Roja and Rachamim

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List of Abbreviations

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

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CHAPTER 1

RESEARCH OVERVIEW

1.1 INTRODUCTION

Progress in human society is dependent on our ability to obtain information. The more knowledge available about plants, animals, the environment, buildings, cars, in fact just about everything, the more optimally and sustainably can these be utilised. To obtain and analyse information about the state of a specific environment, the actual physical events, such as light, movement, sound and temperature changes need to be converted into electrical signals. These electrical signals can be processed and analysed to improve human understanding about the current state of the environment.

Current systems rely on sensors to obtain data about a specific environment. These sensor nodes are standalone devices without access to a continuous energy source and are located either within or close to the phenomena they are observing. The nodes communicate with one or more central control point(s), generally called a sink or base station. A large number of these sensors deployed across an application area so that each sensor is within radio range of at least one or more other sensors create a Wireless Sensor Network (WSN). As stated by Krishnamachari, WSNs bridge the virtual world of information technology and the real physical world, and are used for information gathering in smart environments (Krishnamachari, 2005). A smart environment is an application area saturated with small, computational electronic devices (sensor nodes). Sensor nodes are embedded in everyday objects and by linking together hardware, software, networking and communication methods, form a WSN.

The architecture of a wireless sensor node (as shown in Figure 1.1), is that of a small electronic device, comprising one or more transducers (for monitoring a specific physical phenomenon), a processing unit to convert the electrical signal received from the transducer into an intelligible message format and to perform simple computations, a communication unit for transmitting and receiving messages and a non-renewable power source to provide energy to the above units (Krishnamachari, 2005; Akyildiz et al., 2002; Pottie & Kaiser, 2000; Karl & Willig, 2005). Some nodes are also equipped with a location finding system. Nodes can range in size from about the size of a grain of sand to that of a shoebox. The sensor nodes sense and react to changes within the application area. Sensors convert a physical phenomenon (such as heat, light, sound or motion) within the target environment into electrical signals (Zhao & Guibas, 2004).

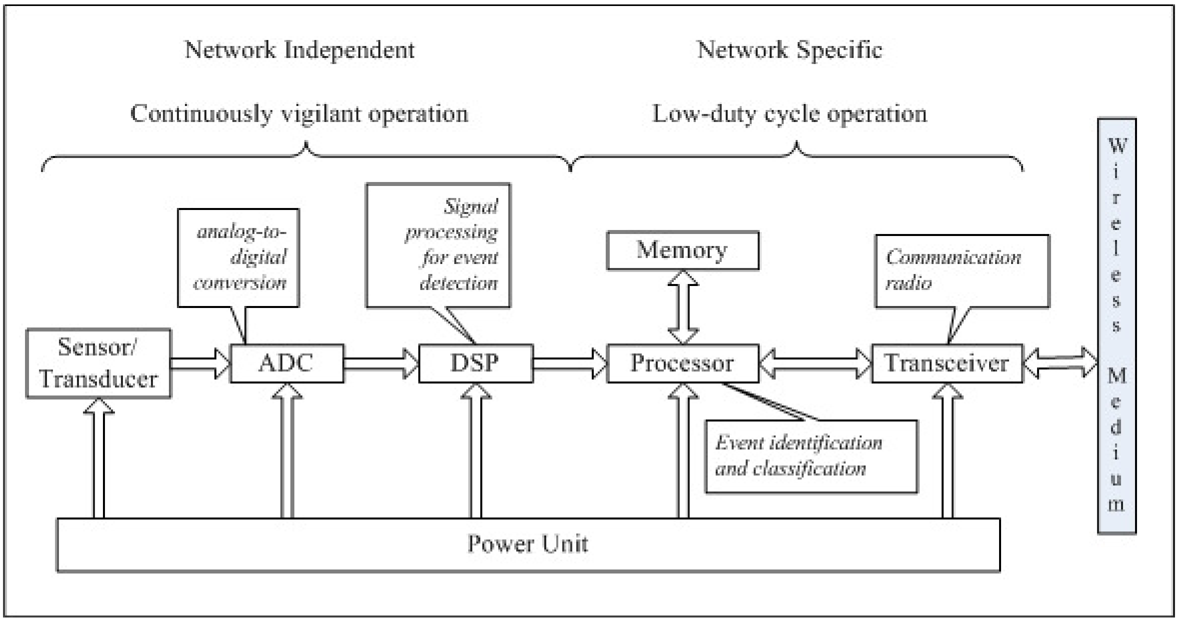

Figure 1.1: Wireless sensor node architecture

Sensors are placed within the application area to ensure adequate coverage of the area. A WSN application contains hundreds to thousands of sensor nodes. These sensor nodes are designed for unattended operation and are generally stationary after deployment. Because of the need to conserve battery lifetime, WSNs have low data rates and data traffic is discontinuous. In WSNs the flow of data is predominantly unidirectional, from nodes to sink (Rentala et al., 2002). Communication traffic in WSNs occurs in short bursts of activity with low data rates. Communication is initiated when data-specific information about the immediate environment around a node is requested or a specific event that the sensor has been set-up to monitor is triggered.

When an event that the WSN has been set-up to monitor is triggered, the neighbouring sensors that have detected the event aggregate their data and transmit a single message to the central data-capturing centre (sink node). The sink node re-transmits the information to a human interface device where the data can be evaluated. The sink transfers the message data over a wireless link to an external interface. The human or machine that receives the message data processes this information and then records the event and determines if the event needs to be reacted to. The current architecture of many WSN applications is shown in Figure 1.2 adapted from (Akyildiz et al., 2002), with permission. The sensor nodes that will pass a message from the source node that detected an event to the sink node are the message's route (highlighted in Figure 1.2).

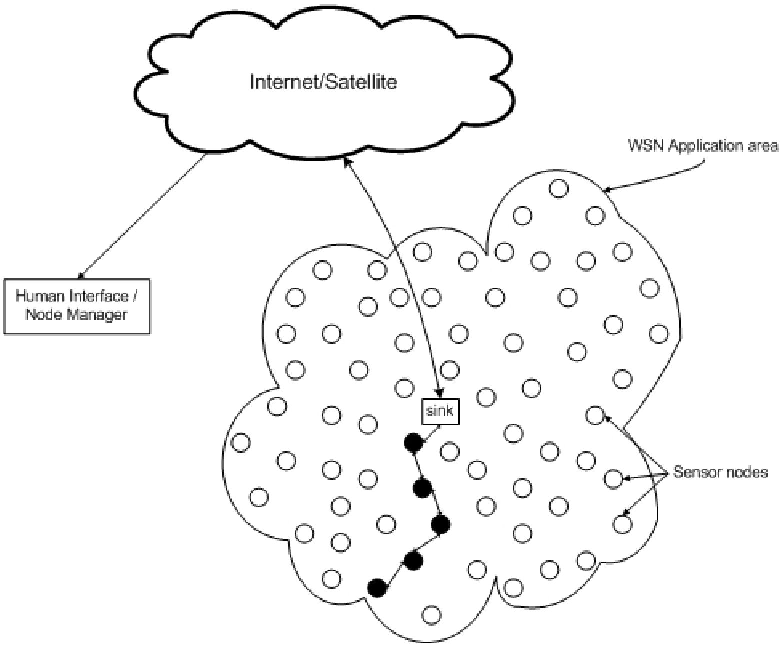

Figure 1.2: Single sink interfaces to external manager (Akyildiz et al., 2002)

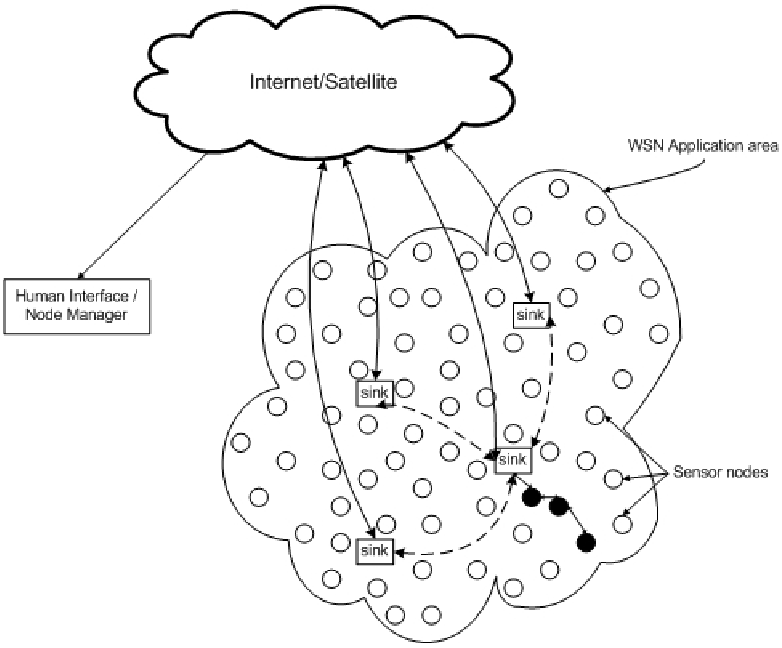

Figure 1.3: Multiple sink/actor interfaces to external manager (Akyildiz et al., 2002)

Alternatively, where a more immediate real-time response to an event is required, one or more mobile sinks or actors are placed within the target environment (refer to Figure 1.3 adapted from (Akyildiz et al., 2002)), with permission. The sensors transmit messages directly to the actors to enable faster reaction and response to events. In the event that an actor node is required to react to the data received, the actor node will do so. Actor nodes within a WSN are typically larger and better resourced than sensor nodes and can usually perform some sort of physical task.

A WSN differs from local area networks in the following key areas (Wang et al., 2006; Katz & Shamai, 2005):

1. Each sensor node communicates with one or more base stations (sinks). Traffic is mainly between individual sensor nodes and a base station.
2. The network topology is a multi-hop star-tree that is either flat or hierarchical.
3. They are used in diverse applications, which may have different requirements for quality of service (QoS) and reliability.
4. Most network applications require dense deployment and physical collocation of nodes.
5. Individual sensor nodes have limited resources in terms of processing capability, memory and power.
6. Power constraints result in small message sizes.
7. The placement of nodes in a WSN is application-dependent and may not be pre-determined.

A WSN also differs from other wireless networks, such as cellular networks and mobile ad hoc networks (MANETS) because these networks are linked to a wired or renewable energy supply. In cellular networks and MANETS, the organising, routing and mobility management tasks focus on optimising QoS and ensuring high bandwidth efficiency. There is a large amount of network traffic and the data rate is high to cater for the demand for multimedia-rich data. These networks are designed to provide good throughput/delay characteristics under high mobility conditions. Sensor nodes mainly use broadcast, while most MANETs are based on the peer-to-peer communication paradigm. Energy consumption is of secondary importance in cellular networks and MANETS as the battery packs can be replaced or re-charged as needed, whereas WSNs are limited in power, computational capacity and memory, and may not have global IDs (Rentala et al., 2002; Yoneki & Bacon, September, 2005). Also, sensor nodes have short ranges. It is not feasible for sensor nodes to try to transmit a message over a large distance because the required transmission power increases as the square of the distance between source and destination (Lewis, 2004).

The rest of this chapter describes applications of WSNs, the relevance of using WSNs, the scope of the work undertaken, the problem statement, the research objectives, the research contribution and the main themes of the research undertaken.

1.2 WIRELESS SENSOR NETWORK APPLICATIONS

The limited resources, non-renewable power supply and short radio propagation distances, (and hence large number required for deployment), of sensor nodes impose constraints on WSN applications not found in wired networks. The term "wireless" implies that even in an indoor environment, WSN applications will have energy constraints.

WSNs are typically used to monitor situations which are too dangerous or time consuming to be monitored physically or which are too difficult to monitor using a wired network. Many WSNs are essentially concerned with one of the following three types of applications (Culler et al., 2004):

1. *monitoring space*, e.g. habitat monitoring, precision agriculture, indoor climate control, surveillance, treaty verification, and intelligent alarms;
2. *monitoring things*, e.g. structural monitoring, ecophysiology, condition-based equipment maintenance, medical diagnostics, and urban terrain mapping; and
3. *monitoring the complex interactions of things with one another and the encompassing space*, e.g. monitoring wildlife habitats, disaster management, emergency response, ubiquitous computing environments, asset tracking, healthcare, and manufacturing process flow.

Most WSN applications encounter the following operational challenges (Rentala et al., 2002):

1. Un-wired for energy and communication, requiring maximum focus on energy efficiency.

2. Ad-hoc deployment requiring that the system should be able to cope with the resultant distribution and form connections between the nodes.
3. Dynamic environmental conditions requiring the system to be adaptive in nature to changing connectivity and node failure.
4. Unattended operation requiring configuration to be done automatically and repeatedly.

The second, third and fourth operational challenges are related and are due to the fact that the network topology is not fixed. A standard, easily reproducible method of designing a WSN is not always feasible, as resource constraints often mean each application is designed to maximise performance gains.

1.2.1 Application design space and design challenges

To obtain a generic solution to WSN applications that may be most appropriate at the time of implementation, certain design space criteria have been proposed. The main criteria to consider when designing a WSN for a specific application are as described by (Culler et al., 2004; Rentala et al., 2002; Romer & Mattern, 2004; Krishnamachari, 2005; Akyildiz et al., 2002; Pottie & Kaiser, 2000) below and summarised in Figure 1.4.

1. *Lifetime*: a WSN must operate for long periods of time, but a typical sensor node has limited energy (battery). This constraint influences the required degree of energy efficiency and robustness required of sensor nodes. In the quest to reduce energy consumption, most components, including the radio in a sensor node, are switched off at periodic intervals. The death of a node due to power failure can cause significant topological changes and may require re-routing of packets and reorganisation of the network.
2. *Deployment*: affects properties such as expected node density, node locations as well as regular patterns in node locations, and the expected degree of network dynamics. Sensors can be manually placed and data routed through pre-determined paths, or randomly scattered resulting in an ad-hoc routing structure.
3. *Mobility*: may apply to all or only a subset of nodes in a network. The type of mobility (active or passive), the degree (duration) of mobility and node speed, influence the network protocols and algorithms used.

4. *Quality of service*: may include real-time constraints on reporting of an event (responsiveness). To extend network lifetime, nodes may switch between sleep and wake-up modes, which may negatively affect the responsiveness of the sensor nodes to an event.
5. *Cost*: must be low in view of large number of sensors deployed in an application. There is a correlation between cost per node and resources available to a node. Need to design synergistic protocols that share the nodes' storage, computation and communication resources to optimise performance of WSN. Also, node deployment and maintenance must remain inexpensive.
6. *Size*: varies according to application and whether it is intended not to be easily visible.
7. *Resources*: limited by size and cost constraints. Size and cost affect available power, processing ability, storage space and communication range.
8. *Energy*: power can be stored via a battery (non-renewable energy source), or scavenged from the environment, e.g. by solar cells (renewable energy source).
9. *Heterogeneity*: nodes deployed within a WSN may differ from one another according to application requirements. Some nodes may have a global positioning system (GPS) for location determination, or more computational power etc., which affects the complexity of computer algorithms that can be executed on a node. The number of nodes that differ from one another in a WSN directly influences the management of the WSN and may result in a two- or more tiered, cluster-based network architecture.
10. *Transmission media (communication modality)*: the different types of wireless communication mechanisms include among others infra-red, sound (underwater), radio, laser or other types of optical media. The design of medium access and communication protocols is dependent on the communication modality used.
11. *Infrastructure*: whether nodes communicate directly with one another (ad hoc) or with base station devices (infrastructure). Hybrid mix of infrastructure and ad hoc communication may also be used.
12. *Network topology*: it is impractical to configure each node in large WSNs manually. Nodes in a WSN must be able to configure their own network topology; localise, synchronise and calibrate themselves, coordinate inter-node communication and determine other important operating parameters as an ensemble network of nodes. The diameter of the network (i.e. the maximum number of hops between any two nodes in

the network) affects network characteristics such as latency, robustness, capacity and complexity of data routing and processing.

13. *Coverage*: this is the degree of coverage by sensor nodes in an application area. Network coverage can be sparse, where only areas of interest are covered by sensor nodes or dense where the area is (almost) completely covered by sensors, or redundant, where multiple sensors cover the same location. The degree of coverage is determined by the required observation accuracy, redundancy and robustness of the system.
14. *Connectivity*: sensor nodes are closely coupled to a changing physical environment and the network connections are determined by the sensors' location and range. The nodes forming the network will experience wide variations in connectivity and will be subject to potentially harsh environmental conditions. Networks can be always connected or intermittent if occasionally partitioned or sporadic where the nodes are isolated most of the time. Network connectivity has an influence on data gathering and the type of communication protocols used.
15. *Network size*: networks must be scalable from a few nodes to tens, or hundreds, or thousands of sensor nodes. Network size is influenced by network connectivity, throughput and coverage requirements and the network algorithms and protocols used will have to be distributed.
16. *Fault tolerance (robustness)*: the network remains functionally operational and survives if certain nodes or sets of nodes fail.
17. *Security*: the wireless medium creates additional security risks such as preventing eavesdropping and ensuring message integrity, as well as being unobtrusive in the application area. Security influences network coverage and connectivity.
18. *Self-optimisation and adaptation*: uncertainty about initial operating conditions, as well as a changing operating environment, implies that a WSN is not operating efficiently at start-up, and needs to monitor sensor and network measurements continuously to improve performance.

Analysis of these factors and their inter-relatedness indicate that the main goals of WSN application design is prolonging network lifetime and preventing connectivity degradation through aggressive energy management. There is a trade-off between a node's cost, energy, size and node range.

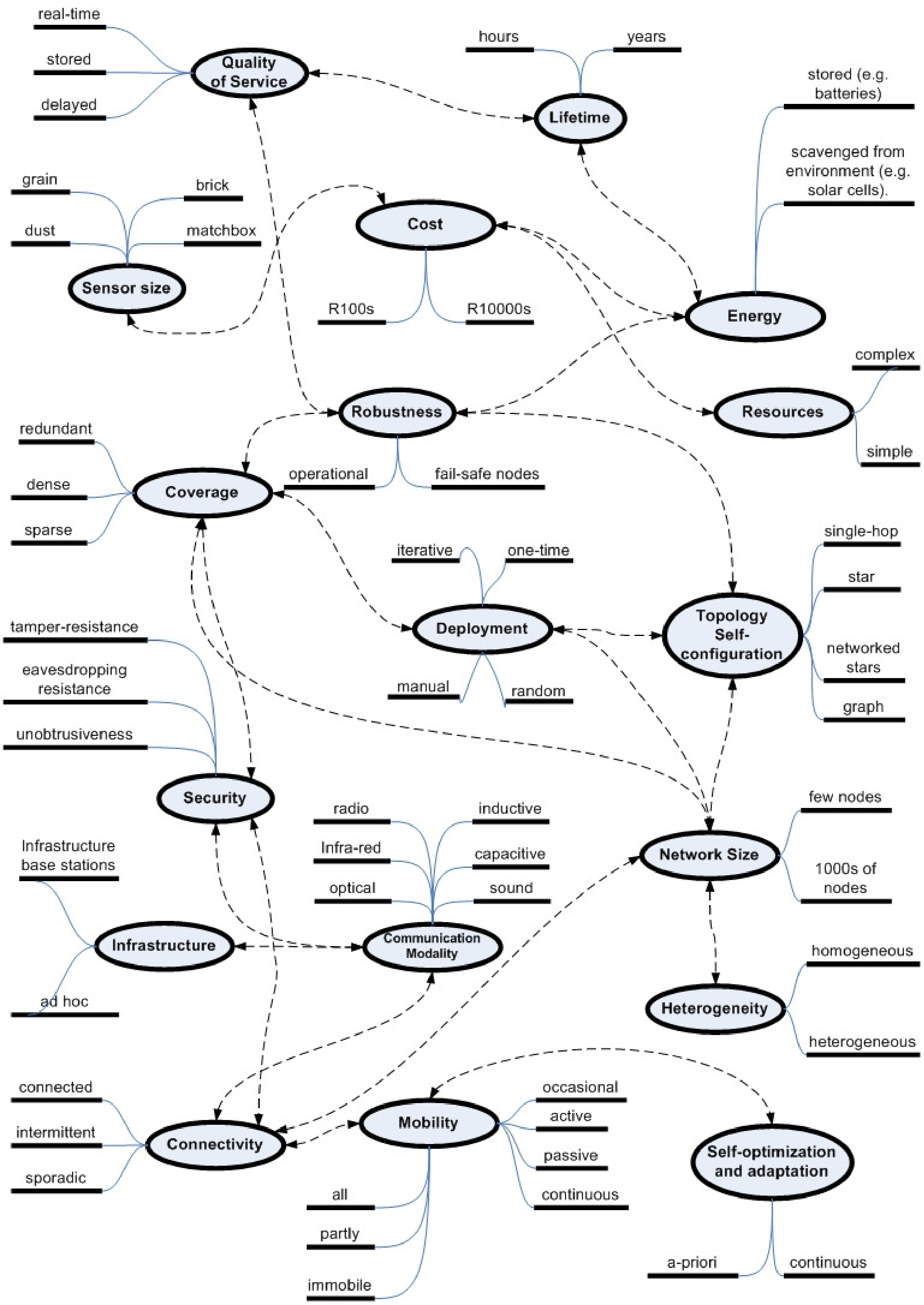

Figure 1.4: Factors to consider when designing WSN applications

1.2.2 Examples of WSN applications

Initial sensor networks were used in military applications such as large-scale acoustic surveillance systems for ocean surveillance to small networks of unattended ground sensors for ground target detection. The decline in the cost of sensors and communication networks has resulted in more commercial applications, such as infrastructure security, environment and habitat monitoring, industrial sensing and vehicle traffic monitoring and control (Chong & Kumar, 2003).

WSNs have been used to monitor the breeding behaviour of a colony of small birds and the social interaction behaviour of wild zebras, as well as for volcanic monitoring in Ecuador, agricultural monitoring of soil, humidity and temperature, power consumption monitoring of large office buildings, vital sign monitoring of patients in a hospital environment and in military applications such as sniper location and tracking of military vehicles (Romer & Mattern, 2004; Yick et al., 2008). From these diverse applications, it can be observed that WSNs can provide useful functionality to enhance quality of life and improve sustainable use of resources.

1.3 RELEVANCE OF WIRELESS SENSOR NETWORKS

A group of internetworked sensors linked by a wireless transmission medium are not essential to the proper functioning of data communication or computer networking. Information can be gathered from individual sensors and transmitted over a wired transmission medium to a data centre to be aggregated and analysed. To understand the significant benefits WSNs provide in the gathering, analysing and transporting of data it helps to consider the two main determinants that led to the creation of a WSN.

1.3.1 Multiple connected sensors versus a large single sensor

For some applications the gathering of information about the surrounding environment can be obtained from a set of distributed sensors or a single large sensor. A distributed set of sensor nodes generate a networking cost not found within a single-sensor environment. There is a trade-off between using a single large, resource-rich, long-range sensor and multiple sensors in a distributed network. Using a resource-rich sensor with long range to cover the application area is not always an optimal solution because of the following physical effects (Pottie & Kaiser, 2000; Lewis, 2004):

1. ***Signal propagation laws***: In free space, electromagnetic waves decay in intensity as the square of the distance, and they are subject to absorption, scattering or dispersion effects in other media that can cause even steeper declines in intensity with distance, as well the possibility of being blocked by an obstruction. For a large single node, the distance from the target may be large. Therefore, a set of networked nodes distributed around an application area can provide a larger signal-to-noise-ratio (SNR) than a single, large, powerful node.
2. ***Detection and estimation theory fundamentals***: There are fundamental limits of estimation accuracy. To compute a good estimate of any particular feature, either a long set of independent observations or high SNR is required.
3. ***Communication constraints:*** Propagation is influenced by reflections off multiple objects and antenna elevation. For low-lying antennas, intensity drops as the fourth power of distance due to partial cancellation by a ground-reflected ray. The combination of Maxwell's Laws (governing propagation of electromagnetic radiation) and Shannon's capacity theorem (establishing fundamental relationships among bandwidth, SNR and bit rate) together dictate that there is a limit on how many bits can be conveyed reliably, given power and bandwidth restrictions. Multipath propagation losses can be improved by employing some combination of frequency-hopped spread spectrum, interleaving and channel coding. By increasing node density, clear line-of-sight paths to at least a few other nodes are created, which reduces losses.
4. ***Energy consumption in integrated circuits:*** There are limits on the power required to transmit reliably over any given distance. The power-amplifier stage typically burns at least four times the radiated energy, and so, in time, dominates the energy cost of radios.
5. ***Transmission power***: The required transmission power increases as the square of the distance between source and destination. Therefore, multiple short message transmission hops require less power than one long hop. In fact, if the distance between source and destination is defined as R, then the power required for single-hop transmission is proportional to R^2. If nodes between source and destination are taken advantage of to transmit in short hops instead, the power required by each node is

proportional to $\frac{R^2}{n^2}$. This is a strong argument in favour of distributed networks with multiple nodes

There are additional challenges for single nodes, such as inadequate coverage, possible holes, lower sensing performance, lack of flexibility in overcoming environmental effects, lower fault tolerance and lack of infrastructure to replenish energy (Rentala et al., 2002).

1.3.2 Wired versus wireless

A WSN consists of resource-constrained sensor nodes with a non-renewable power supply and short radio propagation distances. As the term "*wireless*" implies, there is no fixed physical connection between sensors to provide continuous energy and an enclosed communication medium. This creates the following problems:

1. ***Superfluous message reception:*** all transmitted messages will be detected by any listening device within receiving range, which then has to decide whether to accept, forward or ignore the message. This signal transmission and reception has a power cost.
2. ***Ad hoc deployment***: WSN applications do not have a pre-planned network topology and nodes are only aware of their immediate neighbours. There are no pre-defined routing tables specifying the optimum shortest path to the sink.
3. ***Finite energy***: the sensor has a finite amount of energy, which once depleted, disables the sensor and hence reduces network lifetime. This need to conserve energy, because of the lack of a continuous energy source, has an impact on communication between nodes. It costs energy to transmit and receive messages, and the wireless medium means that all nodes within range receive a message. Hence, a significant proportion of current research on WSNs is focused on energy preservation, by reducing the number of messages transmitted within a WSN, to ensure longer node and hence network lifetime.

If wireless networks pose so many problems, then why are researchers developing applications that communicate over a wireless medium? The primary constraint is cost. It costs money (in terms of the actual wires and labour) to install wired networks. The ease of deploying wireless networks reduces the cost of the application significantly. Also, wireless applications provide greater flexibility in data gathering, as there is no fixed upfront cost. This means that WSNs can rapidly adapt to changing environmental conditions. Sometimes, the type of application specification means that it is not possible to use wired networks, for example monitoring mobile entities such as livestock. In these instances, the only possible solution is to use wireless sensor nodes to track and observe mobile entities.

Where infrastructure exists, it makes sense for sensor networks to be integrated into the wired network, thus eliminating the energy and communication constraints of a wireless application. However, as the need for data about environments increases, sensor networks will be deployed in areas where no wired infrastructure to piggy-back off exists. In addition, to monitor environmentally sensitive locations, it may not be feasible to install wired systems, which requires digging and/or the installation of pipes. The ease of deployment, rapid installation and low impact on the surrounding environment means that WSNs will become the preferred network type of choice in future applications requiring data collection and monitoring of environments.

In summary, wireless communication requires more energy to communicate over increasing distances and the wireless signal strength can be depleted by environmental obstructions and interference. Therefore, there are many instances where a distributed set of communicating wireless sensor nodes with short ranges is better able to detect events reliably than a single large, resource-rich, long-range sensor, whatever the networking cost. The requirements of the physical environment create the need for WSNs.

1.4 SCOPE

The scope of this research thesis is to improve message routing between sensors and sinks in order to increase the network lifetime, and to coordinate which mobile sinks (actors) will respond to an event in real-time. For routing of messages, sensor nodes are assumed to be stationary and the sensor node locations do not change after deployment. Sink nodes can be stationary or mobile.

Areas of related research such as node deployment, network topology and media access protocols are not covered in depth. It is assumed that adequate coverage of the application area has been achieved and that all nodes spaced within the specified range of one another are able to communicate with neighbouring nodes. Security concerns such as eavesdropping from the wireless medium are not addressed. The primary focus is on routing at the network layer. Related issues such as flow control and quality of service are not considered as influencing the energy usage effect of routing messages across the network.

1.5 PROBLEM STATEMENT

One of the primary problems faced in any deployment of WSNs is the limited power supply of a sensor node, which in turn places energy restrictions on the network's routing and localisation protocols. For short-range communication, radios consume essentially the same power whether transmitting or receiving. WSNs are designed so the radio is off as much of the time as possible and otherwise transmits only at the minimum required level. This means that in most WSNs, the nodes operate with low duty cycles and communicate sporadically, over short distances with low data rates.

The main energy-consuming activities (TRADS) in a WSN are depicted in Figure 1.5 and are listed below (Korpeoglu, 2007):

1. ***T***ransmission of messages
2. ***R***eceiving messages
3. ***A***wake time, i.e. the time period a node is listening on the wireless medium.
4. ***D***istance between nodes, as the energy expenditure is proportional to the square of the distance a signal is transmitted. Can also relate to the total distance a message has to travel between source and destination node.
5. ***S***ize of message: larger message sizes imply more energy spent in transmitting and receiving the message.

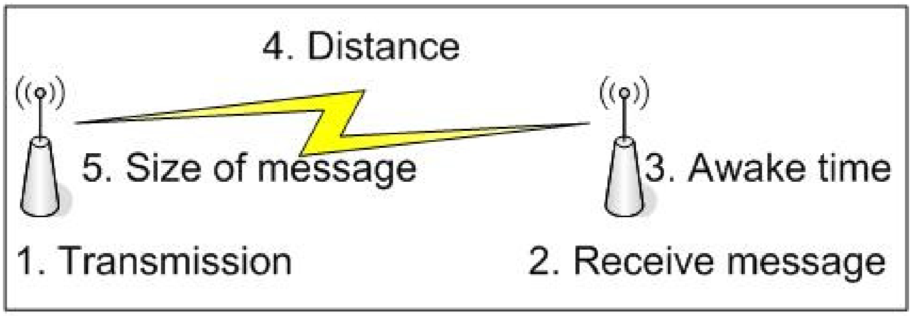

Figure 1.5: Main energy consuming activities in a WSN (TRADS)

As sensor nodes are only aware of their immediate neighbours and nodes in a WSN have no prior knowledge of the network topology, it is difficult to determine the optimum path to route a message to the sink. The determination of a message route is important in WSNs because of the limited energy supply of nodes which places a limit on the number of messages sensors can send and receive. In addition the wireless nature of the communication medium means that even nodes that are not the intended recipient of a message will detect the communication. As receiving a message also consumes significant energy, communication within a WSN needs to be optimised to restrict the number of messages sent within the network.

An area of active research for a number of years has been how to notify the central sink (or monitoring hub) about an event in real-time by using the minimum amount of power of sensor nodes. Initial message routing protocols assumed the sink or destination node was in a fixed location, and that network nodes had no or limited knowledge of the network topology (Akkaya and Younis, 2003). Numerous routing solutions have been suggested, such as a hierarchical structure where nodes are allocated to clusters, and a node sends messages only to its specific cluster head. Other solutions advocate a flatter structure and depend on geographic information or techniques such as flooding or gossiping to route a message to the sink. These methods may increase the number of messages transmitted and received in a WSN, thus increasing energy consumption of numerous nodes in the message path, which reduces these nodes' lifetime and hence reduces the network lifetime.

In this thesis, a solution to these problems is proposed based on placing multiple sinks at pre-determined locations within the application area; *so that each node is at a maximum* *number of specified hops from a sink*. The idea behind the specific placement of sinks is to emulate the long edge in a small world network. The creation of this long edge should improve message throughput, the time it takes a message to reach its destination and lower the overall node and network energy used when routing an event message to a sink. On network initialisation, each sink sends an initialisation message (IM) to all nodes within communication range. This message is re-transmitted by the receiving node to the node's immediate neighbours. This process continues for the specified number of hops and ensures that all nodes obtain at least one route path to the sink. An investigation is conducted into how the use of multiple sinks, small world network theory and certain decision theory concepts that deal with uncertainty, such as info-gap decision theory (IGDT), can be used to reduce the number of messages transmitted within a network, and allow an event to be responded to in real-time.

1.6 RESEARCH OBJECTIVE

The objective is to increase node longevity by limiting the number of messages transmitted within the application area. To achieve this, a novel, energy-efficient method of routing messages to sink or mobile actor nodes is proposed that limits the number of messages transmitted within the application area. The following key aspects of the idea were investigated:

1. Analyse the effect of only allowing nodes on the perimeter range of a transmitting node to re-transmit message data on reducing the number of messages re-transmitted as well as obtaining more accurate node location estimates.
2. Model uncertainty about an actor's energy and location as an information gap, and calculate the actor(s) set that should respond to the event, in order to determine if it is possible to select a few optimum actors that will adequately respond to an event, even when there is uncertainty about the other actors' energy and location.
3. Model a WSN as a small world network, by optimally placing sink nodes a specified number of hops from a sensor node, so as to determine if it is possible to place a number of sink nodes optimally in a WSN area, so that a message from any node within the application area will reach a sink node within a small predetermined number of hops.

4. Compare a WSN modelled as a small world network, against message routing using gossiping and flooding to determine if the small world model has significant advantages.
5. Determine the optimum route a mobile sink can travel that will reduce the number of messages transmitted within a network, allow equitable usage of all nodes to transfer an event message and still allow an event to be reported in real-time.

1.7 RESEARCH CONTRIBUTION

There are three contributions from this research, namely:

1. A WSN is modelled as a small world network by placing sink nodes at specific points within the application area. The sink nodes create long edges within the network, resulting in the total number of messages sent and received being significantly less. It is shown in chapter 3 of this thesis that modelling a WSN as a small world network is possible as long as the number of sinks are placed a specified distance from each other and irrespective of whether the sensor nodes are randomly scattered or carefully placed within the application area. The effect of modelling a WSN as a small world network on total number of messages sent and received within an application area is analysed in chapter 4. A comparison of the small world routing model and routing using flooding and gossiping indicates that the small world routing model reduces the total number of messages transmitted within a network when routing a message from a sensor node to a sink. The effect of using an initialisation message in a small world model to determine a route path versus routing using flooding at the individual node level in terms of the total number of messages sent and received by individual nodes is discussed and analysed in chapter 5. The results of the analysis in chapter 5 indicate that using an initialisation message does not negatively impact the energy resources of any node. The results of chapters 3, 4 and 5 indicate that routing using the small world model and initialisation message results in increased node longevity and hence increased WSN lifetime.
2. Actor-actor coordination needs to be able to choose an actor(s) to respond to an event as quickly as possible, even when there are uncertainties about an actor(s)'s resources. IGDT can be used where robust solutions are required in an uncertain environment. Uncertainty about an actor's energy and location is modelled as an information gap,

and the optimum set of actor(s) that should respond to the event is calculated. In chapter 7, an IGDT model is used to coordinate which actor(s) should respond to an event in real-time, while ensuring that the number of messages transmitted in the network to reach a decision is kept to the bare minimum required to inform the relevant actor(s) of an event and the decision of which actor should respond. An analysis of the results from simulations in chapter 7 show that IGDT can be used as an effective method to select a few optimum actors, which will adequately respond to en event, even when there is uncertainty about other actors' energy availability and location. The robustness of the decision ensures that even if the optimal set of actors is not chosen to respond to an event, then those actor(s) chosen have sufficient resources to respond to the event.

3. The calculation of an optimum path for a mobile sink or actor to follow in an application area is described in chapter 8. The use of a mobile sink or actor ensures that those nodes that are located close to a static sink are not unduly burdened with the responsibility of re-transmitting messages from other nodes to the sink. An analysis of the number of intermediate re-transmissions of messages required when routing a message to a mobile sink or actor is discussed in chapter 8.

1.8 OUTLINE OF THE THESIS

A brief overview of the work in each chapter is given next.

Chapter 2 provides a brief summary of aspects of WSN research activity, such as routing, localisation, mobile elements and wireless sensor actor networks that are relevant to this thesis.

Chapter 3 explains how small world theoretical concepts are applied to model a WSN as a small world network.

In Chapter 4, an algorithm that uses the small world model to create optimum routing tables to a node's nearest sink is discussed. A comparison and analysis of small world routing (SWR) against gossiping and flooding and the effect on node lifetime is discussed.

Chapter 5 analyses the effect of the routing algorithm at individual node level. The number of messages received per individual node at a given hop count is analysed to determine if there is an optimum hop count to place sinks and reduce the number of messages sent and received at an individual node.

Chapter 6 examines whether the use of multiple sinks and the idea from the routing algorithm whereby only nodes on the perimeter range of a node re-transmit messages can be used to determine the location of a sensor node effectively.

Chapter 7 uses a decision theory algorithm to coordinate which actor or set of actors should respond to an event without flooding the network with many messages.

In Chapter 8, a path for mobile sinks or actors is proposed to minimise the number of messages sent within the WSN application area.

1.9 FLOW CHART: THESIS' THEMES AND PUBLICATIONS

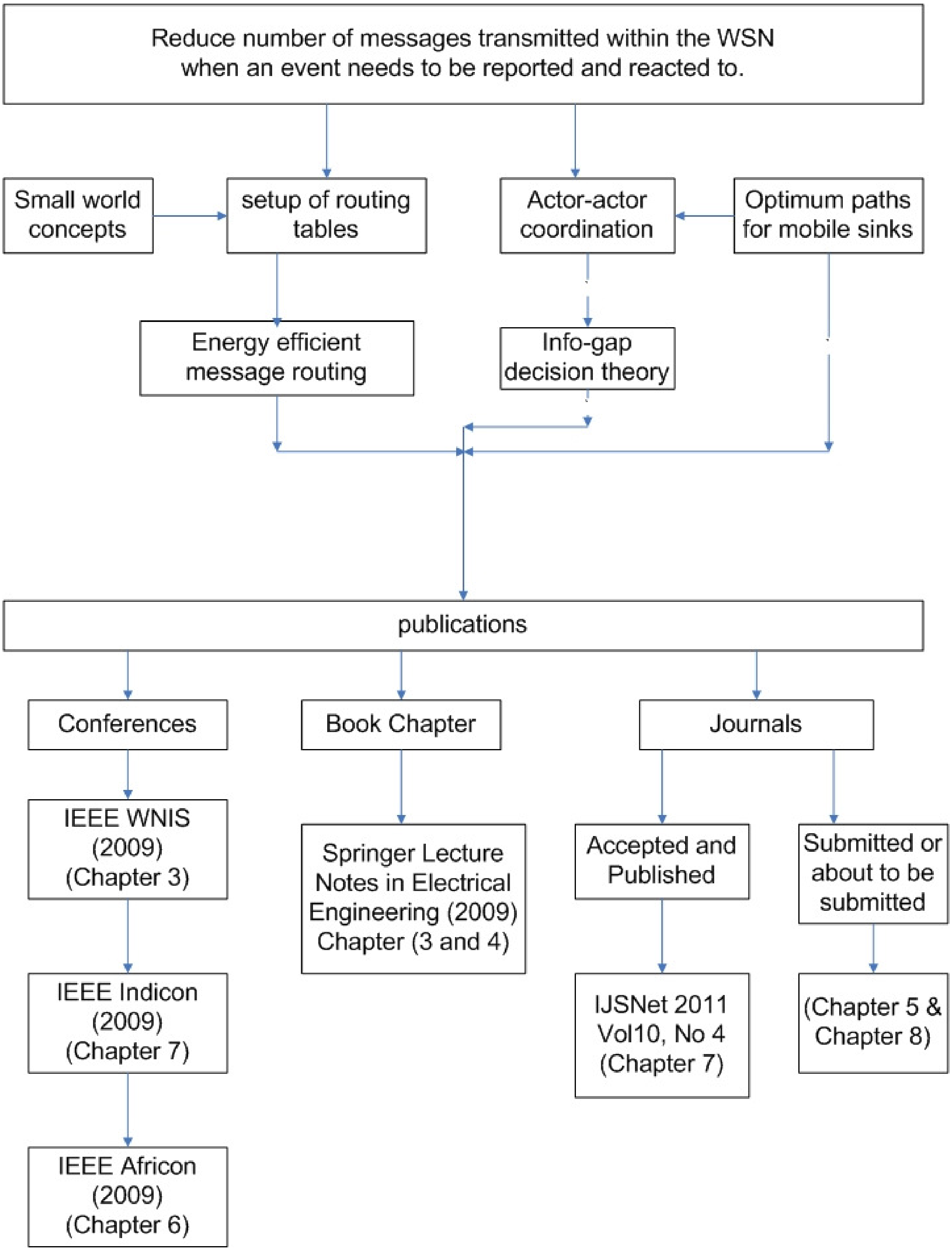

Figure 1.6: Thesis flow chart

CHAPTER 2

OVERVIEW OF WIRELESS SENSOR NETWORKS

This chapter provides an overview of WSN routing techniques, localisation schemes, mobile elements, and currently available actor coordination strategies in wireless sensor and actor networks (WSANs). The literature review reflects the most important themes applicable to this research thesis, and briefly describes the most important characteristics of each one of them.

2.1 INTRODUCTION

In wired networks two main algorithms are used for routing messages, namely link-state and distance vector algorithms (Abolhasan et al., 2004). In link-state routing, each node periodically broadcasts the link-state costs of its neighbouring nodes to all other nodes using a flooding strategy. Upon receipt of one of these update packets; a node uses the information in a shortest path to calculate the next hop node for each destination. In distance-vector routing, each node keeps the distance for every destination. This allows each node to select the shortest path to each destination. The distance-vector information is updated at each node by a periodical dissemination of the current estimate of the shortest distance to every node. The traditional link-state and distance-vector algorithm are not suitable for WSN applications because the periodic route updates deplete the power supply of the nodes rapidly.

2.2 ROUTING IN WSNS

Routing in WSNs is concerned with finding the shortest path between the source node and the destination sink while sending the minimum number of messages. Two classical mechanisms for relaying data within a network without requiring continual knowledge of network topology and routing algorithms are flooding and gossiping (Kazem Sohraby, 2007).

2.2.1 Classical routing techniques

2.2.1.1 Flooding

Flooding uses a reactive approach whereby each node receiving a data or control packet re-broadcasts the message received to all its neighbours. After transmission, a packet follows all possible paths. This process continues recursively, until the message reaches its intended destination. To prevent a packet from circulating indefinitely in the network, either a hop count field or a time-to-live field is included in the packet. As the packet travels across the network, the hop count is decremented by one for each hop that it traverses. When the hop count reaches zero, the packet is simply discarded. Similarly, the time-to-live field, records the number of time units that a packet is allowed to live within the network. At the expiration of this time, the packet is no longer forwarded.

Despite the simplicity of its forwarding rule and the relatively low-cost maintenance that it requires, flooding suffers several deficiencies when used in WSNs including:

1. ***traffic implosion***, whereby two or more nodes sensing the same area send similar messages to the same neighbour node. This duplication of messages consumes a large amount of energy as sensor nodes use almost the same amount of energy to receive messages as the nodes use to transmit, because of the short transmission distances used in WSNs;
2. ***overlap problem***, which occurs when two nodes covering the same region send packets containing similar information to the same node; and
3. ***resource blindness*** caused by not taking into consideration the energy constraints of the sensor nodes when forwarding messages. As such, the node's energy may deplete rapidly, reducing considerably the lifetime of the network.

2.2.1.2 Gossiping

Gossiping also uses a simple forwarding rule and does not require costly topology maintenance or complex route discovery algorithms. Instead of sending the packet to all neighbours, in gossiping a receiving node randomly chooses one of its neighbours to forward the received message to. This process continues iteratively until the message reaches its destination or the maximum number of hops for the message is exceeded.

Gossiping avoids the implosion problem by limiting the number of packets that each node sends to its neighbour to one copy.

The random selection of the node to route a message can cause propagation delays (Akkaya & Younis, 2003) or result in the message becoming stuck in a circular route without ever reaching its intended destination.

2.2.2 Current routing techniques

Current routing techniques for WSNs are dependent on the underlying network topology. There are various categories of WSN routing protocols, including cluster-based, data-centric, hierarchical, location-based, quality of service, network flow or data-aggregation protocols (Akkaya & Younis, 2003). In the following sections, routing protocols in WSNs have been broadly classified into four categories, namely flat, hierarchical, geographic (location), or network-structure based protocols. Figure 2.1 briefly summarises the key routing categories and provides examples of their various implementations (Al-Karaki & Kamal, 2004; Akkaya & Younis, 2003; Umar et al., 2007).

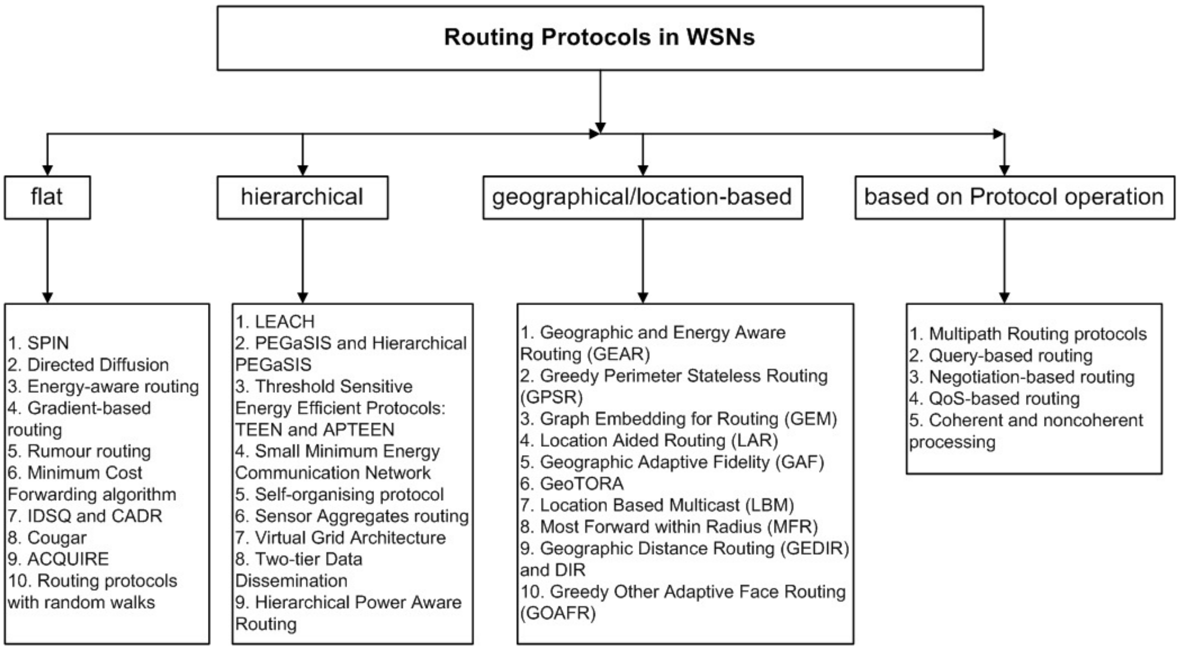

Figure 2.1: Current routing categories

Niezen et. al compare flooding, multi-hop routing, *L*ow *E*nergy *A*daptive *C*lustering *H*ierarchy (LEACH) and ad hoc on-demand distance vector (AODV) (Niezen et al., 2007). In their results, flooding proves to be worse than multi-hop routing and the LEACH protocol in terms of time for node(s) to fail, while AODV sends even more messages in the network than the flooding protocol; it was not initially designed for a WSN low-power environment.

2.2.2.1 Flat or data-centric routing protocols

All nodes are equal and collaborate with one another to perform a sensing task. The application area is densely populated with nodes and it is not practically viable to assign a unique global identifier to each node (such as an IP-type address). The lack of an identifier makes it difficult to distinguish which node or sets of nodes in a specific locality to query, or which nodes can route a message to a specific destination node. This lack of knowledge of the correct position of a set of nodes results in many unnecessary messages being transmitted, which reduces node lifetime within the WSN. To reduce the number of redundant messages, data-centric routing has been proposed. Attributes are assigned to specify the properties of data. A query is sent based on specific data attributes and only nodes with information that complies with the requested data attributes respond. Nodes can also follow an event-driven model and only send data when an event occurs.

2.2.2.2 Hierarchical (clustered) routing protocols

As the application area, network size and node density increase, the possibility of the sink (base station) becoming overloaded increases. As the number of messages within the network increases, a single sink may be unable to handle all communication effectively in a reasonable time-frame. To enable more effective communication, it has been proposed that the WSN be divided into clusters, with each cluster assuming similar roles to the single sink, to increase the efficiency and scalability of the network. Nodes send event data and respond to queries from a designated cluster, creating a hierarchical model for data routing. There can be a single layer of clusters or the clusters can be multi-tiered. Some of the advantages of clustering include (Abbasi and Younis, 2007):

1. Localises a route within a cluster and reduces the size of the route table.

2. Conserves communication bandwidth by preventing sensor nodes from exchanging messages with nodes outside their cluster and limiting the scope of inter-cluster interactions between cluster heads.
3. Reduces maintenance of network topology as sensors are only concerned with changes within their cluster and their cluster head.
4. Effects aggregation of data collected by sensors in cluster.
5. Ensures increased node longevity by allowing nodes to switch to low-power sleep mode most of the time.

2.2.2.3 Location or geographical routing protocols

Sensors can be randomly deployed within an application area (e.g. dropped from an aircraft in hostile military situations or due to natural disasters restricting access to an area), or manually placed at specific points within an application area (e.g. in an indoor factory or an outdoor field for agricultural monitoring). Many network functions such as geographic routing, coverage and tracking and location-dependent computing require prior knowledge of the position of nodes in a WSN. In geographic routing, a data message is routed to a geographic region instead of a destination node specified by an address (as in IP networks) (Umar et al., 2007). Routing protocols can use the location of a node to determine which nodes should forward a message.

2.3 ROUTING DESIGN CHALLENGES

In the Chapter 1 section 1.2.1, the main factors to consider when designing a WSN for a specific application are discussed. The focus is now placed on the specific design aspects of energy-efficient routing protocols in WSNs. There are many overlaps between design features for WSN applications and design issues for routing protocols in WSNs, because in both, efficient utilisation of the limited energy supply is a primary requirement. One of the main design goals of a WSN routing protocol is to carry out data communication while trying to prevent connectivity degradation by employing aggressive energy management techniques (Al-Karaki & Kamal, 2004). The following are the main factors to consider when designing a routing protocol for a WSN (Al-Karaki & Kamal, 2004; Akkaya & Younis, 2003; Umar et al., 2007; Korpeoglu, 2007).

1. ***Node deployment***: Sensors can be manually placed and data routed through pre-determined paths, or randomly scattered in a self-organising system, resulting in an ad hoc routing infrastructure. In randomly deployed, self-organising systems, the distribution of nodes is not uniform and the position of the sink or cluster head is crucial in terms of energy efficiency and performance.
2. ***Energy consumption without losing accuracy (node lifetime)***: Most WSNs are multi-hop networks because it uses more energy to transmit data over larger distances (approximately proportional to the distance squared) than using a single hop to the sink. The death of a node due to power failure can cause significant topological changes and may require re-routing of packets and reorganisation of the network. Therefore, as most wireless sensors are dependent on batteries, energy-saving forms of computation and communication are necessary. The use of multi-hop networks increases the complexity of topology management and medium access control protocols.
3. ***Data-reporting method***: The routing protocol is highly influenced by the data-reporting method in terms of energy consumption and route calculations. The three types of data-reporting methods are:
    a. **time-driven**: data about the surrounding environment sent to the sink at periodic time intervals;
    b. **query-driven**: when a node receives a message requesting information about the immediate environment it responds with a message to the sink containing the relevant data; and
    c. **event-driven**: changes in the surrounding environment exceed pre-defined limits, resulting in the actuator triggering an event. The sensor transmits a message to the sink to notify the sink of the triggered alarm.

    If the WSN application requires continuous monitoring and reporting, then a larger amount of traffic will be generated. Data-aggregation techniques would have to be taken into consideration in the design of the routing protocol. If the application only requires messages to be sent once a specific critical value has been breached, then very little data will be transmitted within the network.
4. **Node/link heterogeneity**: If the nodes in a WSN are not homogeneous, then some nodes may have more energy resources than others and some nodes may monitor

different aspects of the surrounding environment, thus using more or less energy than other nodes in a WSN. Generally the sink node or cluster heads (in a hierarchical topology) may have more energy, memory and processing resources than other nodes, as they will receive more messages and may be required to transmit these messages to the external human user. Designing a routing protocol has to take cognisance of the different resources available to nodes in a WSN and the different types of data-reporting methods that will be used.

5. **Destination specification**: the intended destination of a message can be based on the numerical addresses (or identifiers) of nodes, the geographic location of nodes or the type of data being transmitted. The routing path can be a destination-initiated or source-initiated protocol. Generally destination-initiated routing protocols, where the sink initiates path setup, are proactive in that the routing path is set up before there is a demand for routing traffic, whereas a source-initiated routing path is reactive and the routing protocol is activated when a data message needs to be sent and distributed to other nodes.
6. **Fault tolerance**: failure of a few nodes (due to energy depletion, physical damage or environmental interference), should not affect the overall functionality of the WSN. However, if many nodes fail, medium access control (MAC) and routing protocols must accommodate the formation of new links and routes to the sink and should provide multiple levels of redundancy.
7. **Scalability, connectivity, coverage**: a WSN may contain tens, hundreds or thousands of sensor nodes. This initial high density of sensor nodes should ensure that all nodes are highly connected and there is sufficient coverage of the application area. Any routing scheme must be able to work with small as well as large numbers of nodes, and should be able to respond to events within the application area. As battery life ends and nodes fail, the routing protocols must adapt to changing network topology and reduced network size.
8. **Network dynamics**: Routing requirements are different for fixed sensor and sink nodes compared to mobile sinks and/or sensor nodes. Routing messages from or to moving nodes is more challenging, since the network topology changes and routes to the destination change. Keeping track of dynamic events is also more difficult. The network can operate in a reactive mode when monitoring static events. For dynamic

events, more traffic is generated to be routed to the sink, as the sink has to be periodically notified of the current location of the event.

9. **Transmission media**: As the communication medium is wireless, new approaches to MAC design and routing protocols have to be considered to conserve energy.
10. **Data aggregation**: Nodes located relatively close to one another will have similar types of data to report to the sink. The analogous data from various closely located nodes can be aggregated before a single message is transmitted to the sink, in order to reduce the number of messages transmitted within the WSN application area. The data from multiple sources is combined according to a specific aggregation function to achieve energy efficiency and data transfer optimisation in a number of routing protocols. Data aggregation increases the overall complexity of the WSN application and negates the use of many security techniques for WSN applications.
11. **Quality of service**: Some WSN applications may have a bounded time limit on when a message must reach its destination. Most WSN applications consider conservation of energy more important than message latency or the quality of data sent and energy-aware routing protocols are required to capture this requirement.

2.4 LOCALISATION

The usefulness of information received from sensor nodes is directly related to being able to predict the sensor's location accurately in relation to observed phenomena or triggered events. Therefore, all wireless sensor nodes in a network need to provide some form of data (in addition to the sensing information), that indicates the node's position. The process of determining the position of nodes in a WSN is called localisation (Aspnes, Goldenberg and Yang, 2004).The ability to determine the location of nodes in a WSN accurately is important for both network operation and data interpretation (Lederer et al., May 2008). Many network functions, such as geographic routing, coverage and tracking and location-dependent computing, require prior knowledge of the position of nodes in a WSN. Some examples of WSNs that require data about a node's (or triggered events') location include applications such as surveillance and tracking moving targets or hazardous material, as well as fire monitoring and certain military applications.

Power, cost and density constraints limit the number of nodes that can be equipped with a location-finding system. Therefore, it is not feasible for all sensor nodes to be equipped with a GPS (Savvides et al., 2001) or similar types of location-determining equipment. Also, network localisation is dependent on the application (indoor or outdoor, mobile or static), the range of nodes, the deployment environment (for example, wooded or rocky areas may limit the node range), signal interference and the density of sensors over the application area.

Savvides et al. describe six categories of localisation systems, which can be divided into active and passive localisation (Savvides et al., 2004). In active localisation, sensor nodes actively emit signals into the environment in order to measure the target range. In passive localisation, range measurements are calculated from monitoring of received signals. Techniques such as radio received signal strength (energy), time difference of arrival and angle of arrival are measured for each received packet and used to estimate a single node's location with respect to a known node (Farahani, 2008). Many WSN localisation algorithms are based on measurements between neighbouring sensors for location estimation. Figure 2.2 briefly summarises the main categories.

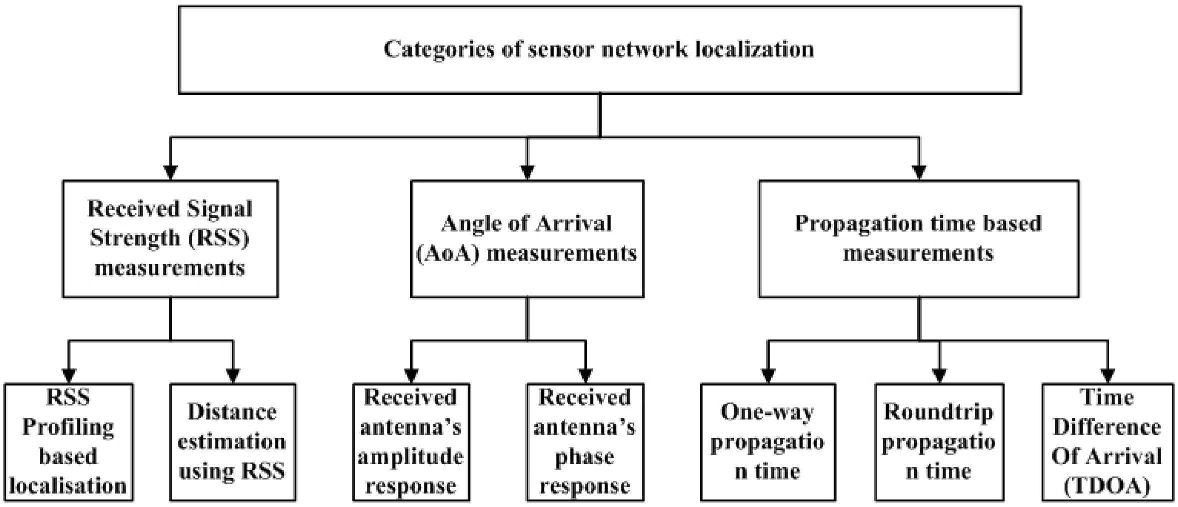

Figure 2.2: Categories of localisation measurement techniques in WSNs

To determine the location of all nodes in a WSN, various network localisation methods are used, e.g. in the work of (Krishnamachari, 2005; Bulusu et al., 2001; Savvides et al., 2001; Lederer et al., May 2008; Biswas et al., 2006; Pan et al., 2006; Patwari et al., 2005):

- Constraint-based methods: use a set of constraints and reference nodes as inputs to a semi-definite programming function. Biswas et al. describe a set of semidefinite programming (SDP) algorithms to determine the location of nodes in a WSN. The primary disadvantage of this approach is that SDP algorithms do not scale to larger densities very well.
- RSS-based joint estimation or proximity-based localisation: uses a matrix of received signal strength to estimate a location set for all nodes.
- Multilateration and iterative multilateration: on network initialisation a small number of nodes know their location. The unknown nodes determine their distance from their neighbours, using a node location technique such as received signal strength or time of arrival to estimate the distance between an unknown node and three reference neighbour nodes to triangulate its position. This node then becomes a reference node and the process iterates until all node locations are known.
- Collaborative multilateration: the location of unknown nodes within a set of collaborative subgraphs of reference and unknown nodes is obtained from a constrained set of quadratic equations.
- Multi-hop distance estimation methods: estimate distance (in terms of hops) to reference nodes, and use triangulation to determine location.
- Cooperative localisation: sensor nodes cooperate in a peer-to-peer manner to form a map of the network. The nodes use statistical models to calculate localisation performance bounds on location estimation precision; based on time of arrival, angle-of-arrival and received-signal-strength measurements.
- Anchor-free localisation: none of the nodes knows its location and a relative coordinate system of the network geometry is calculated using global rotation and translation from local knowledge of network connectivity. Typical applications of anchor-free localisation are in remote areas or indoor/underwater environments in which GPS does not work or is too expensive.
- Clustered two-tier WSN: the WSN is divided into clusters. Within each cluster is an application node. The application nodes communicate with a base station. Pan et al. describe an algorithm to calculate the optimum location of a base station in a two-tier WSN.

The above approaches are constrained by the non-renewable power supplies of sensor nodes, so the nodes should not expend excess time and energy in receiving and transmitting location-based messages.

2.5 WIRELESS SENSOR ACTOR NETWORKS

In typical WSNs, after an event occurs (e.g. temperature change), the sensing nodes activated by the event need to coordinate the messages between the nodes to send a single aggregated data message to a sink node, which then transmits the data to a remote end user for evaluation and response. The real-time response of the WSN thus depends on the reaction of the human entity in question. To enable better response to events, mobile non-human devices called actors are placed in the application area to form a WSAN. The use of mobile actors within a WSN application enables rapid response to data received from sensor(s) (Yoneki & Bacon, September, 2005).

A WSAN is defined by Akyildiz and Kasimoglu as a group of sensors and actors linked by wireless medium to perform distributed sensing and acting tasks. In such a network, sensors gather information about the physical world, while actors take decisions and then perform appropriate actions upon the environment, which allows a user to sense and act effectively at a distance (Akyildiz and Kasimoglu, 2004). Compared to the resource-constrained sensor node, actors are resource-rich mobile nodes with better processing and communication capabilities. Because of the larger costs, actors are not as densely deployed within an application area as sensor nodes. The advantage of WSAN is that sensor-actor-actor coordination will achieve a faster response time than sensor-sink-human responses.

The key differences between a WSN and a WSAN are that a WSAN has the following unique characteristics (Akyildiz and Kasimoglu, 2004):

1. *Real-time requirement* where the application requires rapid response to received sensor data, for example, a fast response is necessary in a fire application, or in the detection and seizure of trespassers or other intruders in an area.
2. *Coordination* among actors and sensors to enable rapid response to triggered events is vital. Sensor-actor coordination provides the transmission of event features from

sensors to actors. After receiving event information, actors need to coordinate with one another in order to make decisions on the most appropriate way to perform the action.

When an event is detected by a group of sensors in a WSAN, the sensors reach consensus to send a single message to one or more actors. When an actor receives a message, it informs all other actors of the event. The actors need to coordinate a response and determine the actor(s) that will respond to the event. To provide effective sensing and actuating, a distributed local coordination mechanism is necessary among sensors and actors.

Akyildiz and Kasimoglu describe four types of scenarios for single-actor and multiple-actor responses, namely (Akyildiz and Kasimoglu, 2004):

1. Single-actor centralised decision (SACD): A single actor receives data about an event and makes a decision on how to respond to the event.
2. Single-actor distributed decision (SADD): A single actor receives data about an event. The actor broadcasts this information to other actors. A collaborative decision is taken as to which actor(s) will react to the event.
3. Multi-actor centralised decision (MACD): Multiple actors receive data about an event and send the data to a central actor, which determines the best actor to react to the event.
4. Multi-actor distributed decision (MADD): Multiple actors receive data about an event and make a mutual decision on which set of actors will react to the event.

2.6 MOBILE SINKS AND MOBILE RELAYS

The application and routing challenges presented by static nodes in a dense, multi-hop WSN has led to the investigation of the use of mobile elements in WSNs for data collection and/or dissemination. The advantages of using mobile entities in WSNs include (Francesco et al., 2011; Hamida & Chelius, 2008):

1. Improved reliability as there is less contention and collisions within the wireless medium because data can now be collected directly through single or limited hop transmissions.

2. Reduced reliance on nodes located close to a static sink to route messages to the sink, resulting in increased energy efficiency and network lifetime.
3. Improved connectivity as mobile nodes can enable the retrieval of collected measurements from isolated regions of the sensor application area.
4. A sparse network architecture implies reduced application cost as fewer nodes are required and nodes can utilise mobile elements already present in the application area such as trains, cars, wildlife, and livestock etc.

The use of mobility in WSNs introduces complications not found in static WSN applications, such as detecting when nodes are within transmission range of a mobile sink, ensuring reliable data transfer as nodes may move as messages are exchanged, tracking sink location and design of a virtual backbone to store data reports so that the mobile sink can easily collect them, and managing sensor nodes to support sink mobility (Francesco et al., 2011; Hamida & Chelius, 2008).

Current strategies for data collection and dissemination using mobile elements include a rendezvous-based virtual infrastructure which uses limited and unlimited multi-hop relays to route data messages, or a backbone-based approach where mobile sinks only communicate with pre-defined cluster heads or gateways, or passive data collection where there is direct communication between the source and sink (Hamida & Chelius, 2008; Faheem et al., 2009).

The mobility patterns of mobile elements (sinks and relays) are dependent on the type of WSN application, its data collection requirements and the controllability of the mobile elements. Current mobility patterns can be classified into the following categories (Faheem et al., 2009; Francesco et al., 2011):

1. *Random mobility*: no network information required because communication does not occur regularly but with a distribution probability. This method does not provide optimal increases in network lifetime due to the need for continuous sink position updates and route reconstruction.

2. *Predictable or deterministic mobility*: mobile elements enter range of sensor nodes at regular, periodic times to collect data, and allow the sensor nodes to predict arrival of mobile entities.
3. *Controlled mobility*: the mobile elements movements are not predictable but are controlled by network parameters such as maximum and minimum residual energy of sensor nodes on a data route, event location, and the mobile elements trajectory and speed. In addition, the mobile entities can be instructed to visit individual nodes at specific times, and stop at nodes until they have collected all buffered data.

2.7 STANDARDS

A need for standardisation in WSN communication protocols was expressed in early 2000 by sensor device suppliers. It was found that most communication protocols performed inconsistently i.e. could sometimes perform better in certain applications but poorly in others. The most important standardisation bodies for WSN technology are the Institute of Electrical and Electronics Engineers (IEEE), the Internet Engineering Task Force (IETF), the HART Communication Foundation, the European Telecommunications Standards Institute (ETSI) and the International Society for Automation (ISA). Although these organisations focus on different areas, they all provide a common platform for interoperability and low power consumption between sensor node devices. The subsections mentioned below list and discuss some of these standards.

2.7.1 IEEE 802.15.4 standard

IEEE 802.15.4 is a wireless network standard that specifies the physical and data link MAC layer protocols for low power, low rate wireless personal area networks (LR-WPAN). There are three frequency bands with 27 radio channels in the physical layer, namely (1) 868.0 to 868.6 MHz, which provides a data rate of 20 kbps, (2) 902.0 to 928.0 MHz with a data rate of 40 kbps, and (3) 2.4 to 2.4835 GHz with a data rate of 250 kbps. Routing is not directly defined by IEEE 802.15.4, because it does not define a network layer. The standard has very broad applications in the area of (but is not limited to) WSNs, industrial monitoring and control, home automation and control, automatic meter reading and inventory management (Lee et al., January 2010).

IEEE 802.15.4-compliant devices have limited power, which has to be conserved to ensure the device remains active for a lengthy time period. There are two classes of IEEE 802.15.4-compliant devices, namely (1) full function devices (FFDs), which have the capability of serving as a coordinator or associating with an existing coordinator/router and becoming a router, and can thus communicate with all other devices and reroute messages; or (2) reduced function devices (RFDs), which can only associate with a coordinator or router and cannot have children, i.e. can only communicate with one FFD (Pan et al., November 2009).

The IEEE 802.15.4 standard provides an energy-saving mechanism that uses a superframe structure in the beacon mode. This is because one of the major energy wastes is idle listening, due to the inherent nature of carrier sense multiple access with collision avoidance (CSMA/CA) MAC. The radio circuitry needs to be in the active mode for idle listening, although it is not transmitting or receiving data frames. The energy consumption of the radio circuitry in the active mode is usually higher than that of a small microcontroller (Lee et al., January 2010).

Although IEEE 802.15.4 was developed to meet the needs for low power, low data-rate wireless communication, it is potentially vulnerable to interference by other wireless technologies having much higher power and working in the same industrial, scientific, and medical (ISM) band, such as IEEE 802.11b/g (Yuan et al., 15-15 Nov. 2007).

2.7.2 6loWPAN

As mentioned previously the IEEE 802.15.4 standard is only concerned with the physical and media access control layers. To ensure effective message communication between wireless devices, the Internet Engineering Task Force (IETF) integrated an IPv6 addressing scheme with the IEEE 802.15.4 standard to provide an effective low power Wireless Personal Area Network (6LoWPAN), (Ma & Luo, 19-20 Dec. 2008). This specification allows the design of smart sensors with an end-to-end IPv6-based architecture carried over an IEEE 802.15.4 network. In addition, 6loWPAN networks are characterised as low bit-rate, short-range and low-cost networks. 6LoWPAN defines a set of compression mechanisms that allows packets to be transported from sender to receiver and vice versa in wireless networks based on the IEEE 802.15.4 protocol (Polepalli et al., 2009).

2.7.3 ZigBee

The ZigBee Alliance was formed to promote the IEEE 802.15.4 standard, provide conformance testing and improve interoperability among devices from different manufacturers. Although the ZigBee specification is based on IEEE standard 802.15.4, it does not exactly follow every part of the standard and it adds a great deal more to the standard in the form of profiles and requirements for higher layers in the networking stack. The goal of IEEE standard 802.15.4 and the ZigBee Alliance is to provide wireless solutions that are low-cost, low data-rate, and low power. The target applications are control and monitoring systems that only infrequently send small amounts of data (Gilb, 2005).

ZigBee enables interaction between the network and MAC layers, which is fundamental for power control in mobile ad hoc networks and WSNs. The power level determines who can hear the transmission, and hence it has a direct impact on the selection of the next hop, which is a network layer issue. The power level also determines the floor that the terminal reserves exclusively for its transmission through an access scheme, which is a MAC layer issue (Muqattash et al., 2006).

The ZigBee standard defines two major protocols: The “ZigBee” and the “ZigBee PRO”. The first model is essentially designed for light-duty purposes in home and office applications, whereas the second model usually provides more reliable performance but requires implementation of a larger and more complicated protocol (Kazem Sohraby, 2007). The ZigBee offers three classes of devices: the ZigBee coordinators, the ZigBee routers and the ZigBee end. Both the coordinators and the routers participate in multi-hop routing of messages, while the ZigBee end device only addresses messages to their associated parent routing device. Although the ZigBee has found a market in home and office applications, this standard has not been as widely used in control and industrial measurement processes. The reason is that its MAC layer is unable to deliver messages efficiently in applications where data reliability is a critical issue.

CHAPTER 3

ARCHITECTURE: SINK PLACEMENT

This chapter discusses small world network concepts and the similarities between small world networks and WSNs that may result in a WSN being modelled as a small world network. In this chapter an algorithm to place multiple sinks at predefined points within the application area is discussed. It is shown that it is possible to model a WSN as a small world network by placing sink nodes at predetermined points within the application area.

3.1 INTRODUCTION

The final recipient node in a typical WSN application is usually a sink node which has specialised equipment that transmits the data to an end user. As shown in Figure 1.2 and Figure 1.3, the network architecture of a WSN can have one or more sinks. The benefit of having multiple sinks placed within a WSN application area is that the number of times that a message has to be re-transmitted to reach a sink is lower for multiple sinks placed across the application area than for a single sink. The reduction in message re-transmissions means fewer nodes receive and/or re-transmit a message, improving the sensor node lifetime and hence the WSN lifetime.

Since most nodes communicate primarily with a sink node, the placement of one or more sinks must be optimised to enable energy efficient communication within a WSN. An investigation is conducted on whether placing multiple sinks at specific points within a WSN application area will result in the development of a small world network. The advantage of small world networks is that the number of steps to route a message from a source node to a destination node, (where each node only has local information of their neighbours), increases logarithmically with the total number of nodes (Newman, 2003).

In a WSN modelled as a small world network, a message from any node within the application area will reach a sink node within a small, predetermined number of hops. The reason for modelling a WSN as a small world network is to reduce the number of messages sent and received by intermediate neighbouring nodes when an event has to be reported.

3.2 SMALL WORLD NETWORKS

In a small world network there are multiple long edges that connect local vertices (nodes) with distant nodes, thus enabling a faster spread of information or viruses etc. Small world networks share characteristics with both regular lattices and random graphs. The main characteristics of a small world network are a low diameter (like random graphs) and a high clustering coefficient (like regular graphs) (Watts & Strogatz, 1998).

In a small world network, the number of steps to route a message from a source node to a destination node, (where each node only has local information of its neighbours), increases logarithmically with the total number (N) of nodes (Newman, 2003). Two models of small world networks are discussed below (Radev, 2008).

3.2.1 Watts-Strogatz model

Watts and Strogatz showed that viable small world networks exist between the two extremes of completely regular or completely random networks. These networks have a high clustering coefficient like regular networks and small path lengths as in random networks. The small path lengths are due to “short cuts” that connect local vertices to long-range edges. Starting with a regular lattice structure, an edge in the graph is disconnected from its end point and rewired to a random node in the graph, until a random graph is obtained. The farther the node being reconnected to, the more the graph diameter is reduced. After only a few steps the diameter of the graph has been reduced dramatically while its clustering coefficient remains large. The Watts-Strogatz model uses a constant shortcuts probability, regardless of whether the node being rewired to is close to or remote from the source.

3.2.2 Kleinberg model

Kleinberg proposes a refinement where the geographical distance between two nodes affects the probability of an edge being rewired between them (e.g.$p \sim \frac{1}{d^2}$). Kleinberg proved a dependency between these small path lengths and the distance between them. A short path between two nodes (vertices) can only be found algorithmically if those nodes chosen to create a short-cut (i.e. those nodes with a long edge) are not chosen randomly, but are chosen related to the geometry of the application area (Kleinberg, 2000). Specifically, long range nodes are placed at a distance from a node that correlates to the actual distance between them in terms of an inverse power law relation, that is: d_{ij}^{-r}, where r = 2.

3.2.3 Similarities between small world networks and WSNs

The properties of WSNs that indicate similarities with small world networks are (Newman, 2003; Kleinberg, 2000):

- The overlap in wireless communication range means that most immediate neighbours of a sensor node are also neighbours of one another. A neighbour is any node that is in immediate radio range, i.e. able to receive and accurately decode data.
- Sink nodes in the network communicate with remotely located users (outside the WSN area). The remote station coordinates communication between sink nodes. (This long edge provided by the sink nodes reduces the diameter of WSNs).
- The average distance between two nodes is short (limited to the nodes' transmission and receiving range).
- There is no central authority to determine optimal routes. Routing is performed at each node with only information about the nodes nearest neighbours.

The questions required to be answered is firstly, how to determine the optimal number and placement of these sink nodes, in accordance with Kleinberg's theory, and secondly, can the number of messages required to route a message be reduced by placing sink nodes at specific points in the application area. The application area is assumed to approximate a two-dimensional grid, where starting from point (0, 0), each sink node is placed at the specified hop distance (i.e. number of hops multiplied by a nodes transmitting range).

3.3 ALGORITHM DESIGN

An algorithm to determine number of sinks required for a specific application area size and the placement of these sinks at specific points within the WSN application area is discussed in this section. Certain assumptions and definitions are provided to clarify the scope of the presented solution and equations.

3.3.1 Definitions

The following definitions are used:

- N = Total number of sensor nodes,
- R = Sensor node communication range,
- H = Number of hops
- S = Number of sink nodes
- X = Width of application area
- Y = Length of application area

3.3.2 Assumptions

- The application area is a two-dimensional rectangular or square grid, with the width and length specified.
- Starting from point $P(x_p, y_p)$, each sink node is placed at the specified calculated distance.
- The application area is always assumed to have at least one sink, irrespective of size and number of hops.

3.3.3 Calculation of number of sensor nodes

Full coverage of the application area by sensor nodes is not assumed and a generalised calculation to place sensor nodes in the application area is calculated as a function of the sensor range and the width and length of the area, i.e.

$$N = \left(\frac{X}{R} + 1\right) * \left(\frac{Y}{R} + 1\right) \qquad [3.1]$$

3.3.4 Calculation of number of sinks (long edges)

To calculate the number of long-range nodes (sinks) required within a WSN application area, the number of hops between the node farthest from a sink and the sink has to be specified. Small world networks are generally analysed to determine the maximum number of hops between two vertices. By specifying the maximum number of hops H to route a message between any two nodes in the network at the beginning, the researcher worked in the reverse direction of how small world networks are analysed.

The number of sink nodes required in the application area for the specified number of hops is calculated to conform to Kleinberg's thesis. Given the dimensions of the application area and the sensor nodes communication range, the number of long-range nodes (sinks) can be calculated as a function of the node range and the number of hops required within the network, as shown in Equation [3.2].

$$S = N * H^{-2} \qquad [3.2]$$

Given that N is dependent on X and Y, then from Equations [3.1] and [3.2]:

$$S = \left(\frac{X}{R} + 1\right) * \left(\frac{Y}{R} + 1\right) * H^{-2}$$

$$S = \left(\frac{X + R}{R}\right) * \left(\frac{Y + R}{R}\right) * H^{-2}$$

$$S = \frac{(X+R)*(Y+R)}{R*H^2} \qquad [3.3]$$

A sensor node is always able to reach a sink node within the specified number of hops. If the result from Equation [3.3] yields a value less than one, then the default value of the sink is set to one. That is, irrespective of size and number of hops, $S \geq 1$.

3.3.5 Placement of sink and sensor nodes

The sink nodes cannot be placed randomly if the topology is to conform to Kleinberg's small world algorithmic model. Each sink is placed the specified number of hops multiplied by the node range, from another sink. The application area is assumed to approximate a two-dimensional grid. If one sink is required, the sink is placed in the centre of the application area. For two sinks each sink is placed in the centre of half of the application area. For more than three sinks, the starting values from point $P(x_p, y_p)$ are calculated based on the simple Pythagorean Theorem in geometry. Figure 3.1 describes the algorithm to place sink nodes in the application area.

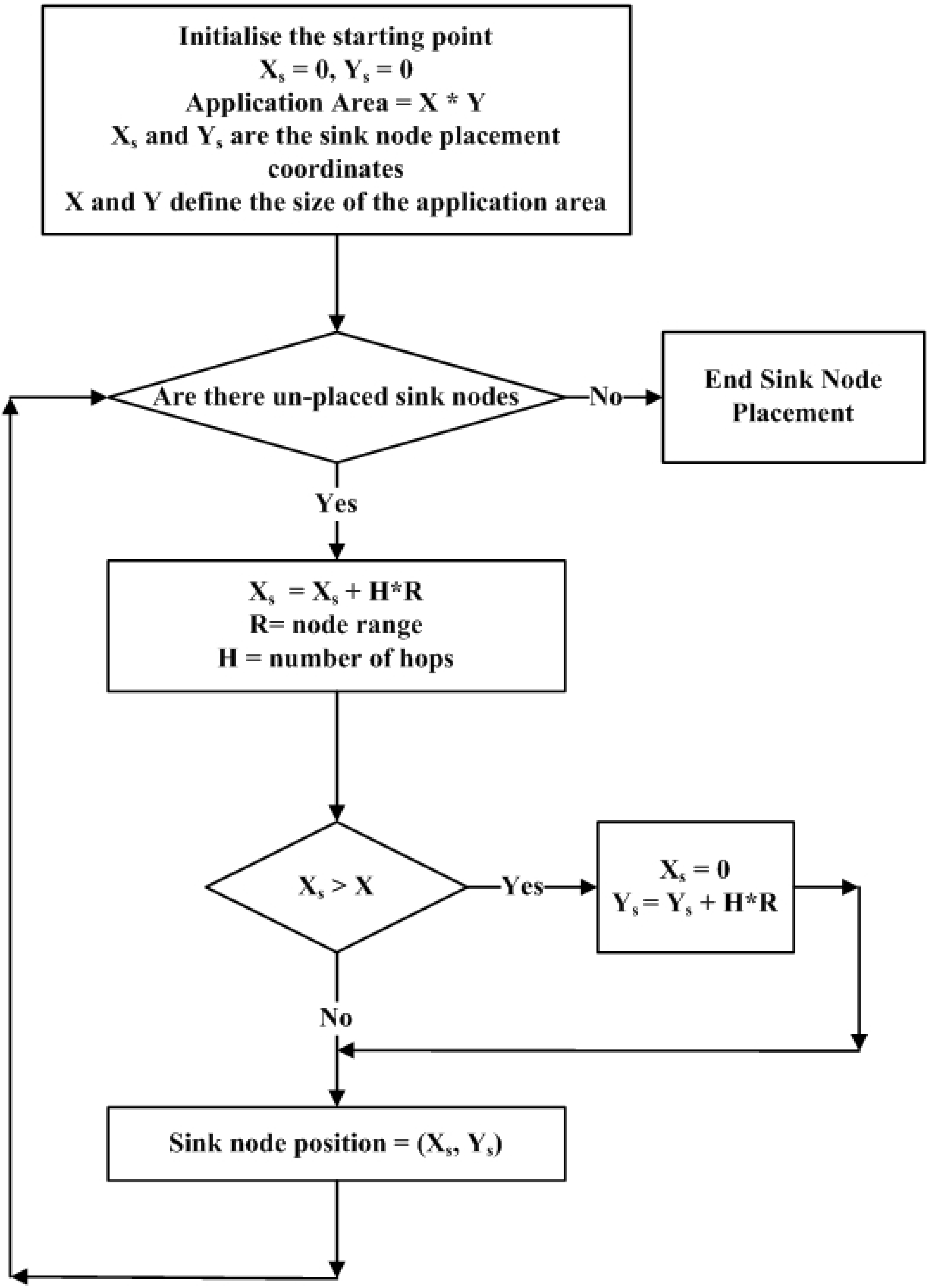

Figure 3.1: Sink node placement calculations

Two scenarios were evaluated for sensor node deployment. In the first scenario, the sensor nodes were placed the distance of the sensor range (R) from each other within the application area. In the second scenario, the sensor nodes were randomly deployed within the application area. The placement of the sink nodes is calculated as a function of the node range and the number of hops required within the network.

3.4 EXAMPLES OF THE USE OF SMALL WORLD NETWORKS IN WIRELESS SENSOR NETWORKS

Aldosari and Moura consider the optimisation of the network within a given class of random networks that exhibit small-world behaviour. Their results confirm that there is a specific range where the generated graphs exhibit a small-world phenomenon, i.e., high clustering coefficient and low path length, which strengthens Kleinberg's thesis that the long edge cannot be totally randomly allocated in a small world network (Aldosari & Moura, 2005).

Helmy showed that it is possible to model a WSN as a small world network by adding a small number of shortcuts. The author shows that the path length is reduced through the introduction of shortcuts without any significant impact on the structure of the network (Helmy, 2003). The key difference between Helmy’s work and the proposed solution is that Helmy chooses a node at random to perform link re-wiring and link addition, which is similar to the Watts-Strogatz model. In the work discussed in this chapter the required number of sink nodes for the application area is calculated and the sink nodes are placed in specified locations from the sensor nodes according to Kleinberg’s model.

Sharma and Mazumdar have suggested that by adding a few wires to a WSN, to simulate a long edge, the average energy expenditure per sensor node, as well as the non-uniformity in the energy expenditure across the sensor nodes, is reduced (Sharma & Mazumdar, 2005). The position of a single sink node is arbitrarily chosen.

Guidoni et. al discuss creating a heterogeneous sensor network based on small world concepts in order to optimise communication between sensors and the sink node (Guidoni et al., 2008). They consider two methods to model a small world network, namely directed angulation towards the sink (DAS) and sink node as source destination (SSD). In DAS, node location awareness is crucial to determine the routing path to the sink node. In the solution presented in this thesis, nodes do not need to be aware of the exact location of the sink; they use an available route path discovered during the initialisation phase. In SSD, short-cuts are added directly to the sink node, to create a small world network and reduce the number of hops. The added short-cuts are dependent on the range of the short-cut sensor and generally will be located close to a sink node. The SWR model uses multiple sinks so that each sensor is a maximum specified number of hops removed from a sink node.

3.5 RESULTS AND ANALYSIS

A program to simulate calculation of number and placement of the sinks was developed. The number of hops and sinks required for various application area sizes was calculated. The application area is assumed to be a two-dimensional square grid.

The results for the calculation of the number of sink nodes indicated that sensor node placement (predefined, i.e. scenario 1 or random, i.e. scenario 2) had no effect on the calculated number of sink nodes required for a given application area size. A sensor node is always able to reach a sink node within the specified number of hops in scenario 1. In random sensor node deployment, some sensor nodes may be placed outside the distance (hops times range) required to reach a sink node. Full coverage of the application area by sensor nodes is not assumed. The results in the following figures are for sensor nodes placed as for scenario 1.

Initially, the number of sinks was calculated using an adapted version of Equation [3.3], to determine if the node range had an effect on the model. Thus Equation [3.3] without considering node range in the application area width and length dimensions is:

$$S = \frac{X*Y}{R*H^2} \qquad [3.4]$$

The results for number of calculated sinks for a specified number of hops for various sizes of application areas ranging in size from 100x100 metres to 10000x10000 metres for a node range of 10m, 20m, 30m and 50 m is shown in Figure 3.2, Figure 3.3, Figure 3.4, Figure 3.5, Figure 3.6 and Figure 3.7. These figures show that the number of sinks required in an increasing application area is dependent on the number of hops in an inverse power law of 2.

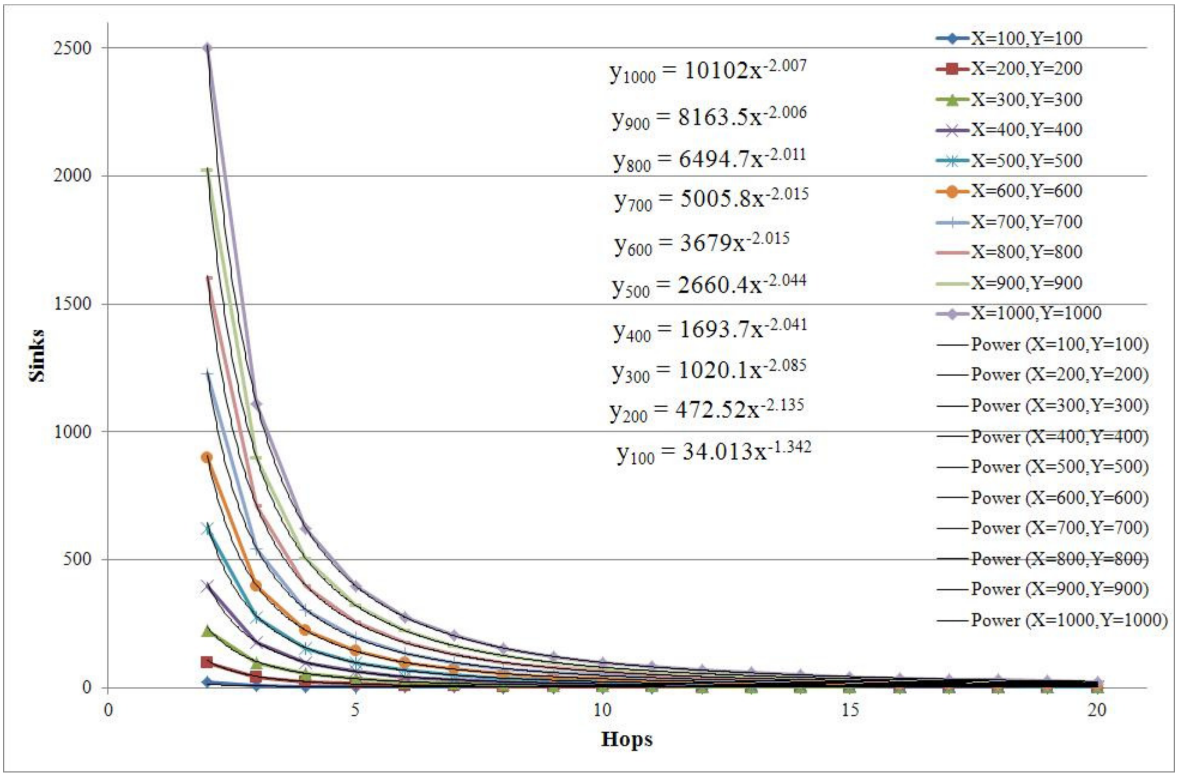

Figure 3.2: Node range is 10m

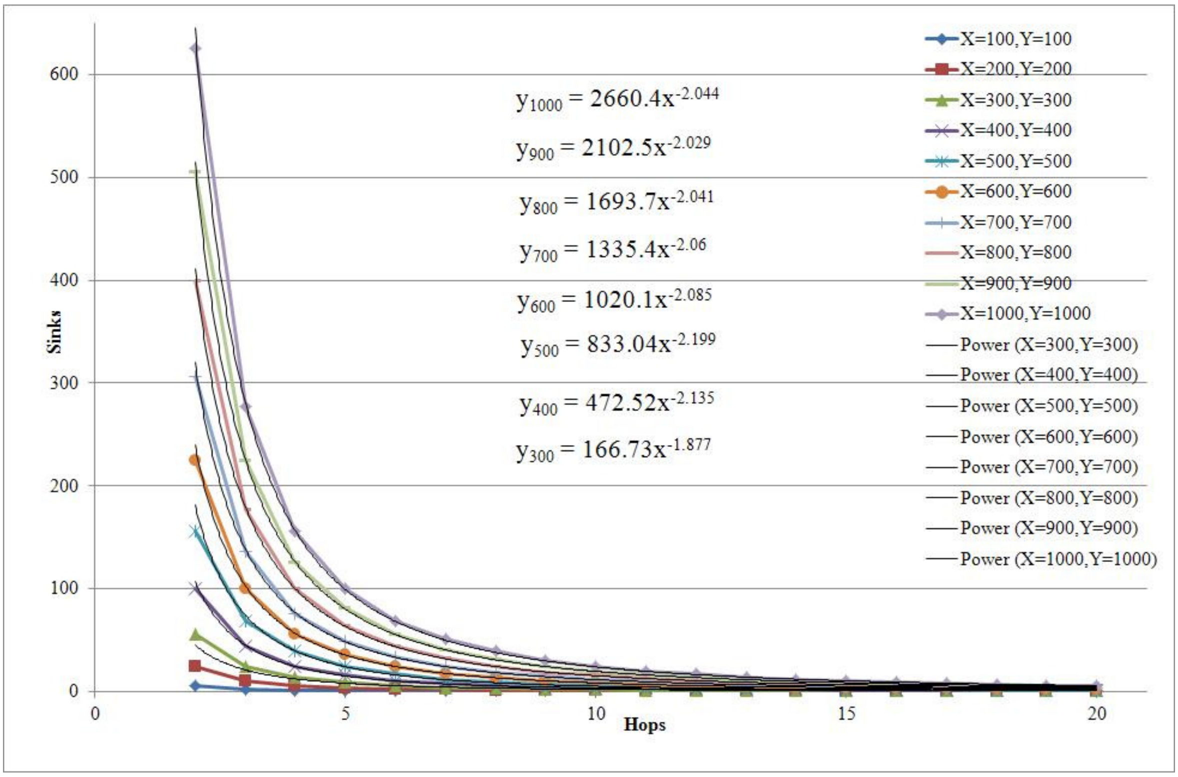

Figure 3.3: Node range is 20m

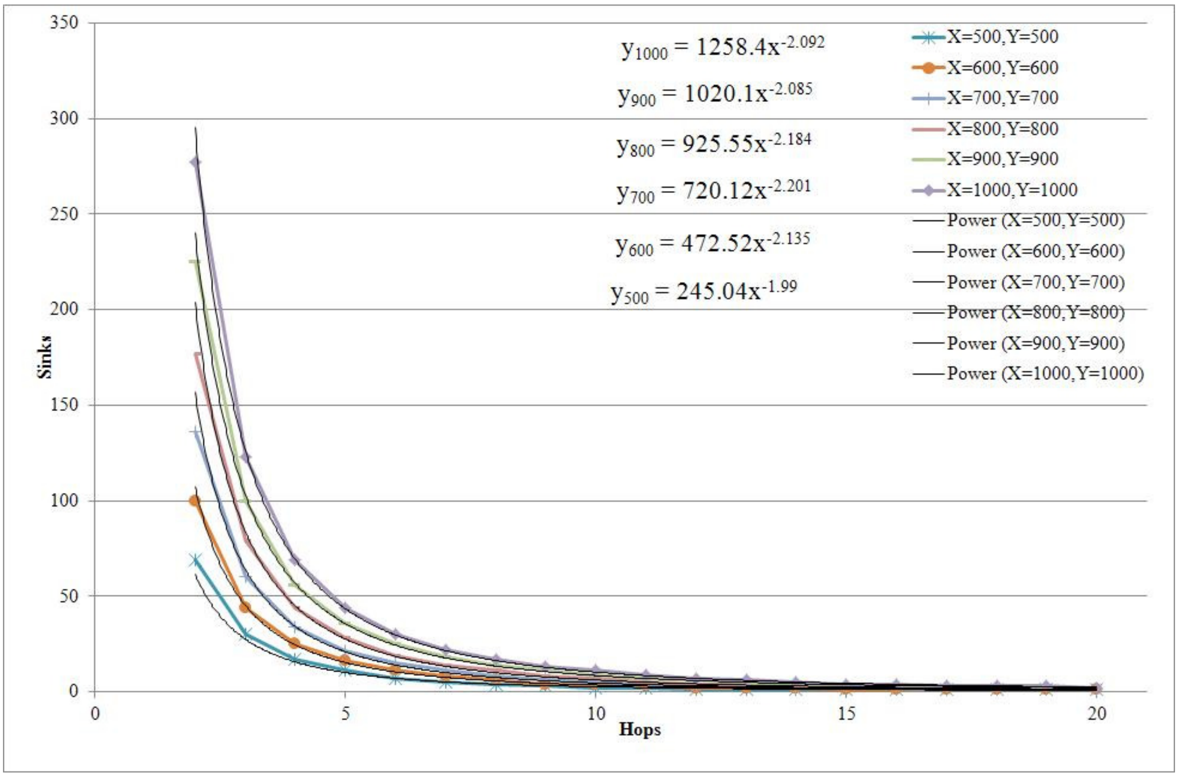

Figure 3.4: Node range is 30m for small application areas

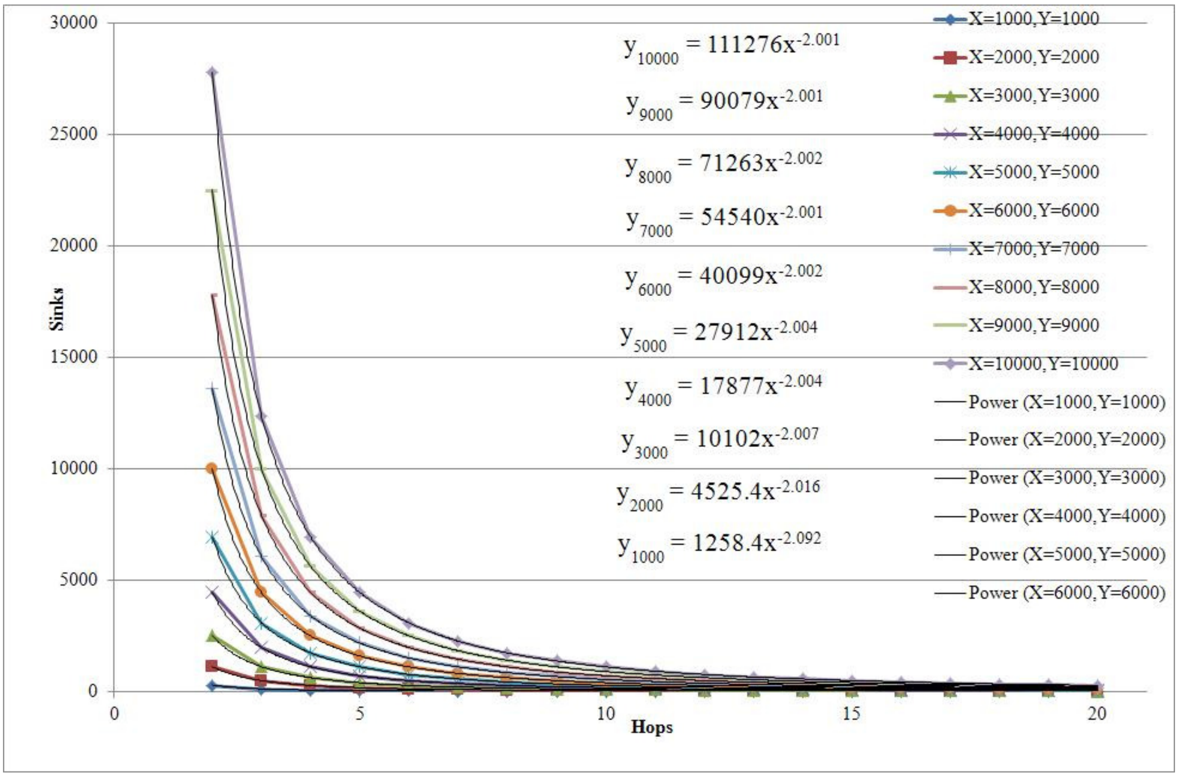

Figure 3.5: Node range is 30m for large application areas

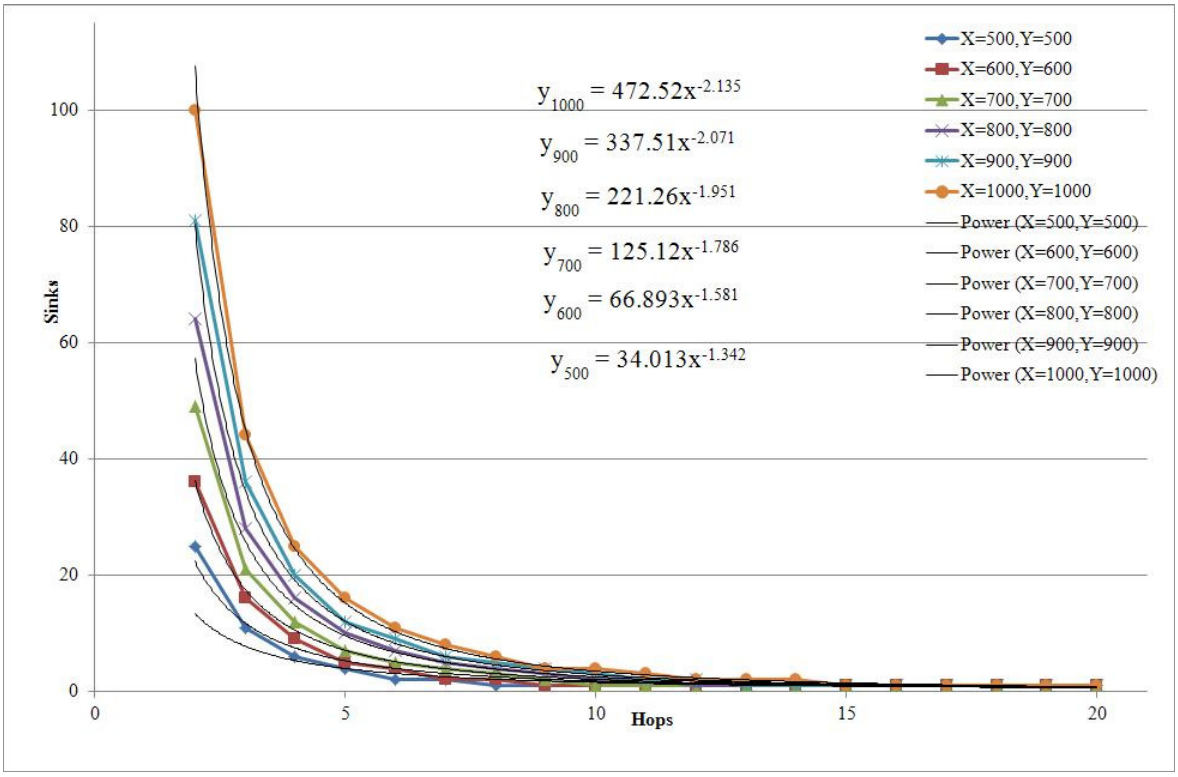

Figure 3.6: Node range is 50m for small application areas

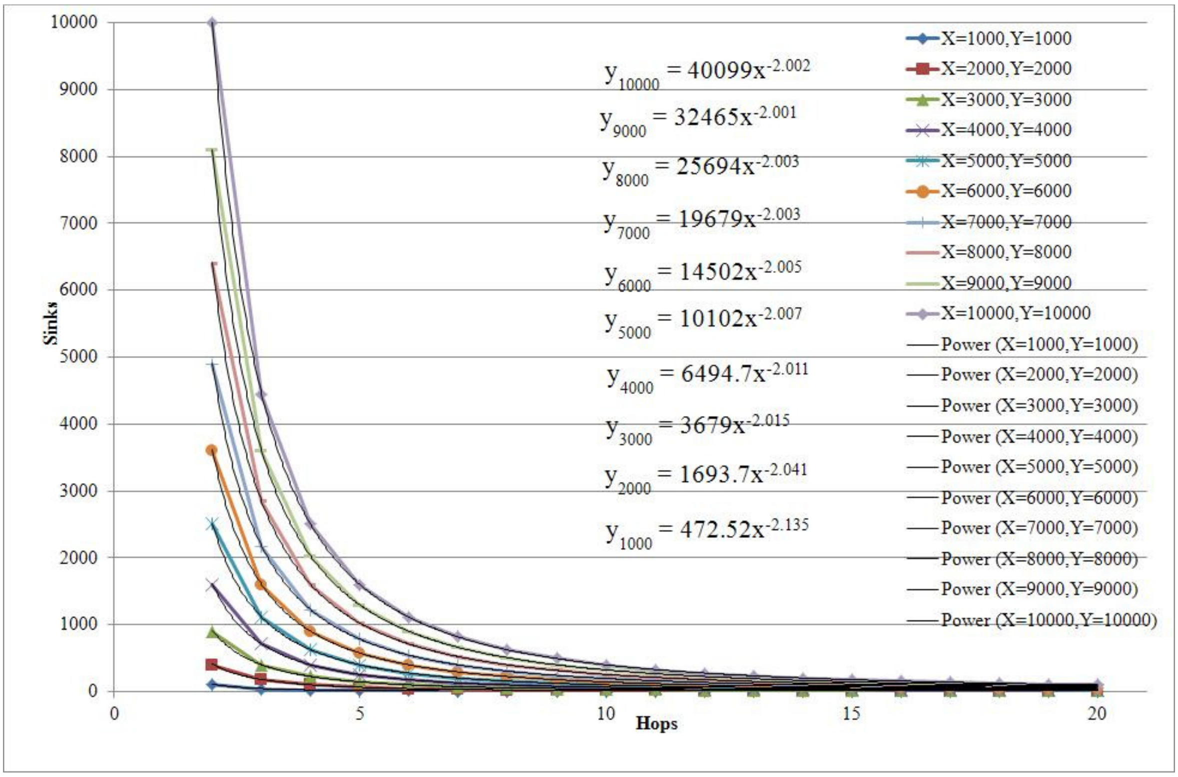

Figure 3.7: Node range is 50m for large application areas

The results from sink placement shown in the figures above confirm Kleinberg's thesis that optimum placement of the long edge (short cut) in a network is at d_{ij}^{-r}, where $r = 2$. Note that the results for small application areas are not always dependent on the number of hops in an inverse power law of approximately 2.

It is possible to model a WSN as a small world network, by using sink nodes to create the long edges. The sink nodes are placed at a distance from a sensor node that correlates to the actual distance between them in terms of an inverse power law relationship between number of hops and number of required sinks. Note that as the range increases, the relationship no longer holds for small application areas, implying a correlation between range and number of hops. To test this theory, the range factor is included as shown in Equation [3.3].

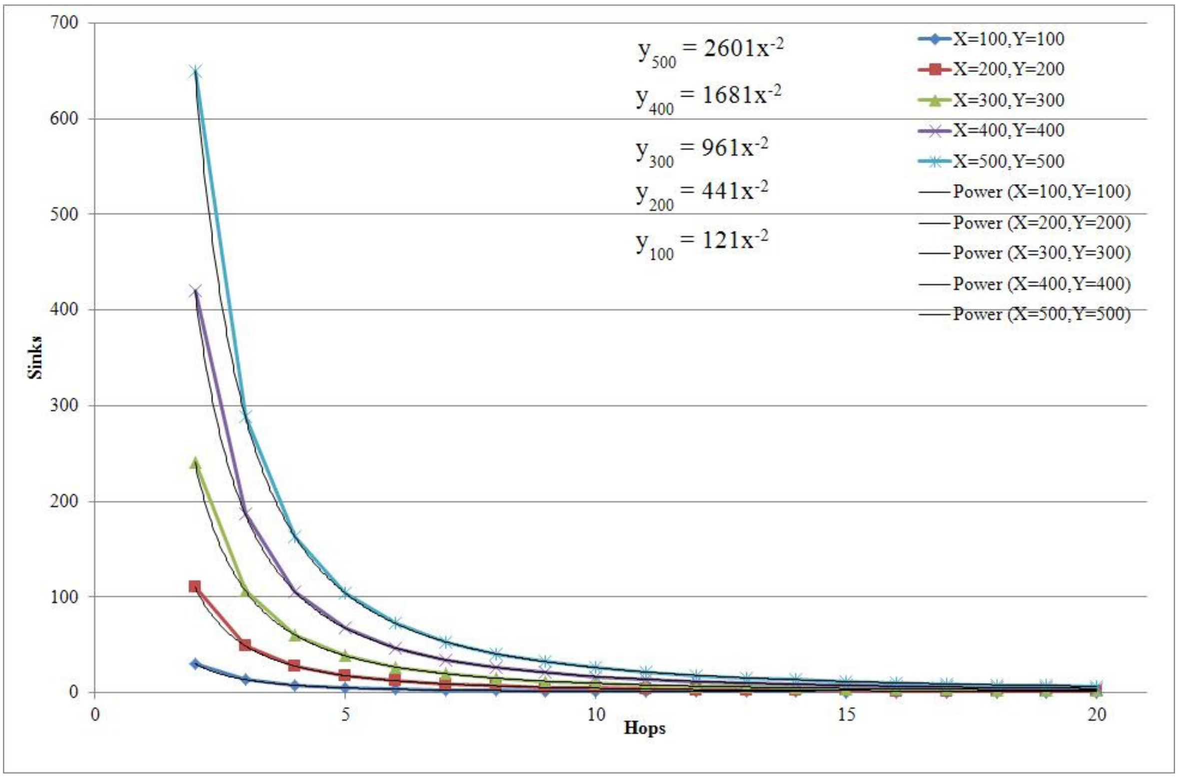

Figure 3.8: Sinks vs. hops (range=10m)

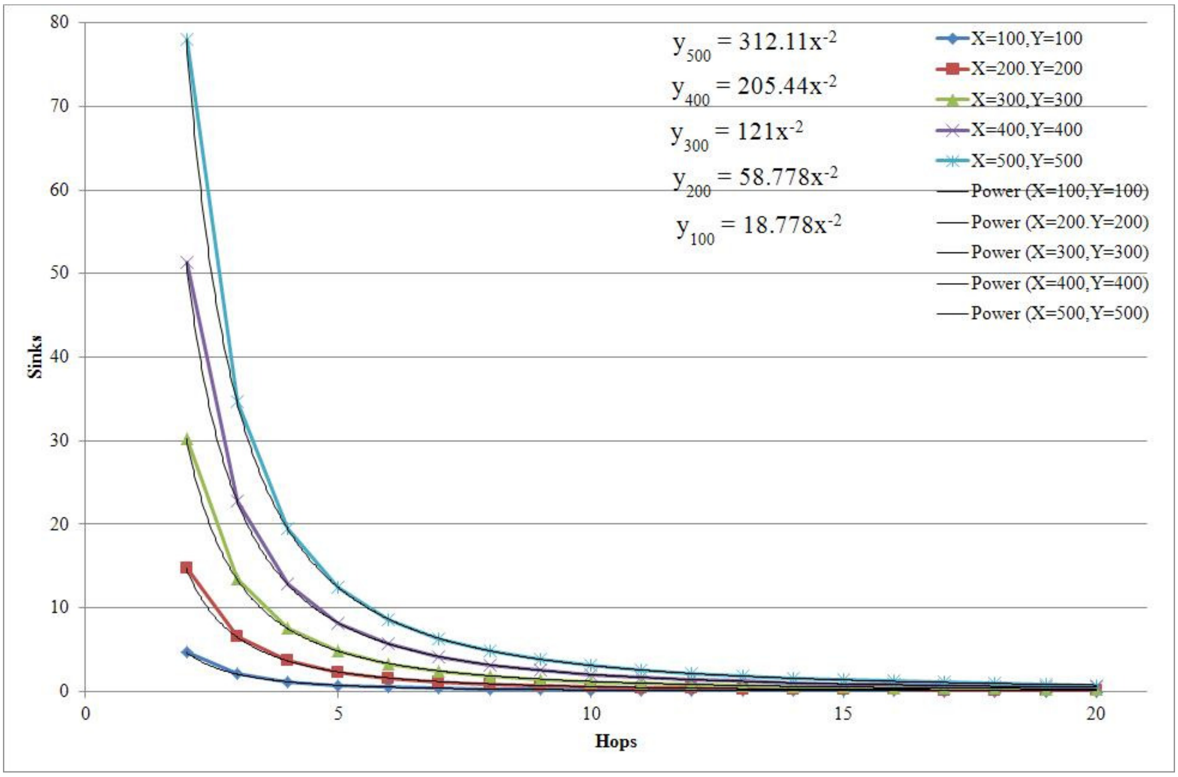

Figure 3.9: Sinks vs. hops (range=30m)

From Figure 3.8 and Figure 3.9 one can see that the hypothesis of simulating a small world in smaller application areas is valid if the node range is taken into consideration. The node range has an impact in smaller application areas because the range is 25% to 30% of the application area's length. For larger application areas (i.e. greater than 1000mx1000m), the node range has a negligible effect on the calculation of number of sinks and placement of sinks.

3.6 CONCLUSION

In this chapter Kleinberg’s thesis that the long edges cannot be chosen randomly has been used to model a WSN as a small world network. This differs from previous research that has tried to model a WSN as a small world network by randomly rewiring links. The algorithm described in this chapter shows that it is possible to model a WSN as a small world network by placing sink nodes at specific pre-calculated points within the application. The result is that a message from any node within the application area will reach a sink node within a small predetermined number of hops. This will reduce the number of messages sent and received to all nodes.

In the next chapter an algorithm that creates one or more routes for each sensor node to one or more sinks within the wireless application area is discussed. It will be shown that there is a reduction in the number of messages transmitted within the network when the WSN is modelled as a small world network. The routing algorithm creates one or more route paths for the specified number of hops.

3.7 DECLARATION

The work in this chapter has been published in the following Conference:
2009 International Conference on Wireless Networks and Information Systems (WNIS 2009), 28-29 December 2009 in Shanghai, China

CHAPTER 4

ENERGY-EFFICIENT MESSAGE ROUTING

In this chapter the work in Chapter 3 is extended by proposing a hybrid routing strategy after the WSN has been modelled as a small world network. In Chapter 3 the correct number of sinks and the location of the sinks for a specific application area has been calculated and placed within the application area.

In Chapter 4 routing paths to a sink are constructed proactively from an initialisation message (IM) sent from each sink. The IM is repeated by every receiving node for the specified number of hops in the small world model. The question analysed in this chapter is whether the number of message re-transmissions required to route a message from a node to a sink can be reduced by proactively creating routes between nodes and sinks after the sinks have been placed at specific points in the application area as done in the small world model discussed in Chapter 3.

4.1 INTRODUCTION

A small world network can be emulated by placing the correct number of sinks a small number of hops away from any sensor node. By imposing a hop count on a message destined to a sink, the number of times the message is re-broadcast to surrounding nodes is limited. It is assumed that a message will reach the sink node within the specified number of hops. However there is still no defined route for the message to travel from a source node to a sink node. This results in unnecessary flooding of messages within the network. Since each sensor node has a limited power supply, the number of messages transmitted within the network must be kept to a minimum.

To reduce the number of messages a node receives, sensor nodes require an accurate route to the destination sink node. Routing data in many wireless sensor network applications differs from traditional network routing schemes because a complete network topology is not available to nodes, the nodes do not have unique IP type addressing and routing tables are not pre-determined. There are no centralised routers with complete knowledge of the network topology. Each node uses only locally available information to route messages.

When a sensor node detects a message, it examines the address in the message header to determine if the intended recipient is itself. If it is not the intended recipient, it re-transmits the message to its neighbours, according to a specific routing protocol the WSN application has been set-up to use.

The routing design issue of WSN is very challenging in terms of providing both responsiveness and efficiency. In a WSN, overhead is usually measured in terms of the utilisation of the bandwidth, power consumption, and the processing requirements on the nodes. To respond to those needs efficiently, three different strategies were defined (Kazem Sohraby, 2007):

- ***Proactive***: it relies on periodic dissemination of routing information to maintain consistency and accuracy on the routing tables across the nodes on the network. The structure of proactive strategy can be either flat (may compute optimal paths) or hierarchical (better suited for routing in large networks).
- ***Reactive***: defines routes to a limited set of destinations on demand.
- ***Hybrid***: this strategy relies on the network's structure to achieve stability and scalability in large networks. Here, the networks are grouped in adjacent clusters providing structures that can be leveraged to limit the scope of the routing algorithm reaction to changes in the network environment. It can be used whenever a proactive strategy is used.

In Chapter 3, modelling a WSN as a small world network by placing sinks at specific points within a WSN application area is proposed. In this chapter, route paths to a sink are constructed proactively from an IM sent from each sink. During the network start-up phase a once-off IM is sent from each sink to set-up multiple route paths for each node. The IM is repeated by every receiving node for the specified number of hops in the small world model. The IM creates a routing table at each node, with one or more paths to a sink. A node can choose from the routes in its routing table to determine the path a message should take to reach a sink. These known paths ensure that unnecessary communication within the WSN is minimised, thus optimising each nodes energy utilisation and lifetime. This approach utilises a hybrid, proactive strategy to enable energy efficient message routing within a WSN.

4.2 ALGORITHM DESIGN

4.2.1 Creating route table algorithm

Sinks are placed at predetermined points in the application area as described in Chapter 3. After the sinks have been placed in the application area, an IM is transmitted by each node in a staggered time format. The time lag can be pre-determined before implementation using a small subset to determine time differentials between receiving multiple IMs at each node. The idea behind the IM is to create a routing table for each node, which can be used to transmit a message from source to destination. As each node only transmits an IM once, the energy cost over the total lifetime of the WSN is low. The routing table is constructed as follows:

- Each node starting from each sink node transmits an IM containing a unique node ID and a list of neighbours. This list is initially empty.
- With the exception of the sink node, a node will wait to receive an IM before transmitting an IM. This ensures that the nodes furthest from the sink node receive valid routing information.
- When a node receives an IM, it will wait a specified time before transmitting its IM. This is because a node may receive two or more IM from its neighbours. The introduction of a time lag ensures that the node updates its routing table with information from all neighbours.
- If the hop count is less than the specified maximum number of hops required for a message to reach its destination, then the receiving node adds the node's ID, as well as the transmitting node's neighbour list to its neighbour list.
- The node replaces the neighbour list in the IM with its updated neighbour list and re-transmits the message.
- This process continues until the hop count exceeds the maximum hop count.
- All nodes are required to transmit an IM.

On initialisation, N number of IMs will be sent within the network, where N is the number of nodes. Each node will only transmit the IM once, thus limiting power usage. Thus all nodes can build up a list of nearest neighbours, and one or more routes to the sink. Although each node sends only one IM, a node will receive multiple IMs depending on the number of neighbours in range. Each received IM route and its hop count will be added to the receiving nodes route table. Figure 4.1 describes the algorithm.

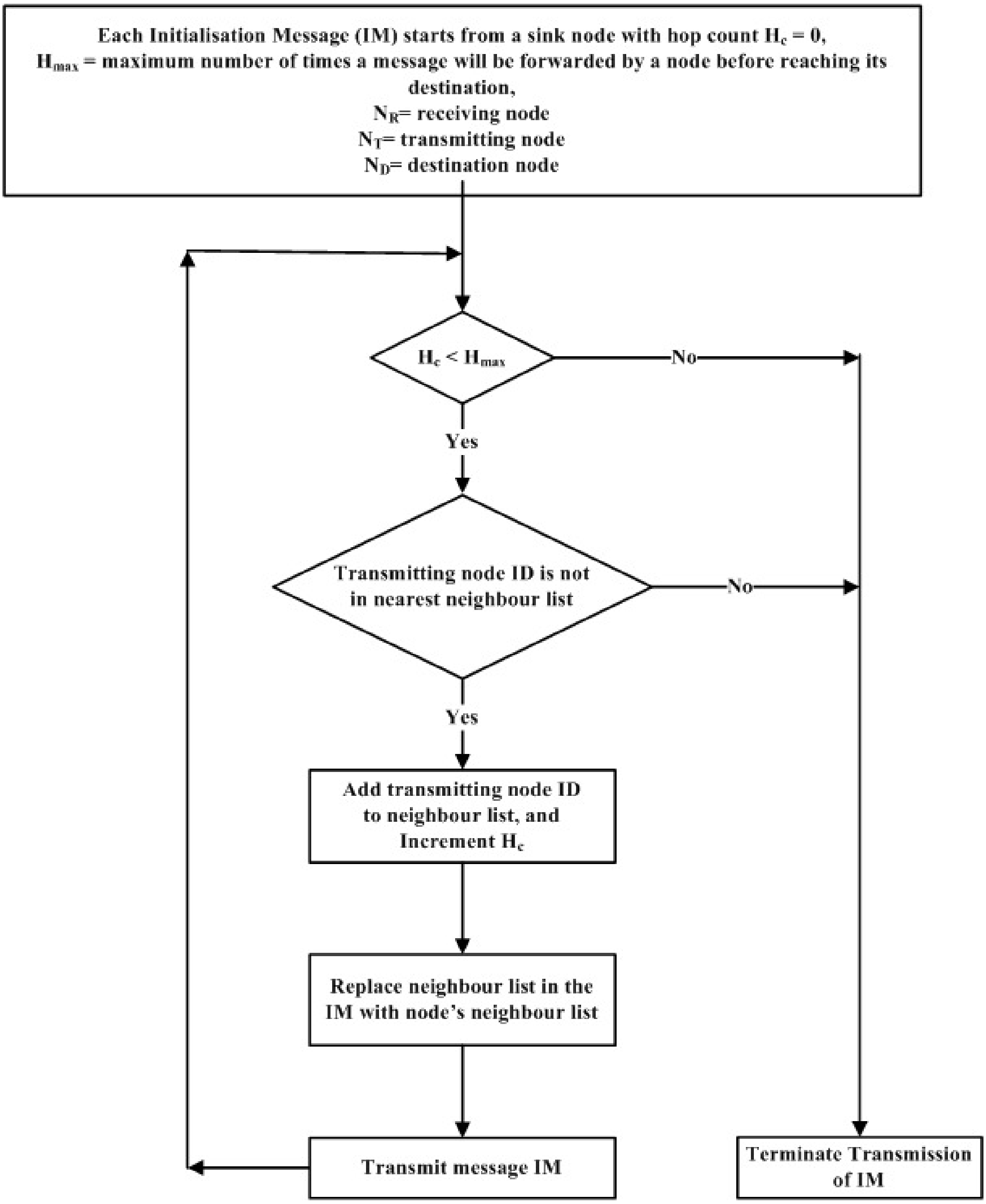

Figure 4.1: Creating route paths with an initialisation message

Sometimes conditions within the application area raise concerns about the reliability of the wireless medium. This can result in a node not receiving an IM. If a node does not receive an IM, it must send a query to its nearest neighbours. When a neighbour receives a query message, it must respond with its neighbour list. This ensures that all nodes will receive a message containing the path to take to the sink in the required number of hops.

The algorithm assumes that the sink nodes are static. In a mobile application, before a sink node changes location, it should send a message to all neighbouring nodes informing them of its change of location, and to allow each node to delete the sink node from its routing table. When a sink node reaches its new location, an IM has to be re-sent so that all neighbouring nodes can update their routing table. This obviously incurs an energy cost that would not be required in a once-off stationary sink placement application.

4.2.2 Routing algorithm

The nature of most applications in a WSN is to detect an event within the network's application area and only then to transmit data. Depending on the number of nodes placed in a particular area, multiple nodes may have events triggered at the same time, and attempt to transmit the data. Current WSN applications generally use some form of data aggregation to reduce the number of messages transmitted in the network.

It is assumed that the data has been aggregated by the nodes, and a single node transmits the data to a sink node. If the sink node is not in the immediate wireless range of the transmitting node, one or more other nodes re-transmit the message until the message reaches the intended destination.

After initialisation, each sensor will have one or more routes to one or more sinks in the application area. When an event occurs and the node needs to send a message, it will choose the route at the top of the table. The next node in the route (i.e. one of its nearest neighbour’s) will be the intermediate destination and the sink node will be the actual destination. Nodes that are not the intermediate destination or the actual destination and that receive the message will update the route and topology information but will not re-transmit the message. The chosen route will be moved to the bottom of the table. This ensures that the same nodes are not used all the time to send a message to the sink. When a node receives a message destined for the sink, it updates its route and topology data. This allows a node to build a reverse direction view of the network topology.

For applications that place many nodes within close range of one another, the following rules will apply:

1. Nodes that are too close to the transmitting node ignore the message
2. A node will use received signal strength to determine if it is at least $\mu*R$ from the transmitting node, where $0.5 \leq \mu \leq 1$ and μ is a variable whose value is set so that the received signal can be accurately decoded.

These checks are done to ensure that nodes which are too close to each other do not re-transmit the message, which results in the hop count reaching its maximum without reaching the actual destination node. The algorithm's logic is shown in Figure 4.2.

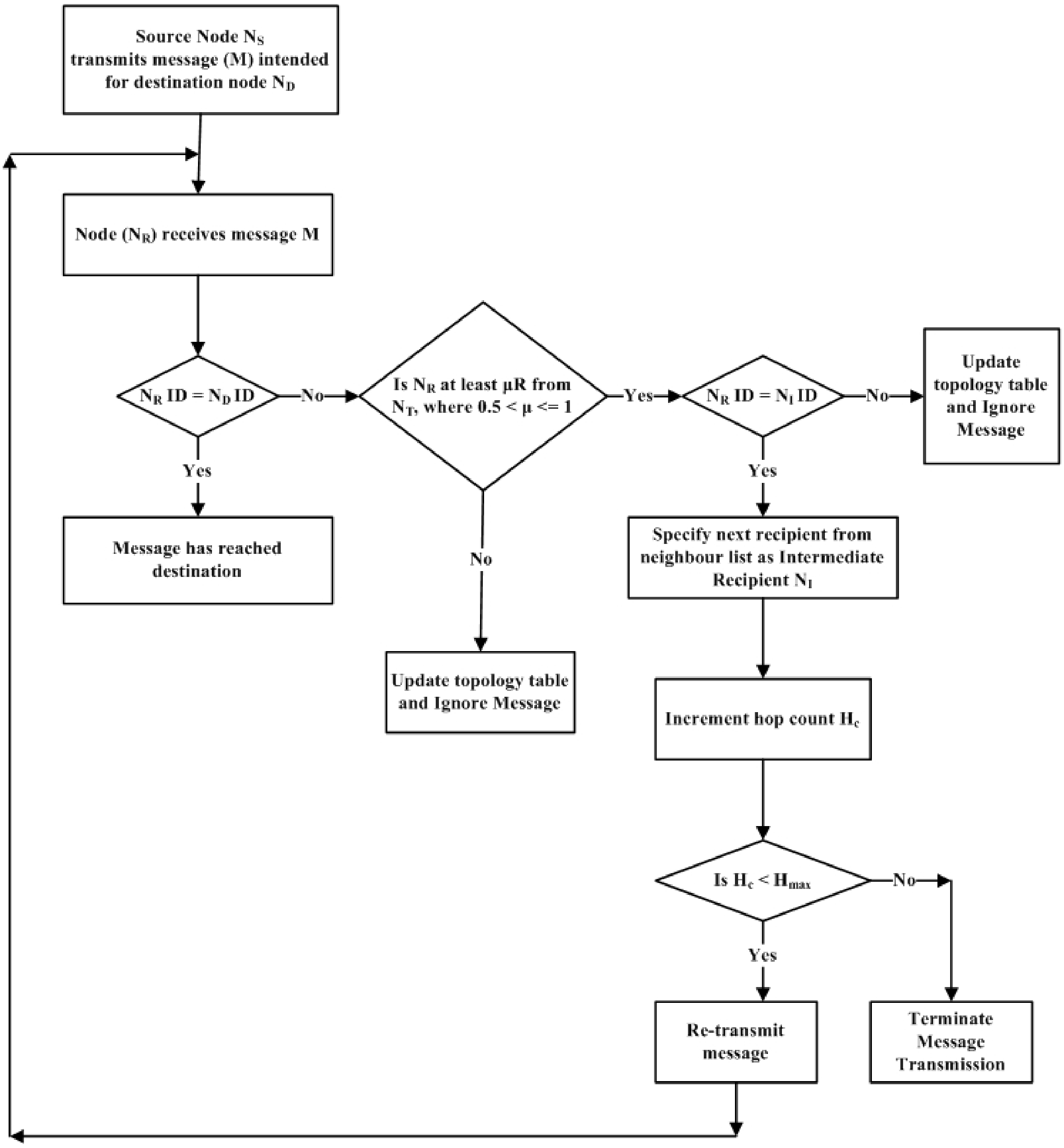

Figure 4.2: Message routing via the nearest neighbour table

The small world routing (SWR) scheme proposed is a combination of multi-hop routing, where a routing table is built and used to calculate the shortest path algorithm to determine the next neighbour node to forward a message to, and AODV concepts during the initialisation stage, when each node sends an IM to its immediate neighbours.

4.3 EXAMPLES OF RELEVANT ROUTING ALGORITHMS

In addition to flooding and gossiping (described in Chapter 2), the results are compared to the published results on the Sensor Protocol for Information via Negotiation (SPIN) published by Heinzelman et al. (Heinzelman et al., 1999). The authors in this article attempt to overcome the disadvantages of flooding (such as data implosion and resource blindness), by proposing using negotiation between nodes based on the nodes current resource levels to transmit data. The proposed data-centric routing protocol (SPIN) initially advertises the data it has using certain meta-data descriptors, to all the nodes immediate neighbours, waits for an interested sensor to request the data and then only sends the actual data to the requesting node. The SPIN family of protocols are energy aware and a node adapts the protocol to its current energy levels, i.e. it only responds to an advertisement if it has sufficient energy to receive and rebroadcast the message. The advertisement mechanism ensures that neighbouring nodes that have also sensed the event do not all send similar messages to their neighbour nodes and only those neighbours furthest from the event will request the data. The advantages and disadvantages of the SPIN family of protocols are listed in Table 4.1 (Al-Karaki & Kamal, 2004; Akkaya & Younis, 2003; Umar et al., 2007).

Advantages	Disadvantages
Since each node only needs to know immediate single-hop neighbours, any network topology changes will be localised.	If intermediate nodes are not interested in data and only distant nodes are, then the data advertisement mechanism will result in the intermediate nodes not responding to the initial meta-data advertisement and the data will not be received and passed onto the intended destination node.
Prevents data implosion as duplicate messages are not sent to the same node.	Although the meta-data message is small, the three-step protocol increases the total number of messages transmitted within the network.
Avoids data overlap by ensuring that two or more nodes sensing the same area do not send similar messages to the same neighbour.	Three-step negotiation process reduces real-time response to event notification.
Increases node lifetime and hence network longevity by preventing nodes with reduced energy from forwarding data messages.	

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

An example of a hierarchical routing protocol is the *L*ow *E*nergy *A*daptive *C*lustering *H*ierarchy (LEACH) proposed by Heinzelman et al. LEACH is a combination hierarchical and cluster-based scheme that groups sensors and appoints a cluster head to transmit messages to the sink, thus saving the surrounding nodes energy (Heinzelman et al., 2000). A percentage of the sensor nodes are selected as cluster heads using a randomised technique. The elected cluster head sends an advertisement message to all nodes in the network.

In our algorithm the “cluster heads”, i.e. sinks are selected from nodes placed at specific points within the application area where these nodes are a specific number of hops from the farthest node. An “advertisement” or IM is sent from each sink to inform all nodes how many hops the node is from the sink and to provide each node with a route table.

Some of the disadvantages of LEACH include inefficient operation if the cluster-heads are concentrated in one part of the network and the potential extra overhead that may result from dynamic clustering (Umar et al., 2007).

Yu et. al demonstrates that a small world routing protocol does reduce the number of broadcast messages required to reach the destination node. The authors select strong (near) and weak (far) links for their routing protocol to create a small world effect for routing a message (Yu et al., 2008). Unlike our solution, where locating sinks at specific locations in the application area is proposed to create the long edge required for small world networks, the authors suggest searching for weak (far) links a specific number of hops away using broadcasts. This imposes an energy cost on network nodes which will exceed that of the proposed IM at network start-up, as these searches will increase the number of messages within a network every time an event message has to be reported.

Xi et. al propose a Small World Topology-Aware Routing (SWTAR) protocol, based on increasing topology awareness of a node's non-neighbours based on small world concepts, so as to enhance traditional geographic routing of messages, where only immediate neighbour nodes are known (Xi & Liu, 2009). This paper indicates that the use of the small world concept has definite applicability in the WSN field to improve packet routing. In this article, the authors propose creating topology awareness of the network similar to work done in this thesis in order to improve message routing. Xi et al. propose dividing the application area into a series of concentric annuluses within which anchor nodes are randomly located in a plane according to the Poisson process with density function decaying exponentially as the length of shortcut between the contact nodes (i.e. Kleinberg's theory). Greedy forwarding is used by nodes until a message arrives at a node which is closer to the anchor point than all its neighbours. This node sends back a message to alert the nodes that this node can be used as a path to the anchor node.

The key difference between the solution presented in this thesis is that an IM is sent from each sink (anchor node) to all neighbouring nodes. This IM is re-propagated through to other nodes in the application area for a specific number of hops. This reduces the total number of messages sent and received in the application area on initialisation. In addition, owing to the “wireless multicast advantage” (Wieselthier et al., 2002), an awareness of the network topology to enable optimal routing is obtained. A sensor node will generally obtain two or more paths to the sink node. This ensures that alternate paths can be used when routing to the sink (anchor) node, thus increasing overall node longevity in the solution presented in this thesis.

4.4 EXPERIMENTAL SIMULATION

A program to calculate the number and placement of the sinks was developed. This program was used to create the node topology (scenario file) for use in the Network Simulator (NS-2). Additional C++ and Tcl programs were programmed to work with the existing NS-2 installation. These programs were used to send an IM from one or more sinks to all nodes for the specified number of hops, and then to send a direct message from a node to the nearest sink node using the routing paths that were formed by the propagation of the IM at start-up.

NS-2 was used to compare the routing capabilities of the small world inspired routing algorithm against the routing capabilities of flooding and gossiping. A comparison of the cost of the IM of the small world inspired routing algorithm to the routing capabilities of flooding and gossiping was done. Afterwards, an indirect comparison of the result obtained to the result presented by (Heinzelman et al., 1999) using flooding and gossiping as the common base is discussed.

To ensure consistency in comparison with Heinzelman et al. the WSN shown in Figure 4.3 was set-up in NS-2. The network assumes nodes are placed in a 40x40 two-dimensional grid. The network consists of 25 nodes, one sink node placed in the centre of the grid and 24 sensor nodes placed three or fewer hops from the sink. It is assumed that all nodes will eventually receive an IM. Similar values were used as those described in Heinzelman et al. In summary, each node has an initial energy of 1.6J, an accurate message range of 10m between neighbours, the power used to send a message is 600mW and the power used to receive a message is 200mW. Each message size is 500 bytes (Heinzelman et al., 1999).

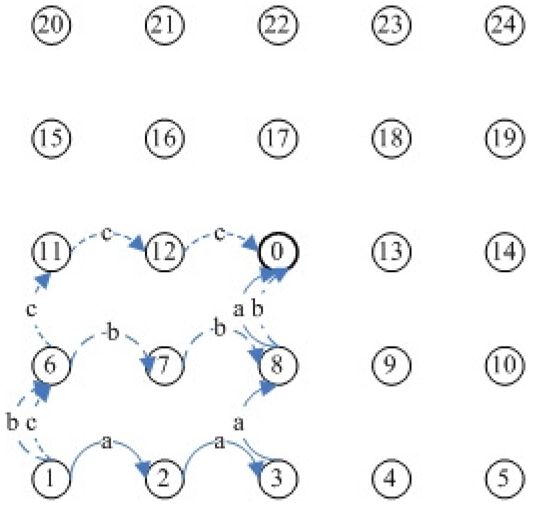

Figure 4.3: Possible routes from sensor to sink

4.5 RESULTS AND ANALYSIS

In order to determine the effectiveness of routing a message within a small world WSN the experiment was run for flooding, gossiping and the SWR algorithm. Two types of experimental topologies are used:

1. Sink placed in the centre of the application area.
2. Sink placed in the top right-hand corner of the application area.

In the first scenario, messages were sent from nodes 1, 5, 20 and 24 to the destination sink, node 0 (Figure 4.3). These nodes were chosen because the nodes are the furthest from the sink node in the given topology. A message was sent four times from node 1, 5, 20 and 24 to destination node 0. In the second scenario, messages were sent from node 1 to the destination sink node 24 (for consistency with (Heinzelman et al., 1999)). In gossiping, a pseudo-random function chose the next node to send the message to. In flooding the message is sent to all neighbours within range.

In SWR, a once-off IM is sent from the sink node, to create a routing table at each node. This IM is re-transmitted by each node that receives an IM for the specified number of hop counts; if the maximum hop count is not reached, the IM is re-transmitted to all the node's immediate neighbours. The small-world algorithm uses the routing table in the IM to build a routing table in each node. The routing table allows a node to decide which of its immediate neighbours should be the intermediary node to route a message to the destination node. This allows a node to send a direct message along a specific path to the destination. Therefore, each transmission by a node uses the specified number of hops or fewer to reach the destination node.

As gossiping is dependent on a pseudo-random function that chooses the next node to send the message to, the destination is not always reached. The gossiping results discussed here are best-case scenarios (destination node actually reached). The best-case scenario in gossiping occurred when the pseudo-random function did not loop back to previously used nodes. When there was loop back, the destination node was not reached. In flooding, messages are broadcast to all neighbouring nodes, even after a message has reached its destination. In gossiping and SWR, the message re-transmissions stop after they reach the specified destination.

4.5.1 Scenario 1

Figure 4.4 shows the number of total messages sent and received from nodes 1, 5, 20 and 24 to reach the destination node (i.e., node 0) over time elapsed. From Figure 4.4, there is no time delay in routing a message for SWR without the IM. In SWR with the IM, there is a time lag at initialisation to send the IM and calculate the route table.

For this particular scenario, a total of 70 messages were required at initialisation to create a routing table at each node. The number of messages sent and received to reach the destination node in SWR with and without the added cost of the IM, shows a significant improvement over both flooding and best-case gossiping.

Figure 4.5, shows the energy used to route a message from nodes 1, 5, 20 and 24 to reach the destination node (i.e., node 0). From the reduced number of messages transmitted in the small world scheme, there is less energy usage which implies longer node lifetime and hence longer network lifetimes can be achieved.

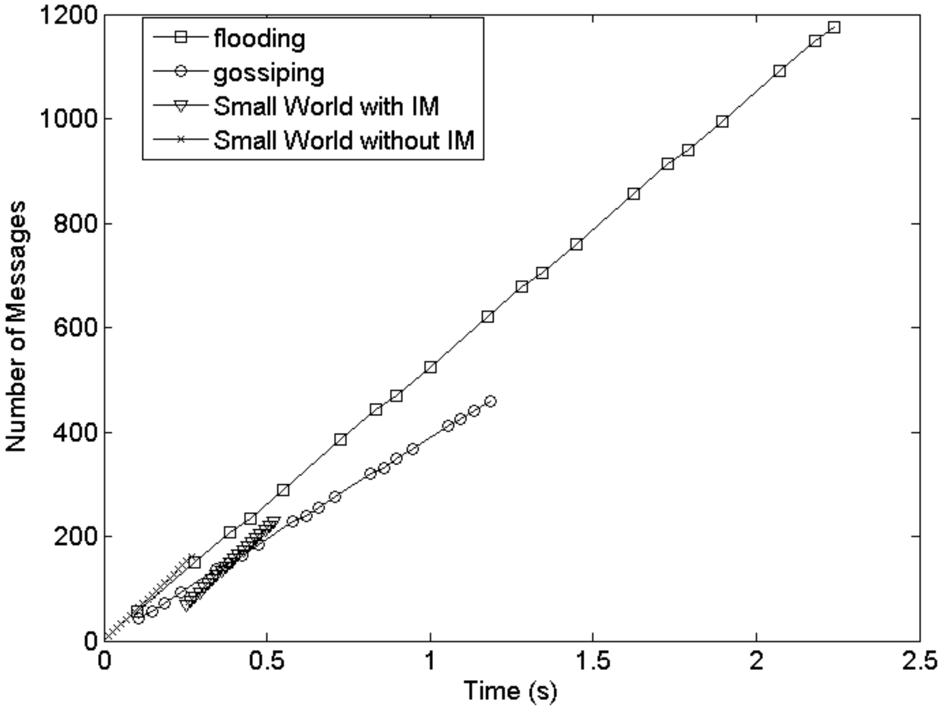

Figure 4.4: Messages vs. time (Nodes [1,5,20,24] to [0])

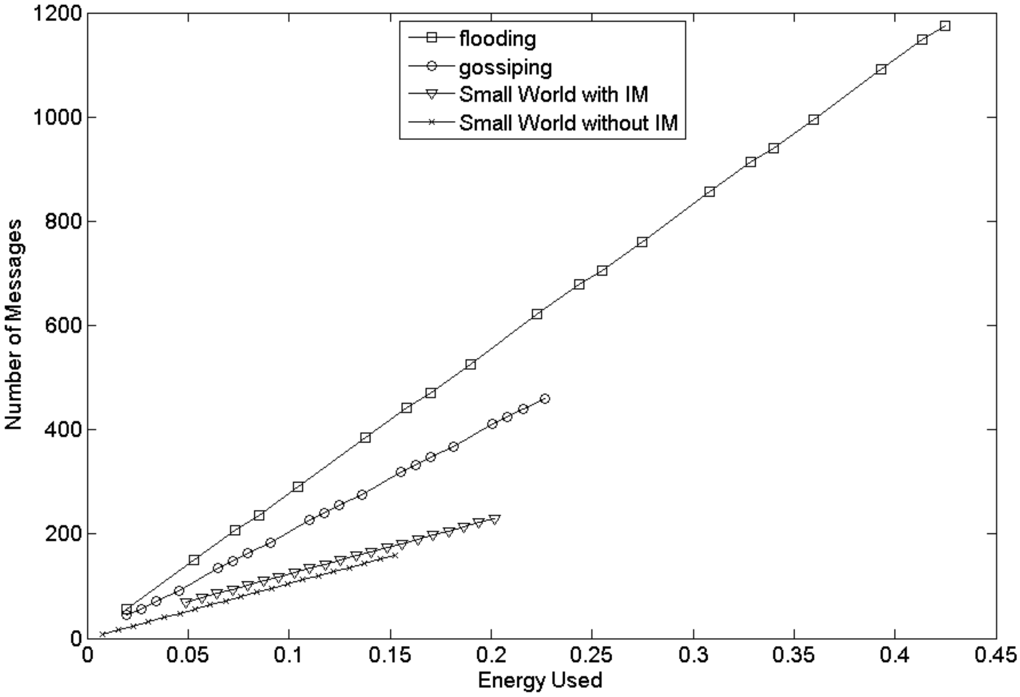

Figure 4.5: Messages vs. energy (Nodes [1,5,20,24] to [0])

4.5.2 Scenario 2

When a message was sent from node 1 to node 24, i.e. the furthest destination from each other, SWR still outperformed flooding. The direct small world (without IM) send was best as the maximum number of sends and receives are limited to the number of node hops plus the sending and receiving nodes. As shown in Figure 4.6, the number of messages increases during the IM phase and then levels off as only send-direct messages are routed. Flooding was the worst performer, even though counting of messages was stopped, once the destination node had received a message. When the gossiping algorithm performed optimally, gossiping performed slightly better than SWR with the IM included. However, its larger gradient indicates that it would eventually perform worse than SWR as the number of messages from the transmitting node increases. When the IM is not included, the SWR algorithm performs better than gossiping as shown in Figure 4.7.

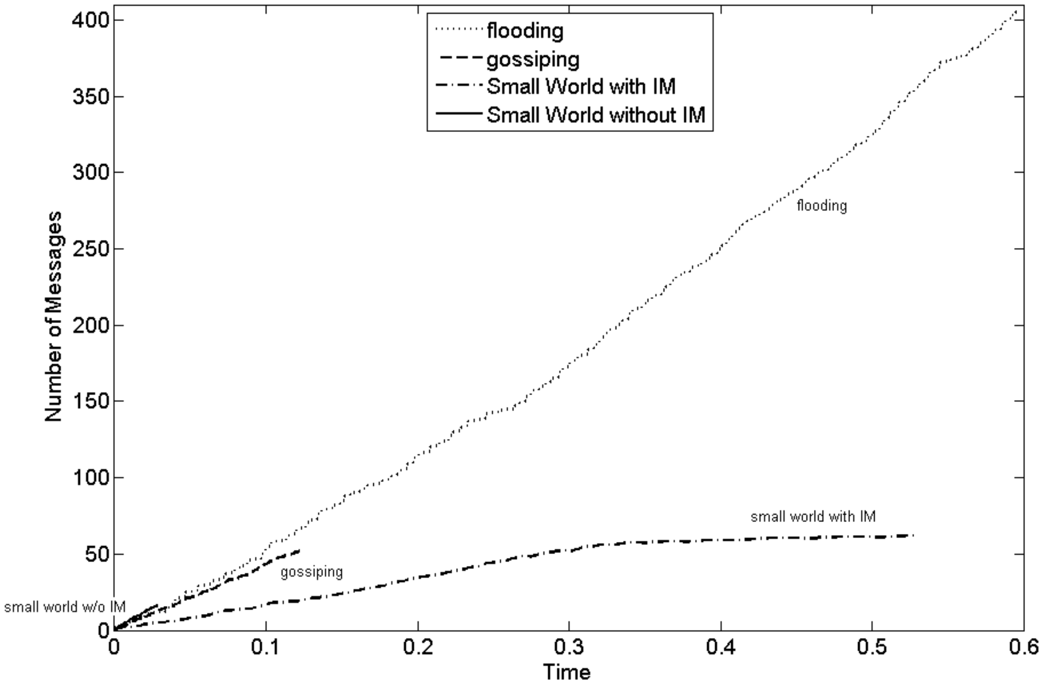

Figure 4.6: Messages vs. time (Node[1]to[24])

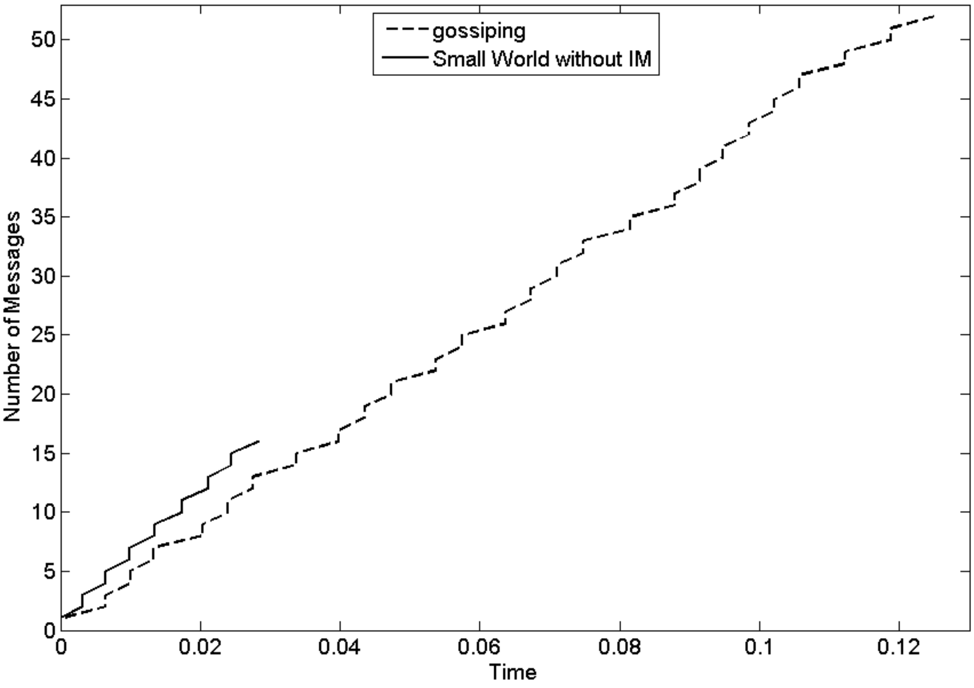

Figure 4.7: SWR without IM vs. gossiping

Figure 4.8 shows the energy used to send an IM from node 24 to node 1, and thereafter, a normal message from node 1 to node 24. It also shows the energy used to send a message from node 1 to node 24 using flooding and gossiping. As can be seen, there is initial large energy consumption that tracks flooding until all nodes have sent an IM. Thereafter, the energy consumption levels off significantly as nodes use a specific path to send messages. When the pseudo-random function chose the optimum route in gossiping, gossiping outperformed SWR. However, when the IM is discounted as a once-off cost in SWR, the SWR algorithm outperforms gossiping, as shown in Figure 4.7.

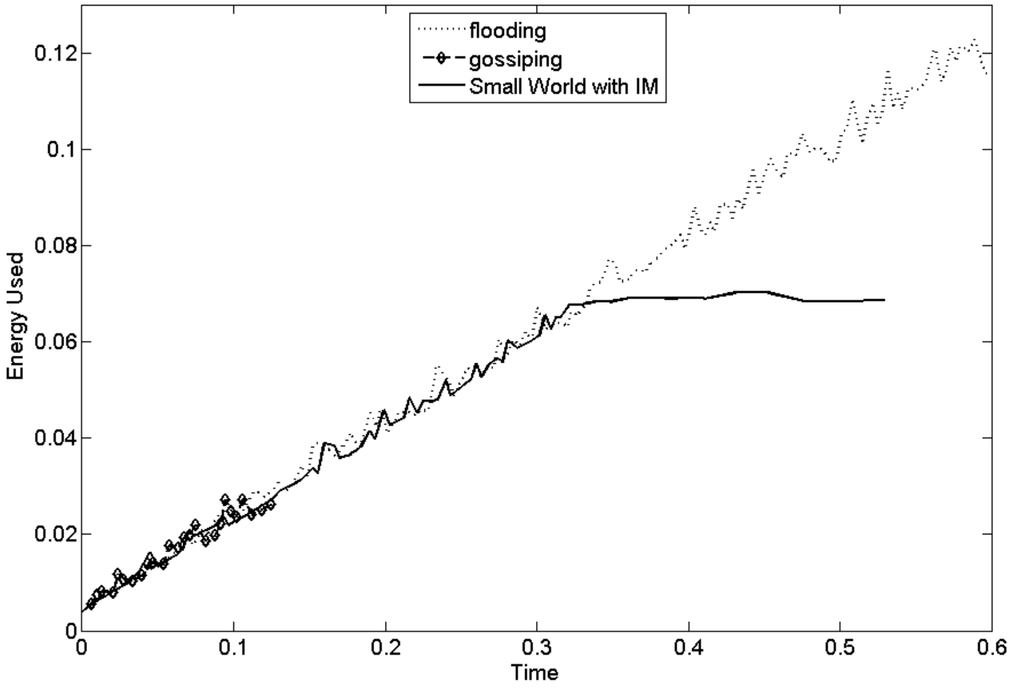

Figure 4.8: Energy usage to send message (Node[1] to [24])

As gossiping is dependent on a pseudo-random function that chooses the next node to send the message to, the destination is not always reached. The gossiping results discussed here are best-case scenarios, where the pseudo-random function did not loop back to previously used nodes. From the figures, one can see that the IM carries a cost. If only one message is transmitted, then gossiping can be more effective. However as the number of transmitted messages increase, the cost of the SWR algorithm increases at most by the number of hops plus one (e.g. four sent messages equate to sending node plus three hop sends).

A direct comparison with SPIN was not performed because no access to the NS-2 agents developed for use in SPIN was available. However, both SPIN and the proposed SWR algorithm appear to perform better than flooding. Better results were achieved with gossiping then (Heinzelman et al., 1999), but this is dependent on the pseudo-random implementation used.

4.6 CONCLUSION

Small world based routing offers significant advantages over other forms of routing, such as flooding and gossiping, provided more than one message is sent. It has been shown that the number of messages required to route a message is restricted to the number of hops from a sink. This results in increased node longevity and hence network lifetime.

The once-off cost at initialisation of transmitting an IM to determine the route to the sink node at an individual node is small. It is hoped that these costs could be included with other initialisation messages when the network is set up to reduce energy usage.

The use of an IM propagated at network start-up from one or more sinks located within the WSN application area creates multiple paths to a sink. These paths can be used to ensure that different sets of intermediate nodes are used to forward the message to the destination sink.

In Chapter 5, the relationship between the number of hops from a static sink and the total number of IMs sent within the WSN and the impact of the IM on individual nodes is analysed.

4.7 DECLARATION

The work in this chapter has been published as a book chapter in the following book: Advances in Wireless Networks and Information Systems, Lecture Notes in Electrical Engineering, Vol. 72, Luo, Qi (Ed.), 1st Edition, 2010, pp.183–192.

CHAPTER 5

EFFECT OF SMALL WORLD ROUTING ON NODE LONGEVITY

It was shown in Chapter 3 that placing sinks at predetermined positions within a WSN creates long edges that can model a small world network. In Chapter 4 an initialisation message (IM) to set-up a routing path to one or more sinks placed within a WSN application area is discussed. The purpose of Chapters 3 and 4 was to develop an energy efficient routing algorithm to reduce the total number of messages transmitted within the network.

In this chapter it is shown that although route discovery using an IM is slightly more resource intensive during start-up, it does not excessively drain any specific node more than others, which means that the processing load for route discovery is balanced out.

5.1 INTRODUCTION

There is an additional problem in the WSN environment - once a route is determined, if the same set of nodes are continuously used to forward messages to the destination node, then the energy resources of this set of nodes will decline rapidly, resulting in shorter node lifetimes and possibly as a result of reduced network coverage, the WSN could die prematurely.

The use of an IM propagated at network start-up from one or more sinks located within the WSN application area creates multiple paths from any node to a sink. The creation of multiple routes means that different nodes can be used to route event messages to the sink. A node can choose from the routes in its routing table to determine the path a message should take to reach a sink. Varying the intermediate nodes used to re-transmit a message allows more equitable usage of nodes in a WSN.

In this chapter, the analysis done in Chapters 3 and 4 is broadened to determine if the number of hops has a significant effect on reducing the total number of IMs sent in an application area. The effect of the hop count on the number of messages transmitted and received at individual node level as a result of the once-off IM is analysed. Finally, a comparison of the total number of messages sent and received by each node in the network when there is only one sink within the application area using the IM and simple flooding is shown. The effect of restricting flooding messages to the same number of hops as the IM as well as almost unrestricted flooding (i.e., a large hop count) was analysed.

5.2 ALGORITHM DESIGN

5.2.1 Node lifetime model

According to Hou, Shi and Sherali, the network capacity is the maximum amount of bit volume that can be successfully delivered to the sink node by all the nodes in the network, whereas network lifetime refers to the maximum time limit that nodes in the network remain alive until one or more nodes drain up their energy (Hou et al., 2008). If this definition of network capacity is extrapolated to include the maximum amount of bit volume that can be successfully received and transmitted by each node in a WSN, the approximate lifetime of each node in a WSN can be calculated, given the following definitions in Table 5.1:

Variable	Description
T	Node lifetime
P	Sensor node power based on battery.
E_c	Total energy consumed
E_{Rx}	Energy used to receive a message
E_{Tx}	Energy used to transmit a message
E_{Route}	Energy required to route a message
E_{Sense}	Energy required to sense for events
$E_{Process}$	Energy required to process data
r	Estimated number of messages a node will receive
t	Estimated number of messages a node will transmit.
p	Estimated number of messages a node will be required to route.

Table 5.1: Description of variables used in node longevity calculations

Each sensor node will consume energy based on the following formula:

$$E_c = E_{Route} * p + E_{Rx} * r + E_{Tx} * t + E_{Sense} + E_{Process} \qquad [5.1]$$

Routing involves receiving a message and then re-transmitting the message, therefore:

$$E_{Route} = E_{Rx} + E_{Tx} \qquad [5.2]$$

For small transmission ranges, the energy to send and receive a message is approximately the same; therefore Equation [5.1] can be re-written by using Equation [5.2] as:

$$E_c = 2 * E * p + E * r + E * t + E_{Sense} + E_{Process}$$

$$E_c = (2p + r + t)E + E_{Sense} + E_{Process} \qquad [5.3]$$

$$where, E = E_{Tx} = E_{Rx}$$

From the network topology, a reasonable estimate of the number of messages a node will receive, transmit and route can be obtained. For network topologies where nodes are randomly scattered, an estimate can be obtained based on the application area and the placement of the sink. For example if the sink is placed in the centre of the application area, nodes near the sink or nodes located in the centre of the application area that have to route messages to the sink will lose energy more quickly than nodes along the edge of the application area.

Based on the nodes hardware, it is possible to determine a good estimate of the energy required to process a message or data and the amount of energy used to sense for an event. All nodes have a battery. The available power can be calculated using the formula:

$$P = V * I$$

The lifetime of a network is dependent on node lifetime. The lifetime of a node is calculated as follows:

$$P = \frac{W}{T} \qquad [5.4]$$

, where *W*=Work (Energy in Joules) and *T* = node lifetime. Therefore, from Equation [5.3] and Equation [5.4]:

$$T = \frac{W}{P}$$

$$T = \frac{(2p+r+t)E + E_{Sense} + E_{Process}}{P} \qquad [5.5]$$

The energy consumed to process messages is related to the size of messages, i.e. the number of bits. Therefore, the node capacity is related to the node lifetime.

5.2.2 Minimising message re-transmissions

Based on the previous equations, a good estimate of the lifetime of a WSN application can be obtained at design time. One key factor to prolonging node lifetime is to reduce the number of messages each node is required to receive, transmit, re-route or process. After initialisation, each sensor will have one or more routes to one or more sinks in the application area. When an event occurs and the node needs to send a message, it will choose the route at the top of the table. The next node in the route (i.e. one of its nearest neighbours) will be the intermediate destination and the sink node will be the actual destination.

When a node receives a message destined for the sink, it updates its route and topology data. This allows a node to build a reverse direction view of the network topology. Nodes which are not the intermediate destination or the actual destination and receive the message will not re-transmit the message. The chosen route will be moved to the bottom of the table. This ensures that the same nodes are not used all the time to send a message to the sink.

5.3 ALTERNATIVE APPROACHES TO IMPROVING NETWORK LIFETIME

Turgut et. al investigate the expected lifetime of a route in mobile ad-hoc networks (Turgut et al., 2001). The lifetime of a particular route is dependent on the speed and direction of movement of all the nodes involved in the route to determine the time at which the nodes move out of each other's range. All the hops (links) in the routes are considered separately because a break in any of the hops will break the route. The expected lifetime for a link was calculated for four different mobility models: deterministic, partially deterministic, Brownian motion and Brownian motion with drift.

The authors argue that if the movement pattern of the nodes is absolutely deterministic, the lifetime of routes can be determined exactly. On the other hand, a chaotic mobility pattern will introduce uncertainty to the lifetime of the route. The difference between the solution presented in this chapter and the solution presented by Turgut et. al is that node lifetime is considered to be linked to the battery lifetime of the sensor node. Thus to increase node longevity, the number of messages received and transmitted must be low.

A graph theoretic approach to maximising the lifetime of stationary (non-mobile) network topologies such as WSNs has been proposed by Kang and Poovendran (Kang & Poovendran, 2005). The network is modelled as a directed graph and the residual battery energy is taken into consideration for a static and dynamic (self-configured) network. The authors show that the static network lifetime increases linearly as a function of the network size per square kilometre region, with a broadcast routing tree given by a minimum spanning tree algorithm. For a self-configured network, the authors observed that by dynamically updating the trees, the achievable gain in network lifetime increases by twice the optimal static lifetime. In this paper, overall network route longevity is evaluated. The lifetime of individual nodes within a route is not analysed.

Nishiyama et al. (Nishiyama et al., n.d.) focus on increasing the node longevity of nodes within the maximum transmission range of the sink node (the Sink Connectivity Area (SCA)). The authors propose a HYbrid Multi-hop routiNg (HYMN) algorithm which combines flat multi-hop routing (within the SCA) and hierarchical multi-hop routing (outside the SCA) in order to decrease the amount of data traffic transferred into the SCA and thus lower the power consumption in the SCA and increase the node longevity within the SCA. Our proposed solution does not restrict itself to the SCA but considers multiple paths.

Heinzelman et al. has proposed a combination hierarchical and cluster based LEACH (Heinzelman et al., 2000) scheme that groups sensors and overcomes the over-usage of nodes located close to a cluster by randomly selecting a cluster head to transmit messages to the sink. The analysis considers total network lifetime and does not consider individual node usage as described here.

Questions may arise why there is no direct comparison against a routing algorithm such as LEACH which also uses the idea of multiple sinks or clusters. It must be understood that according to Heinzelman et al. (Heinzelman et al., 2002), the underlying philosophy behind the development of LEACH was not message routing but data aggregation. In LEACH each node takes a turn to be a cluster head. The location of the cluster head with respect to the location of the base station (BS) or sink is not considered. Thus more data messages within the WSN may result when a message is routed from a cluster head located further from a BS than a cluster head located close to a BS. The assumption is that nodes will transmit with sufficient energy for a message to directly reach a cluster head, thus there are no intermediate nodes required to route a message to the cluster head. There are no restrictions on the distance between the nodes and their cluster heads. To ensure equitable usage of all nodes LEACH does not consider the drain on intermediate or surrounding nodes energy from received signals as the assumption is that nodes are only awake during their allocated time slot to transmit. Thus it can be seen that LEACH cannot be used to provide a valid comparison against the small world routing algorithm because of the key differences and assumptions between the two algorithms.

5.4 RESULTS AND ANALYSIS

The same experimental setup as described in Chapter 4 was run using the network simulator NS-2, with varying application area sizes and hop counts.

5.4.1 Total messages vs. number of hops

The relationship between the total numbers of messages sent and received in the application area as IMs versus the number of hops is analysed. As expected, the total number of IMs declined as the number of hops increased and the number of sinks decreased. This is because each sink will generate and start an IM cycle that will be continued by the surrounding nodes for the specified number of hops. There will be some overlap of IMs with some nodes receiving IMs from more than one sink depending on the network topology. With a single sink, only one IM is generated and required to be passed on by neighbouring nodes. This results in fewer IMs generated on start-up.

If the number of IMs is less with a single sink, does it make sense to have multiple sinks in the application area? This depends on the following factors: size of application area, node density, the required number of hops to reach a sink and expected network lifetime.

For a large application area, a single sink may not be optimum because many hops may be required for an event message to reach the sink. As communication is wireless, this means that a larger number of surrounding nodes will receive (and possibly have to re-transmit) the message en route to the sink. The nodes closer to the sink will receive more messages and hence their battery lifetime will decrease more rapidly, affecting the total network lifetime. More sinks result in fewer messages sent and received by individual nodes within the network, thus increasing node and hence overall network lifetime. Therefore, the once-off cost of the IM with multiple sinks outweighs the benefit of having a single sink.

If the sinks are stationary and only one IM process will be generated during the start-up phase of the network, the total cost of having fewer messages generated within the network outweighs the extra cost of the IM at start-up. Figure 5.1 shows the relationship between hops, sinks and total number of IMs sent within the application area during the start-up phase. The graph plots the total number of IMs for three different application areas typically used in industrial applications, namely 100mx100m, 200mx200m and 300mx300m. As the number of hops increases, the number of sinks decreases until there is only one sink in the application area.

As can be seen in Figure 5.1, after three hops there appears to be a gradual decline in total messages. Therefore a good rule of thumb would be that the total number of hops should be in the range $3 \leq hops \leq max$, where max is the number of hops that would require only one sink for the application area. The closest similar type of comparison that has been found is that done by Heinzelman et al. (Heinzelman et al., 2002), where it was shown that the optimum number of clusters is around 3 to 5 for a 100 node, 100mx100m application area WSN. In their study, the average energy dissipated increases after 5 nodes because the other nodes in the cluster have to transmit data over a larger distance to reach the node's cluster head.

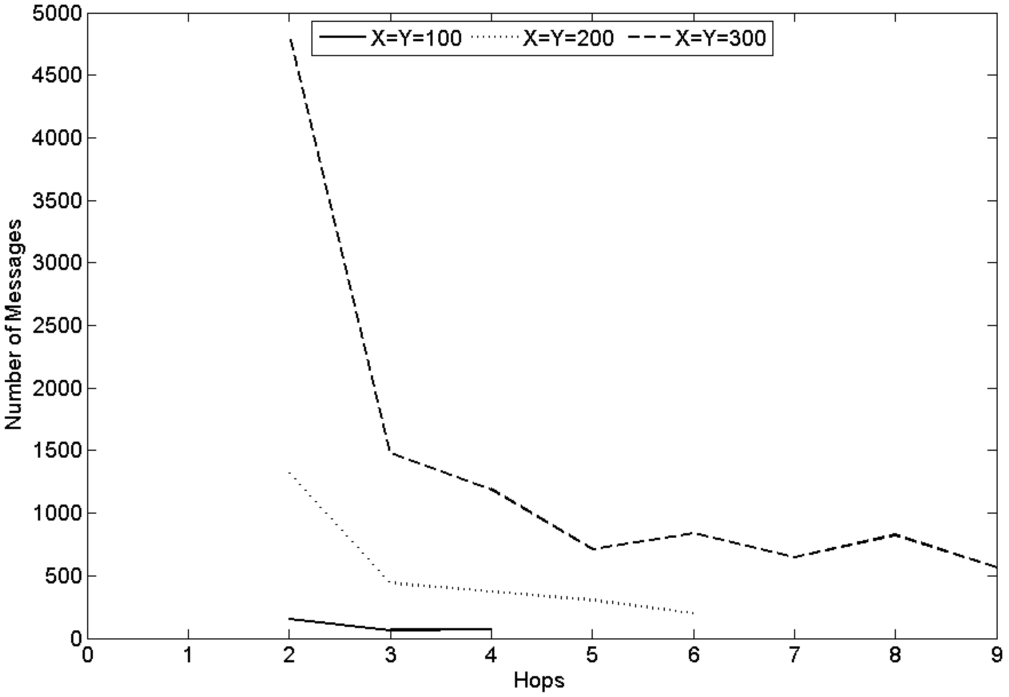

Figure 5.1: Total number of IMs versus number of hops/sinks

5.4.2 Total messages per node vs. number of hops

The effect of the reduction in IMs as the hop count increases and the number of sinks is reduced to one is even more marked when examined per individual node in terms of the total number of IMs sent and received per node. The flooding, gossiping and SWR algorithm was run for three different application areas typically used in industrial applications, namely 100mx100m, 200mx200m and 300mx300m, with a node range of 30 m. Figure 5.2, Figure 5.3 and Figure 5.4 show node and sink placement within the application area, where only one sink is used.

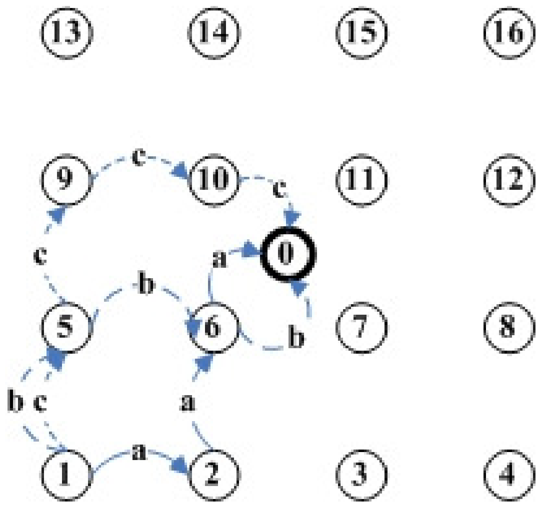

Figure 5.2: Application area 100mx100m

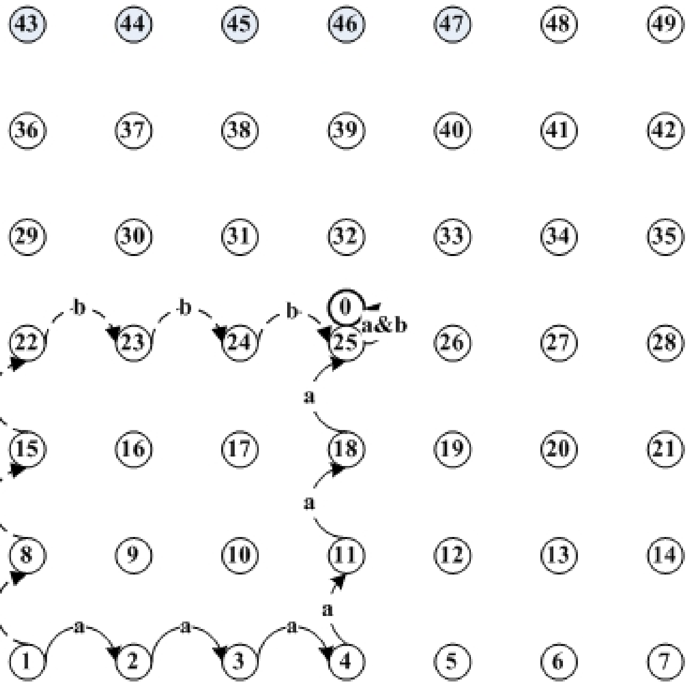

Figure 5.3: Application area 200mx200

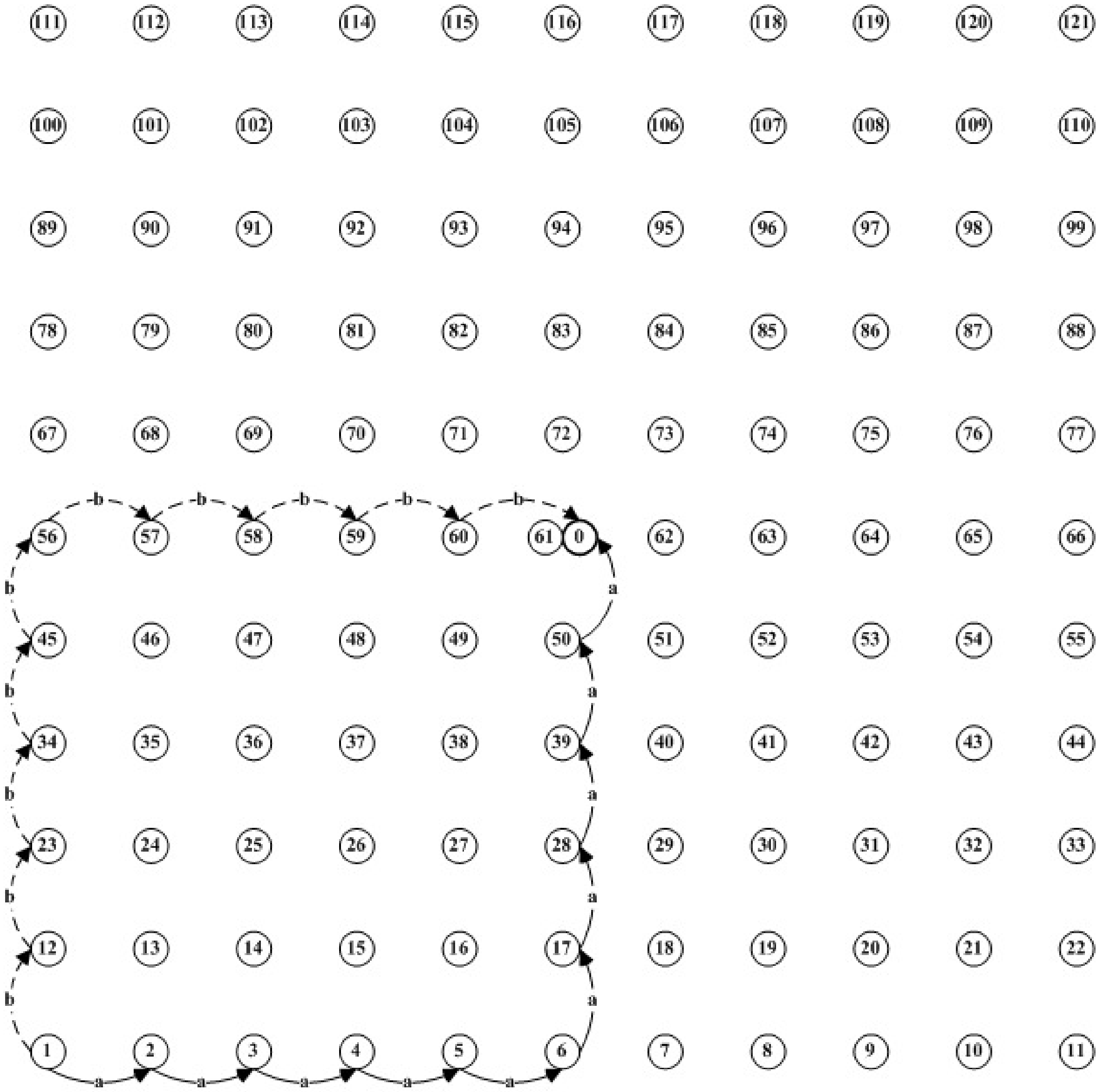

Figure 5.4: Application area 300mx300m

The arrows *'a'*, *'b'* and *'c'* indicate possible routes to the sink from node **1**. In flooding a message was sent from node **1** to the sink. In SWR, first an IM was sent, starting from the sink to all nodes in the application area. Thereafter, node **1** sent a message to the sink. As the previous comparison (Figure 4.6 and Figure 4.7) showcased gossiping, the exact original code was run for gossiping with a larger application area and more nodes. For the larger application areas and node sets, the gossiping pseudo-random algorithm recursively looped through previously chosen nodes without reaching the destination sink (node **0**). Therefore, the following figures show the number of messages sent and received per node for the specified application area for flooding and SWR only.

Figure 5.5, Figure 5.6 and Figure 5.7 show the number of IMs sent or received per node when each application has one or more sinks located within the application area.

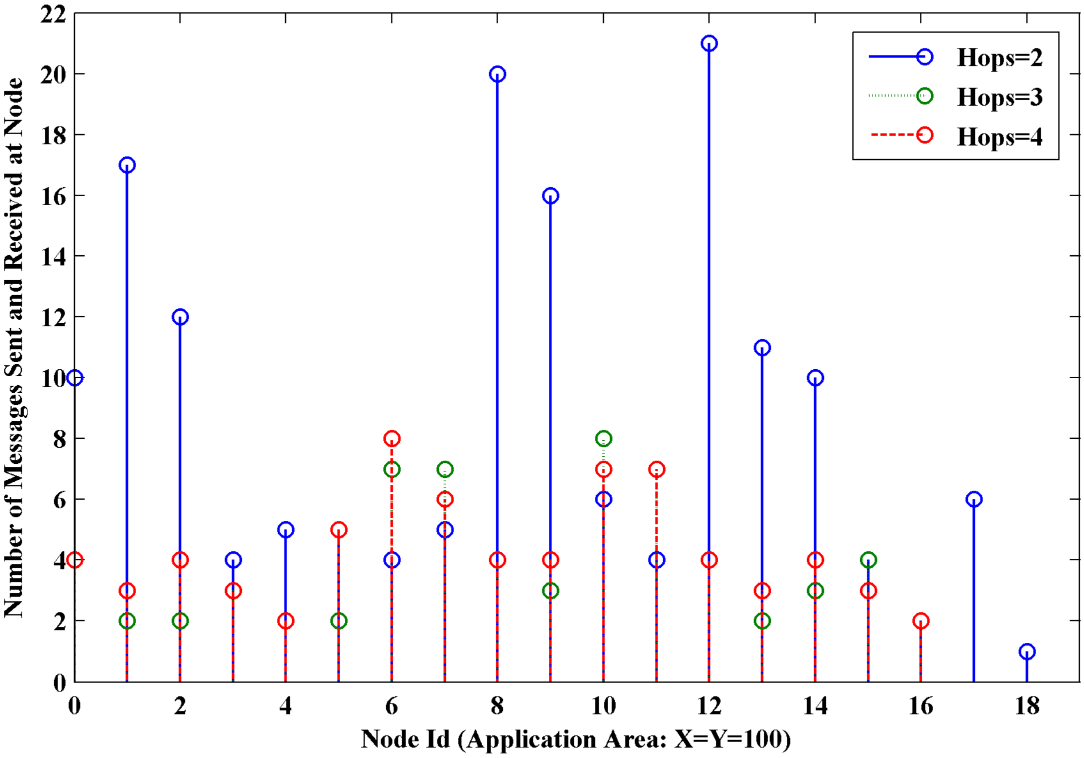

Figure 5.5: IMs per node [area 100mx100m]

In the 100mx100m application area (Figure 5.5), for a low hop count (i.e. hop = 2), each node receives a large number of IMs, with the nodes with the largest number of messages not restricted to nodes closest to the sink node. As the hop count increases (so that only one sink is required), the nodes closest to the sink node (i.e. nodes 6, 7, 10 and 11), receive the largest number of messages. The maximum number of messages is eight (8) compared to the two (2) messages received at nodes 1, 2, 4 and 16.

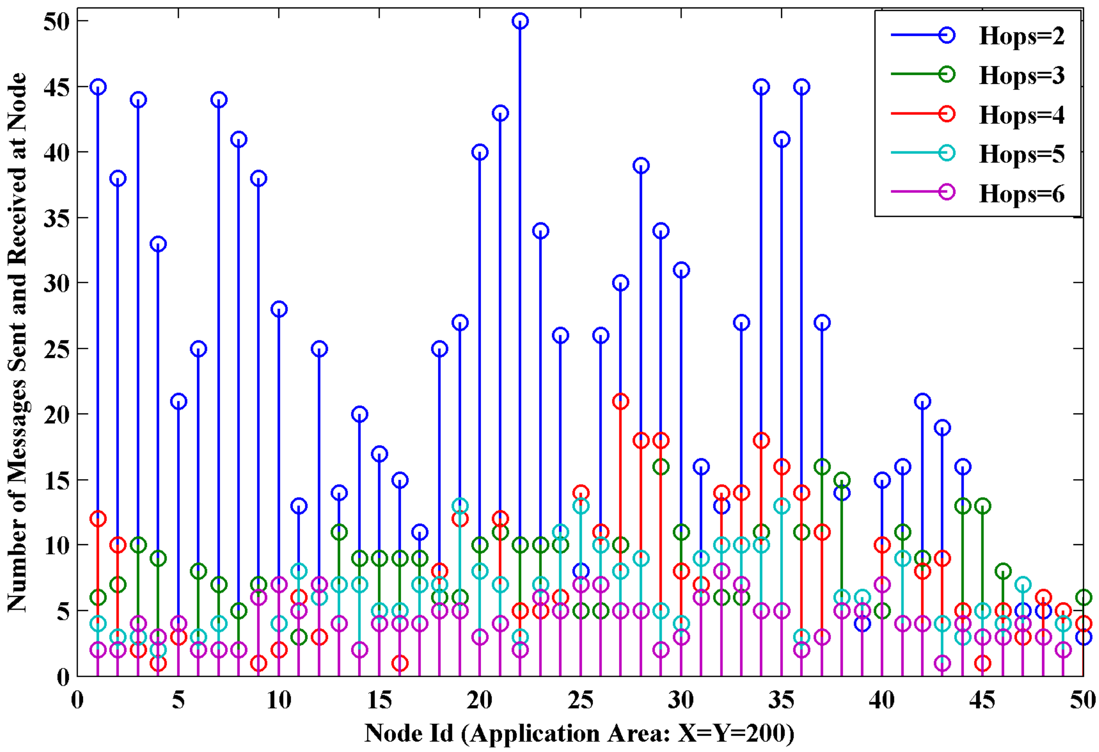

Figure 5.6: IMs per node [area 200mx200m]

In the 200mx200m application area (Figure 5.6), for a low hop count, i.e. two hops, 11 sinks are placed at predetermined locations within the application area. As expected, the nodes closest to a sink node receive more messages. When the hop count increases (so that only one sink is required), the node that receives or re-transmits the largest number of messages is node 32 with eight (8) messages, while the node with the smallest number of messages is node 43 at one (1) message.

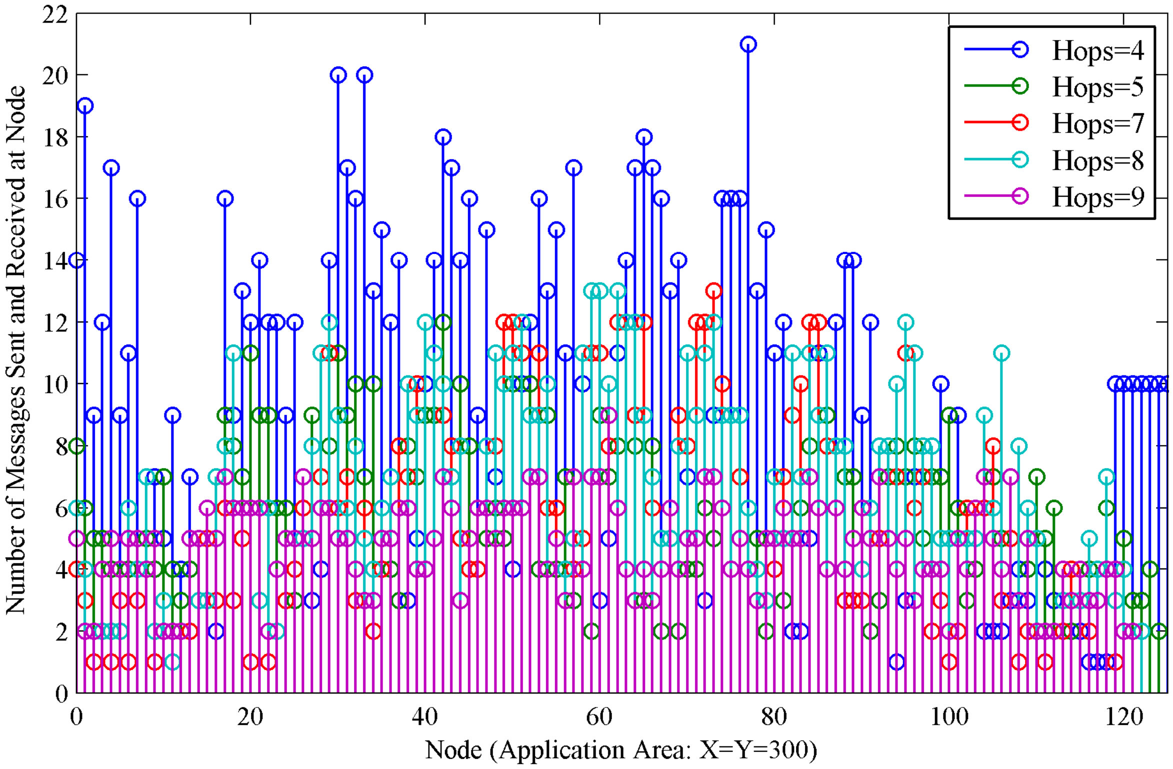

Figure 5.7: IMs per node [area 300mx300m]

In Figure 5.7, the number of messages re-transmitted and received per node for four hops, five hops, seven hops, eight hops and nine hops is plotted. The reason smaller hops are not shown in Figure 5.7 is that the figure will be more overcrowded than it currently is and for a hop count of two the maximum number of messages (at node 36) is 75, for a hop count of three, the maximum number of messages is 27 (at node 82), and at hop count of six, the maximum number of messages is 21 (at node 74). When the hop count increases (so that only one sink is required), the node that receives or re-transmits the largest number of messages is node 61, with nine (9) messages.

As can be seen for hop counts greater than four, the number of IMs per node is not large. Therefore, if a future application of a WSN requires that at least a few messages be transmitted to the sink per node in a 24-hour cycle, placing a few sinks within the application area at a hop count of five will reduce the number of messages seen per node, notwithstanding the larger total number of IMs sent on start-up, because once the route is known, the number of messages seen per node will be significantly reduced, as demonstrated in Figure 4.7. Nodes which are immediate neighbours to the sink node do receive and re-transmit the larger number of messages but by alternating routes to the sink, as discussed in a later section of this paper, the overall number of messages per node can be reduced.

Figure 5.8 shows the number of messages sent and received per node when the flooding is given a hop maximum of three and four hops for a 100mx100m application area and **one** sink, and Figure 5.9 shows the number of messages sent and received per node when flooding is given a hop maximum of 100 hops. Similarly, Figure 5.10 and Figure 5.11 show the number of messages sent and received per node when flooding is given a hop maximum of six hops or 100 hops respectively, for a 200mx200m application area and only **one** sink required. Figure 5.12 and Figure 5.13 show the number of messages sent and received per node when the flooding is given a hop maximum of nine hops or 100 hops respectively, for a 300mx300m application area with only **one** sink.

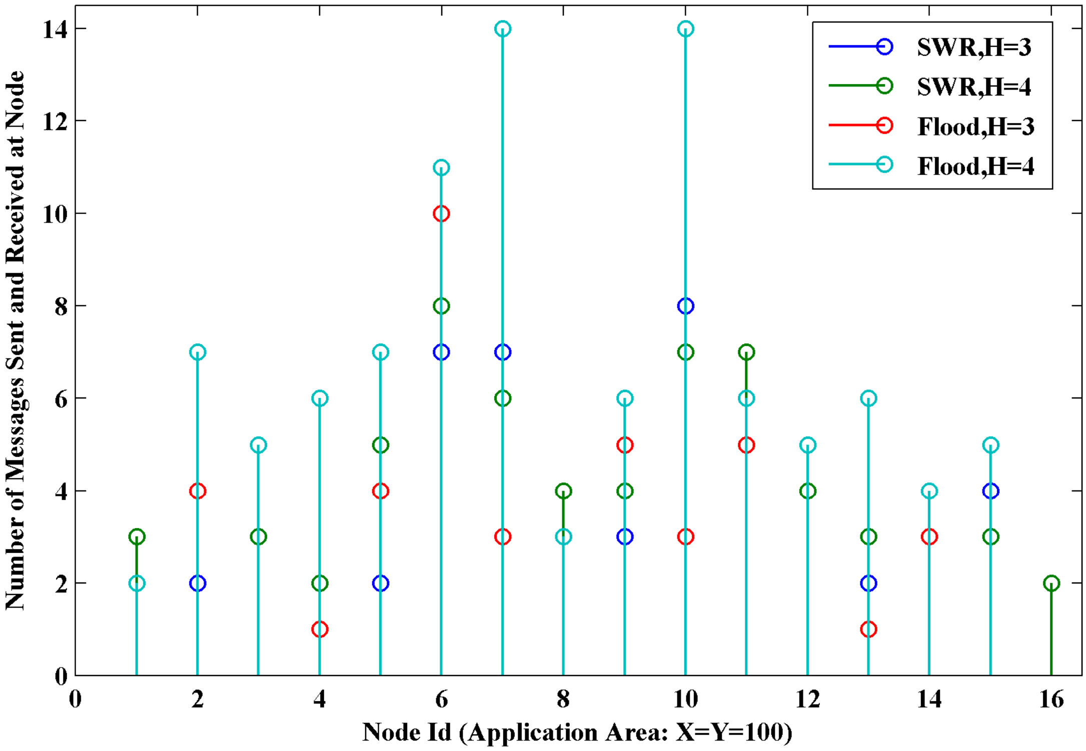

Figure 5.8: SWR and flooding (flooding restricted to same hop count as SWR)

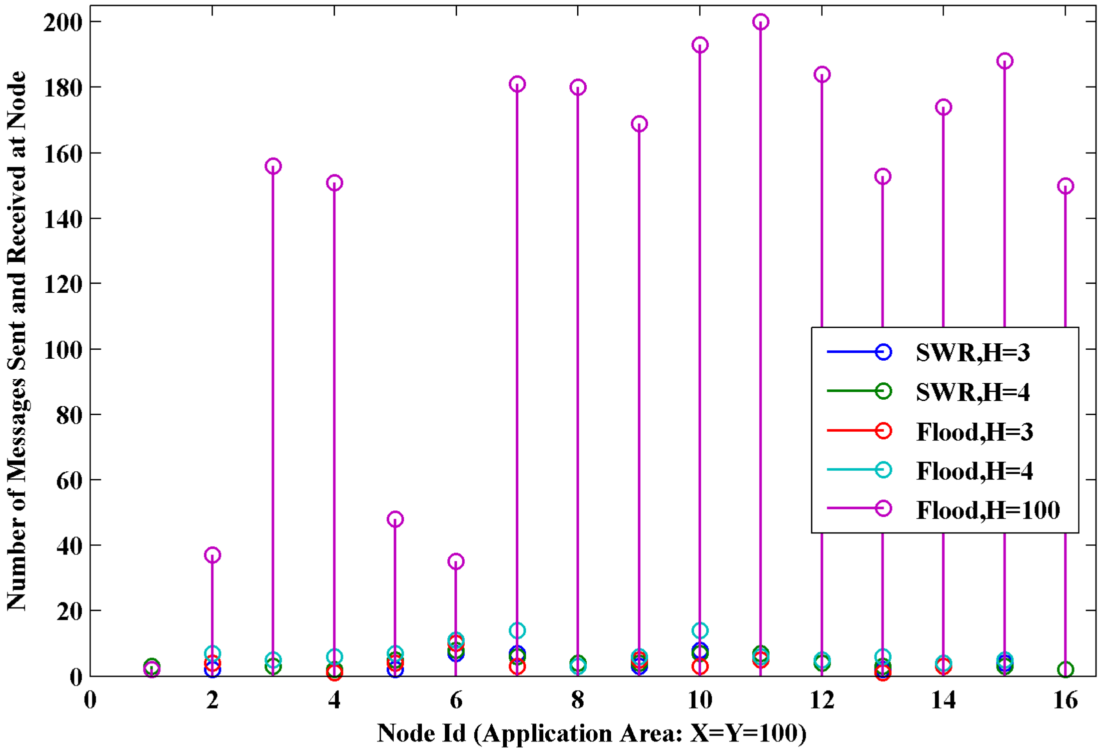

Figure 5.9: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction)

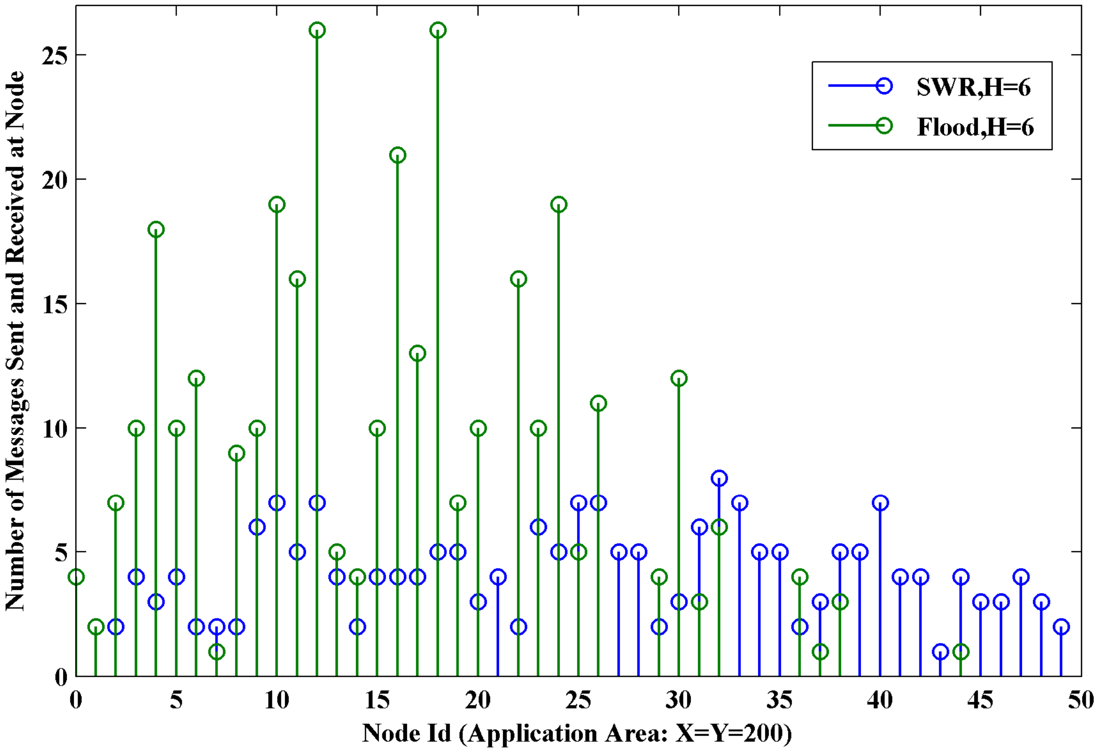

Figure 5.10: SWR and flooding (flooding restricted to same hop count as SWN)

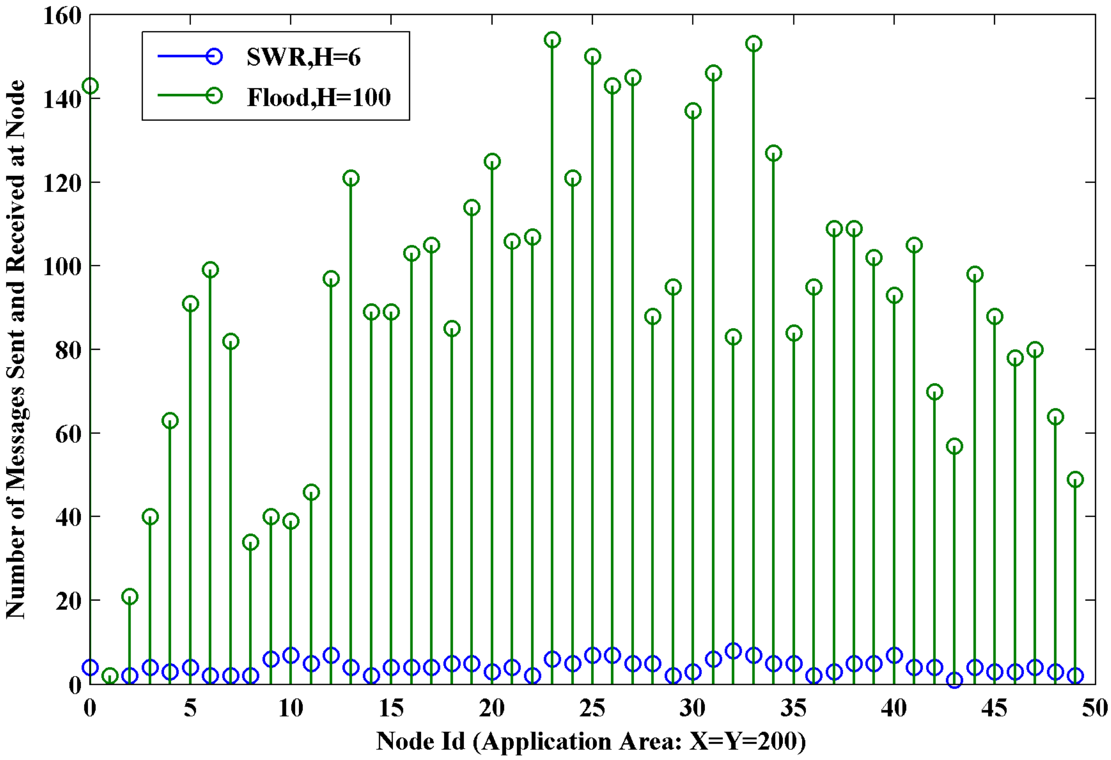

Figure 5.11: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction)

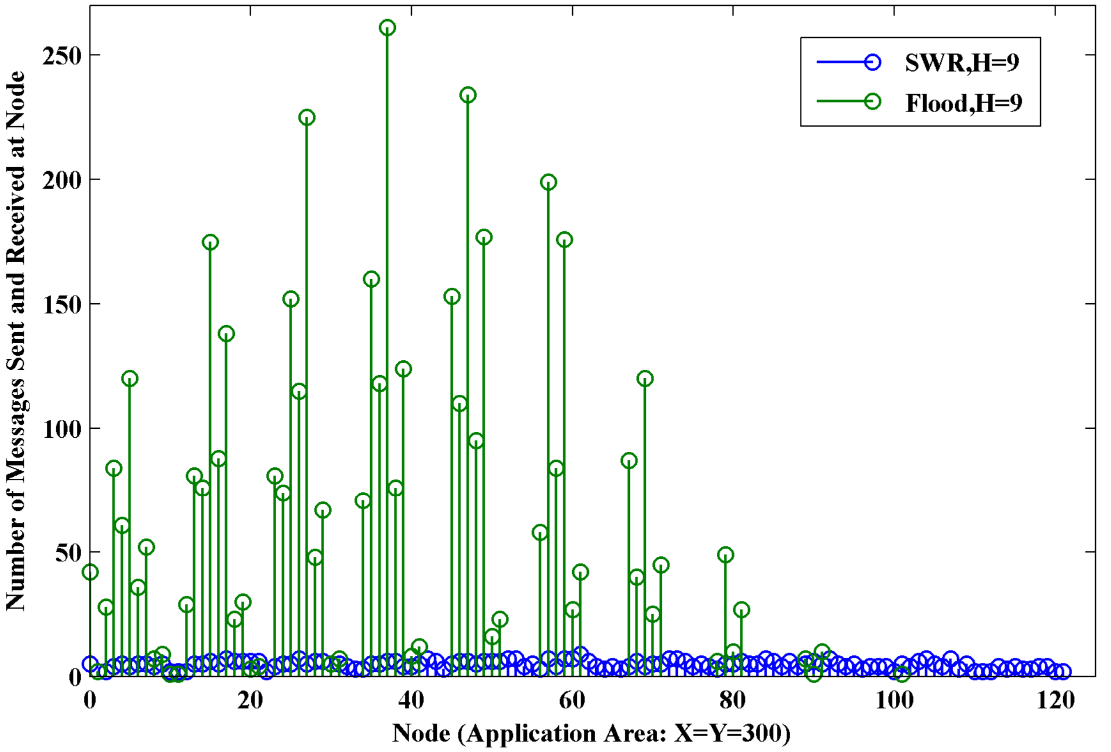

Figure 5.12: SWR and flooding (flooding restricted to same hop count as SWR)

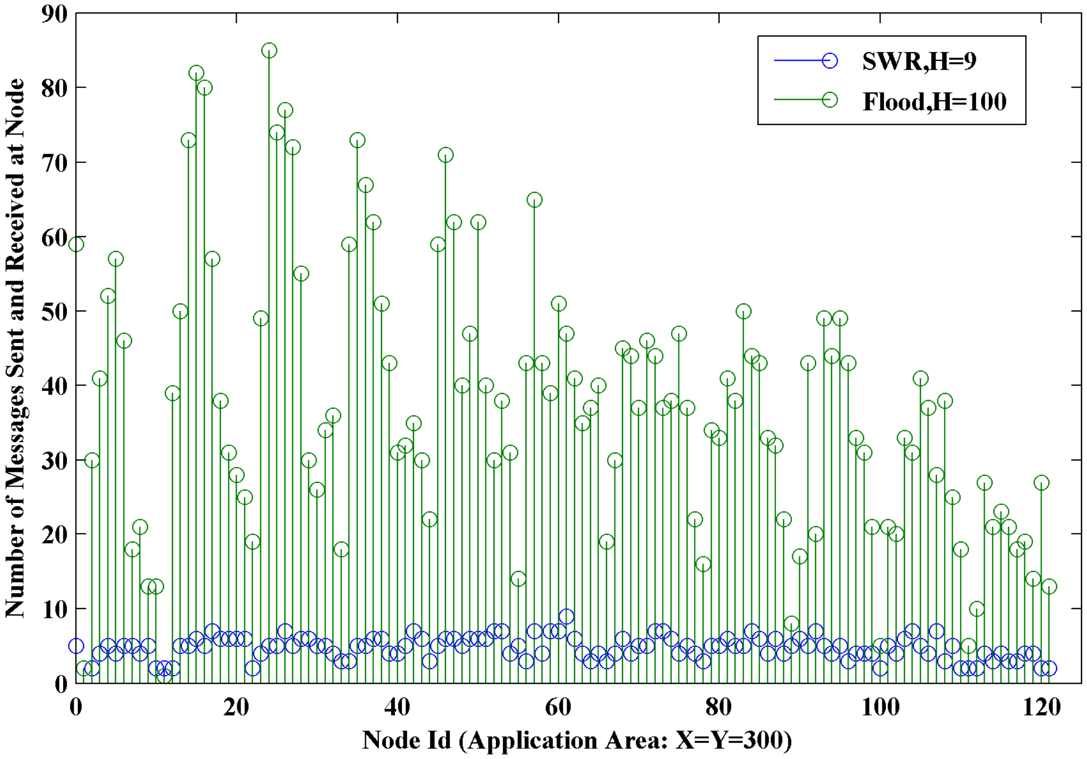

Figure 5.13: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction)

In small world routing (SWR), individual nodes receive significantly fewer messages than with flooding.

5.4.3 Multiple Sinks

In the previous figures, the number of messages sent and received per node is shown when there is a single sink within the application area. Now an investigation of the number of messages sent and received per node when multiple sinks are placed within the application area is undertaken. The scenarios considered were for a 300x300 application area, for the number of hops = 5 and the number of sinks = 4 (Figure 5.14), the number of hops = 6, and the number of sinks = 3 (Figure 5.15), the number of hops = 7, and the number of sinks = 2 (Figure 5.16), and the number of hops = 9, and the number of sinks = 1 (Figure 5.12).

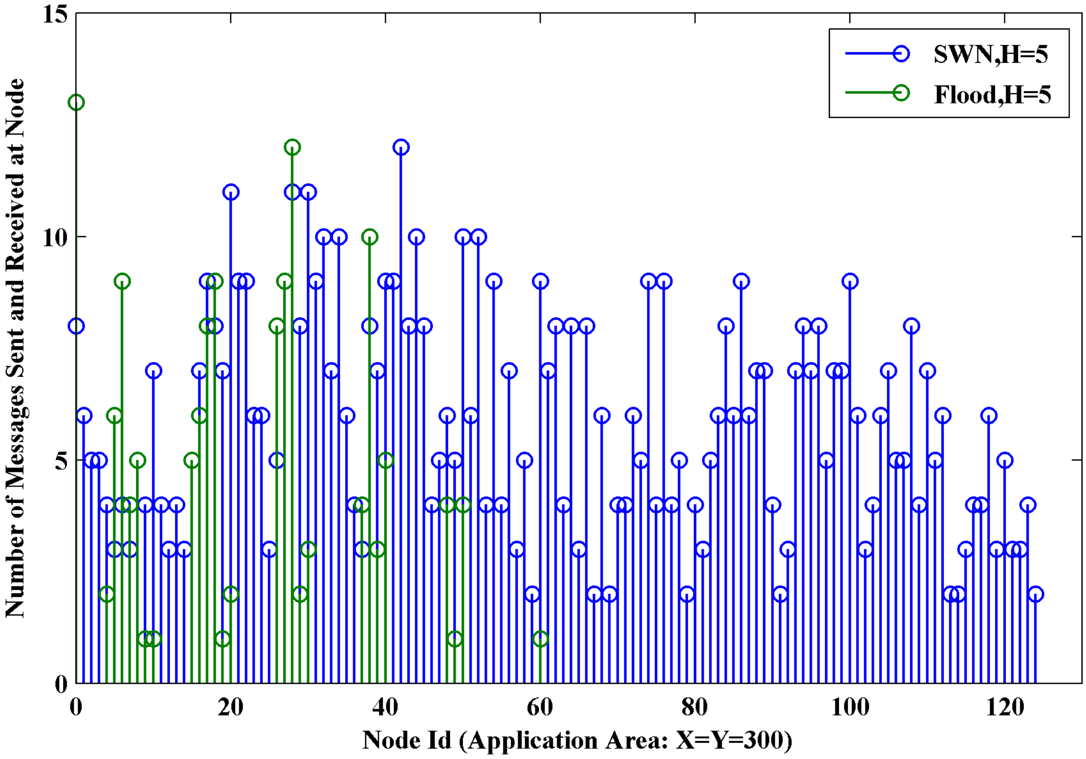

Figure 5.14: Number of messages per node for four sinks and five hops.

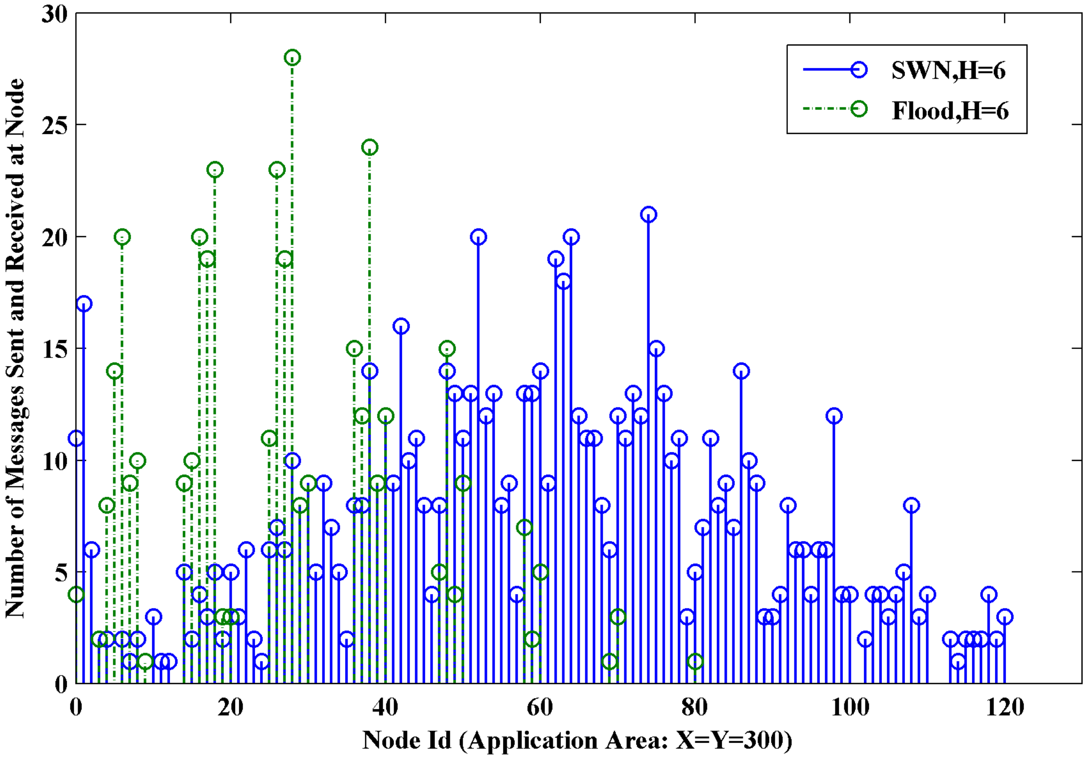

Figure 5.15: Number of messages per node for three sinks and six hops.

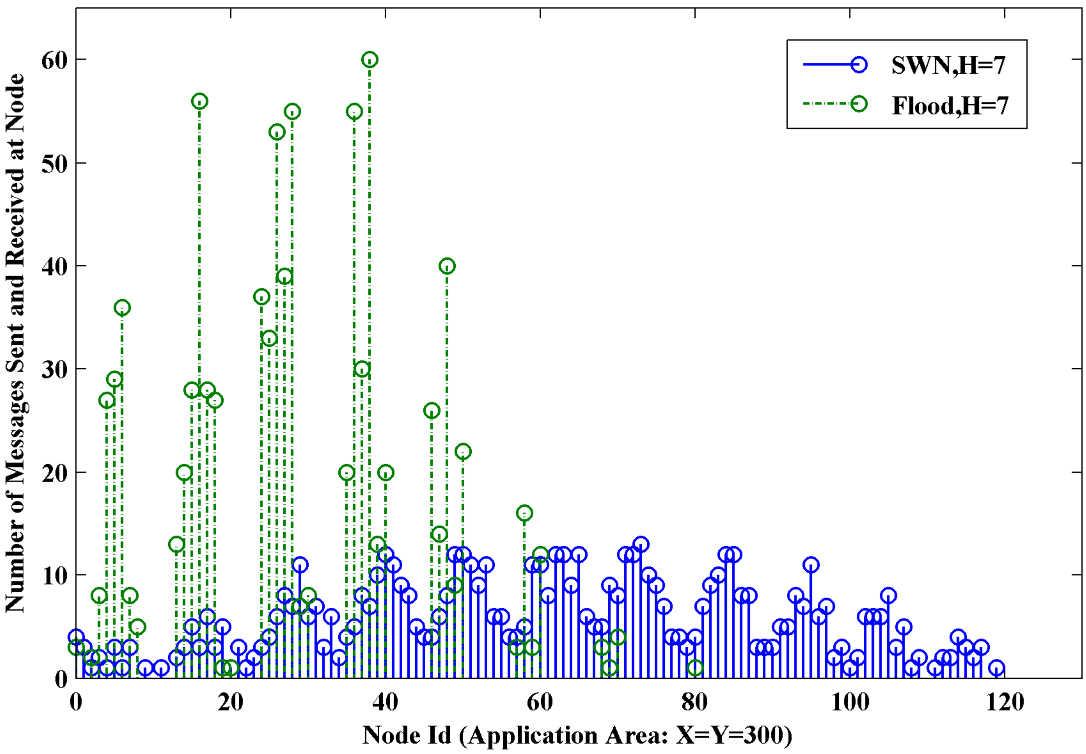

Figure 5.16: Number of messages per node for two sinks and seven hops.

Fewer nodes are receiving and transmitting messages in flooding, especially when there are multiple sinks and small hop counts. When modelling the network as a small world network by placing multiple sinks within the application area and using an IM to create multiple route tables, each node will receive and retransmit a few messages at initialisation. These comparisons are for the IMs, which are once-off messages sent at start-up in the small-world routing algorithm, whereas for flooding, this number of messages will be sent for every event message that needs to be reported to the sink. While the number of messages sent and received per node decreases when using IM and the number of sinks decreases to one, the number of messages sent and received per node increases for flooding as the number of sinks decreases to one. Also, if the hop count is not restricted in flooding, each node will receive and retransmit a large number of messages.

Thus, even though the IM has a cost on start-up, the actual number of messages received per node is usually around 10 messages per node, with a maximum of around 20 messages per node for three sinks, within the application area. All further event messages will only affect nodes in the specific route.

5.4.4 Managing message routes

By using alternative routes for each event message, the lifetime of the nodes surrounding the sink increases and hence the network lifetime increases. For example, the first time a message is sent to the sink from node 1 (refer to Figure 5.3, area of 200mx200m), the route using nodes 2, 3 4, 11, 18, 25 can be used. When the next message needs to be sent to the sink, node 1 can select the route using nodes 8, 15, 22, 23, 24 and 25. The next route could use nodes 2, 9, 16, 17, 24 and 25. This alternating of nodes to route a message to the sink should ensure a more equitable usage of nodes to route messages to the sink. However, the nodes closest to the sink, i.e. nodes 24, 25, 26, 31, 32, and 33, will still be required to forward a message to the sink more often than other nodes.

The advantage of the IM which creates multiple paths to the sink is that if a node dies, an alternate path can be chosen. For example, nodes 3, 4 and 18 were removed in the simulation and an alternative route using nodes 10, 11, 12, 19 and 26 was chosen. Analysis of this route showed that nodes located further from the sink, for example node 1, which is located more than the maximum number of hops away to use this route, will not be able to find an alternate path. To solve this problem, it is suggested that the actual implementation use the calculated hop count and sink placement as minimum values and allow the real hop count to be slightly more that the calculated values. For example if the hop count is increased to eight, then node 1 will use the alternative route path if a node close to the sink dies.

To solve the problem of nodes close to the sink receiving and being required to re-transmit more messages, it is suggested that the sink be moved at set intervals to pre-calculated spots within the application area that is a pre-determined number of hops from nodes on the perimeter of the application area. For example, the sink can move at specified intervals to nodes, 17, 19, 31 and 33, thus allowing all messages to be routed to the sink if the message hop count is: $Hops_{calculated} + Hops_{movedfromcalculated}$, i.e. the calculated number of hops plus the number of hops the sink has moved from the original calculated position. This should ensure a more equitable message redistribution load among the nodes and hence increase node and network lifetime.

5.5 CONCLUSION

As discussed in chapter 1 and shown in Figure 1.5, unnecessary message transmissions and receptions reduce the energy of each sensor node. As each sensor node has a non-renewable energy supply, this ultimately affects the lifetime of a WSN application. Routing a message from a sensor node to a sink node can impose significant and unnecessary energy consumption on surrounding nodes if a direct route between the node and the sink is not known. In chapter 3 a model to reduce the number of intermediate nodes required to re-transmit a message before it reaches the sink node was discussed. In chapter 4 the use of an IM to create multiple route paths between a sensor node and a sink node was discussed.

In this chapter the impact of this IM on reducing the energy of all sensor nodes within the WSN has been evaluated. The intent is to determine if there is a certain distance that a sensor node can be from a sink node which will ensure that the total number of IMs required to create multiple route paths is manageable. An analysis of the total number of IMs sent within three WSN applications areas (i.e. 100m, 200m and 300m) and the distance between a sensor node and a sink (i.e. number of hops) was considered. It was found that the total number of messages sent and received during the start-up phase was significantly larger for a small number of hops, i.e. a smaller number of intermediate nodes used to transmit a message to sink. The reason is that fewer hops require more sinks to be placed within a WSN resulting in multiple IMs received from more sinks by route intermediate nodes for shorter hops than for longer hops.

The total number of IMs within a WSN reduces to a more manageable amount for hop distances greater than five. This will allow a WSN application designer to determine an optimum distance between any sensors and sink node that will ensure the creation of the multiple route paths to a sink without negatively affecting the lifetime of any sensor node.

In this chapter it is shown that although route discovery using the IM is slightly more resource-intensive during start-up, it does not excessively drain any specific node more than others. The effect of the IM at start-up on node lifetime, in terms of the number of messages sent and received per node was investigated. It has been shown that the hop count can be selected to reduce the number of messages transmitted and received per node within the network during the initialisation phase. As expected, the optimum hop count is similar to that for reducing the total number of IMs within a WSN. Thus for a hop count greater than 5, the total number of IMs per node and per WSN is reduced.

The use of an IM creates multiple paths from any node to a sink thus allowing for more equitable usage of nodes to forward messages to a sink and improving network lifetime. Thus, the use of an IM propagated from one or more sinks at start-up can improve energy efficiency and increase a WSN application's lifetime.

CHAPTER 6

LOCALISATION IN A WSN

In this chapter, the ideas from Chapter 3, (i.e. placing multiple sinks at specific locations to model a WSN as a small world network) and Chapter 4 (i.e. a node re-transmits an IM if the received signal strength of the message indicates that a node is on the perimeter range of the transmitting node), is extended to calculate a node's location. The locations of three or more sinks and the number of hops from these sinks are used to calculate the nodes location within a WSN.

6.1 INTRODUCTION

Data received from sensors can only be useful if the data contains information about where the event occurred, i.e. the sensor location must be associated with measured sensor data. A message may have travelled many hops before it reaches its destination sink and the human interface will require the message to indicate the location of the event. Localisation is a technique to determine the location of a node within a WSN application area. Location estimation must be done in an energy efficient manner, especially for networks of sensors with small batteries that must last for years (Patwari & Kasera, 2011).

Accurate and low-cost sensor localisation is a critical requirement for the deployment of WSNs in a wide variety of applications, such as bush fire surveillance, water quality monitoring and precision agriculture. Low-power wireless sensors may be many hops away from any other sensors with *a priori* location information. Also, sensor location information (if it is accurate enough) can be extremely useful for scalable, "geographic" routing algorithms

In many WSN applications, the sensor device costs will need to be low, sensors will need to last for years or even decades without battery replacement, and the network will need to organise without significant human intervention. Traditional localisation techniques are not well suited for these requirements. Including a global positioning system (GPS) receiver on each device is cost and energy prohibitive for many applications, not sufficiently robust to jamming for military applications, and limited to outdoor applications (Patwari et al., 2005). In cooperative localisation, sensors work together in a peer-to-peer manner to take measurements and then form a map of the network.

Methods used to estimate the location of sensors typically assume that small portions of sensors, called anchors or beacons, have *a priori* information about their coordinates. The anchor node coordinates may be obtained by using GPS or by installing the anchor nodes at fixed points with known coordinates (Mao et al., 2007). Non-anchor sensor nodes do not have *a priori* information about their location and location coordinates have to be estimated by a sensor network localisation algorithm.

An algorithm, the Perimeter Echo Algorithm (PEA), to determine the location of sensor nodes in a wireless network is discussed. The algorithm extends the ideas discussed in Chapters 3, 4 and 5 to optimise routing of messages within a network by using the ideas of multiple sinks with known location (as in the small world model) and an initialisation message to calculate a node’s location.

The algorithm assumes a limited number of nodes (anchor nodes, beacons or sinks) in the network are equipped with a location finding mechanism such as GPS. Note that these anchor nodes can be sinks also, but are not required to be a sink. Nodes on the perimeter range of a beacon echo the beacon’s virtual ID to all nodes within range. This approach reduces the number of messages required to achieve network localisation. The advantage of PEA is reduced power consumption and reduced flooding of the network because the beacon nodes only transmit an initialisation message once within a specific range and only those sensor nodes on the edge of a transmitting node's range re-transmit the message. This reduces the flooding that typically occurs during iterative and collaborative multilateration approaches.

6.2 ALGORITHM DESIGN

PEA is a distance-based localisation algorithm based on graph theory, where the Euclidean coordinates of all non-anchor nodes in the network are calculated from the known Euclidean coordinates of a small number of beacon nodes (Mao et al., 2007). PEA requires at least three known distances to beacon nodes to form a trilateration graph. The known distance and coordinates of three beacon nodes are used to estimate the location of a sensor node.

Assumptions

- The algorithm assumes that the sensor antennas are omnidirectional.
- Each node has sufficient memory to store a location table that can store at least three rows, containing the virtual ID of a beacon node and the number of perimeter nodes a message has to hop across to reach the specified beacon node.
- The size of this location table is dependent on the node density.

Consider a WSN with *n* nodes and *m* beacon nodes. The beacon nodes have some form of location-finding system or are given their location a priori. The sensor nodes store the virtual IDs of three beacon nodes and their distance from the beacons (measured in terms of number of hops from a perimeter node). This information is appended to every sensing data message the node transmits. The receiving server can use this information to perform a simple trilateration algorithm to calculate the position of the node in the network.

Since energy is used to receive and transmit messages, the objective of the PEA algorithm is to limit the number of messages in the system to achieve network localisation of all nodes. Also, data messages from sensor nodes are generally evaluated in a central server location (which is most probably connected to a power source), and therefore there are sufficient resources to perform calculations.

Network localisation messages are transmitted on initialisation of the network. When the nodes are deployed, only the beacons (i.e. sensors with known positions) transmit a broadcast message containing the following information:

- ID: unique node identification number,
- latitude,
- longitude,
- altitude, and
- hops: number of hops from the beacon measured in terms of number of messages re-transmitted from nodes located on the perimeter of the transmitting node's range.

All nodes within range of a beacon node, update their location table with the above data. Those nodes located on the perimeter of the transmitting nodes range, increment the number of hops and re-broadcast the above message to all sensors within range. This process continues iteratively until all nodes have three beacon nodes' data in their location tables.

In practical applications the radio signal strength can be used to determine whether a node is on the perimeter. In the computer simulation, all nodes with a distance greater than 0.8 of the nodes range (radius) but which were still within the transmitting nodes range were considered to be perimeter nodes. The perimeter nodes will re-broadcast the received message. The simulation assumes that signals received by the nodes in range $0.8 * \mathrm{R} \leq \mathrm{signal} \leq \mathrm{R}$, (where R is the node radio receiving range), can be correctly decoded.

A receiving sensor node checks its location table and if it is within immediate range of the specified beacon, the message is ignored as the data already exists in the location table. A receiving sensor that is not within immediate range of the beacon node, updates its location table. The location table data is stored in a sorted table with the nearest beacons at the top of the table. The algorithm determines a loop-free route to a beacon, since the shortest path to a beacon is always chosen.

In summary, the rules of the PEA are described below:

```
REQUIRE All beacons transmit ID message on deployment
    IF {node in range}
        Add data to its location table
        IF {node on perimeter}
            Increment number of hops
            Re-transmit message
        ENDIF
    ENDIF
```

Figure 6.1 illustrates the algorithm. A beacon node (1, depicted as a triangle) transmits an initialisation message. The sensor nodes (2, 3, 4, and 7, depicted as rectangles) are within range. The sensor nodes (5, 6, 8, and 9) are out of range. Sensors 4 and 7 are on the perimeter of node 1 and retransmit the message.

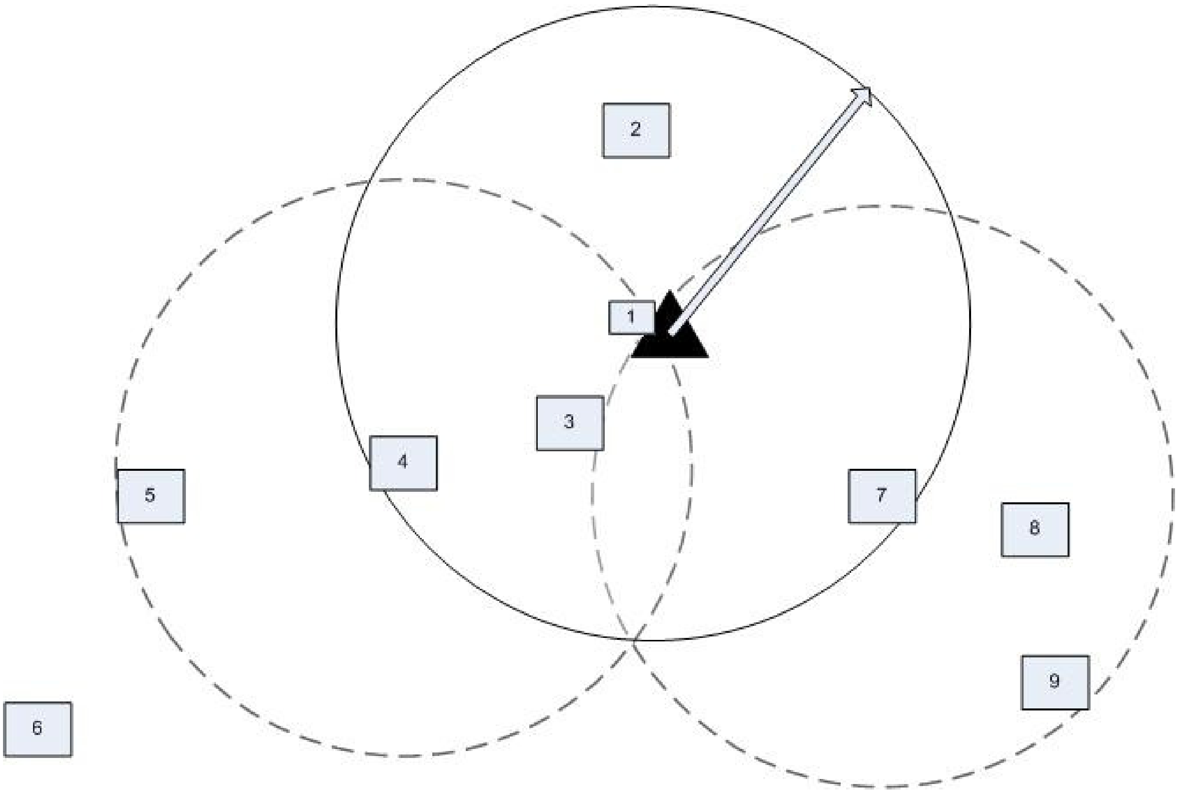

Figure 6.1: Overview of the Perimeter Echo Algorithm

After an event occurs, the sensing node(s) will transmit a message to the sink informing the sink about the event. This message will include the three nearest beacons' IDs and location, as well as the number of nodes the event is from each beacon.

The receiving server uses the data about each beacon's latitude and longitude to determine each beacon's location. An algorithm on the server uses the location coordinates of the three beacons as well as the number of hops from a beacon, to determine the location of the event.

Since only the nodes on the perimeter of the transmitting node's range, re-transmit the message, the number of hops provide a reasonable estimate of the distance from the beacon in terms of *R*hops*, where *R* is the transmitting range of a node. Therefore, from Figure 6.2, node 'A' is five times the radius range from beacon 1, eight times the radius range from beacon 2, and 28 times the radius range from beacon 3. The intersection of the three circles provides the approximate location of node 'A' as described in Figure 6.2. The sensor network application area is assumed to be small enough to ignore curvature issues that arise in large distances.

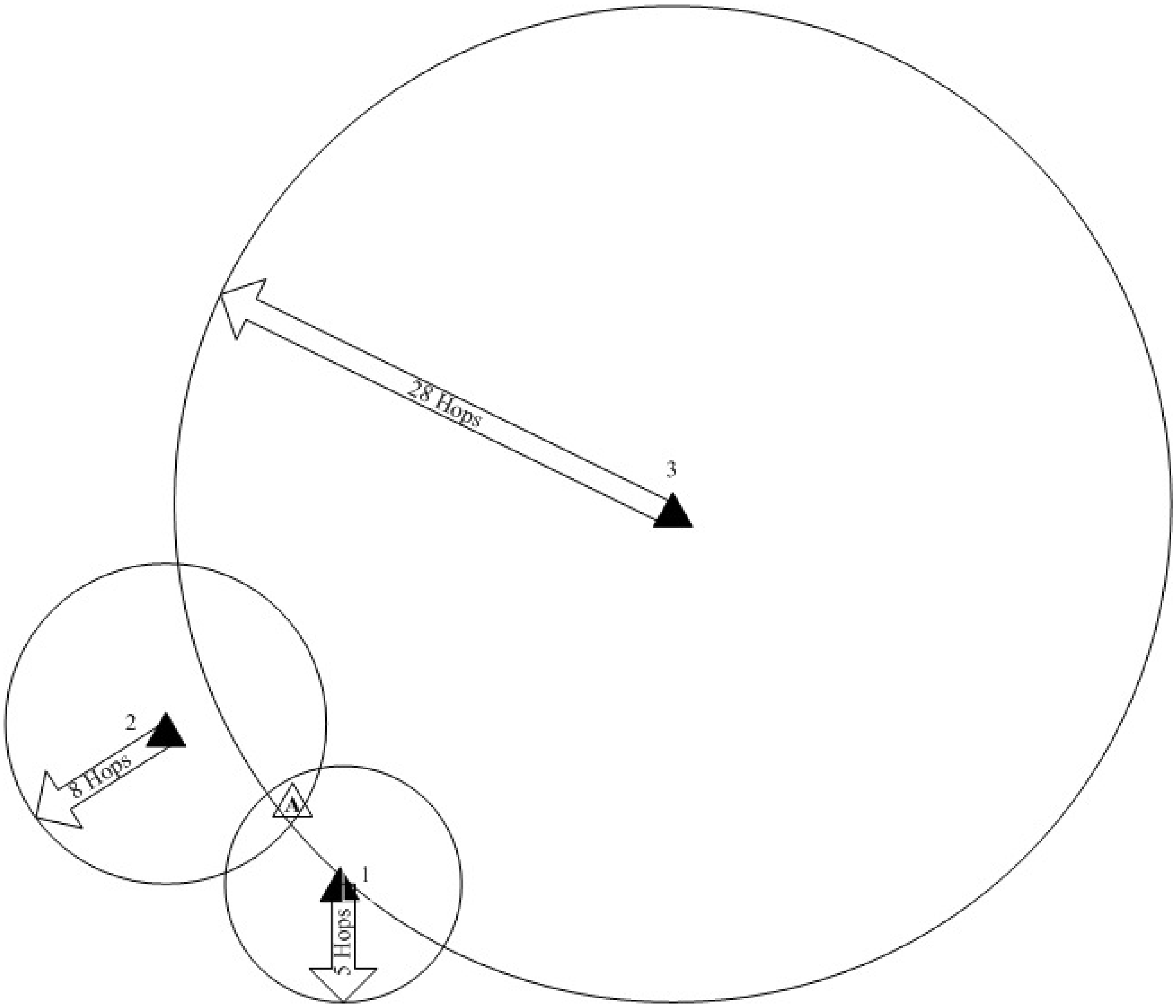

Figure 6.2: Location of node using trilateration

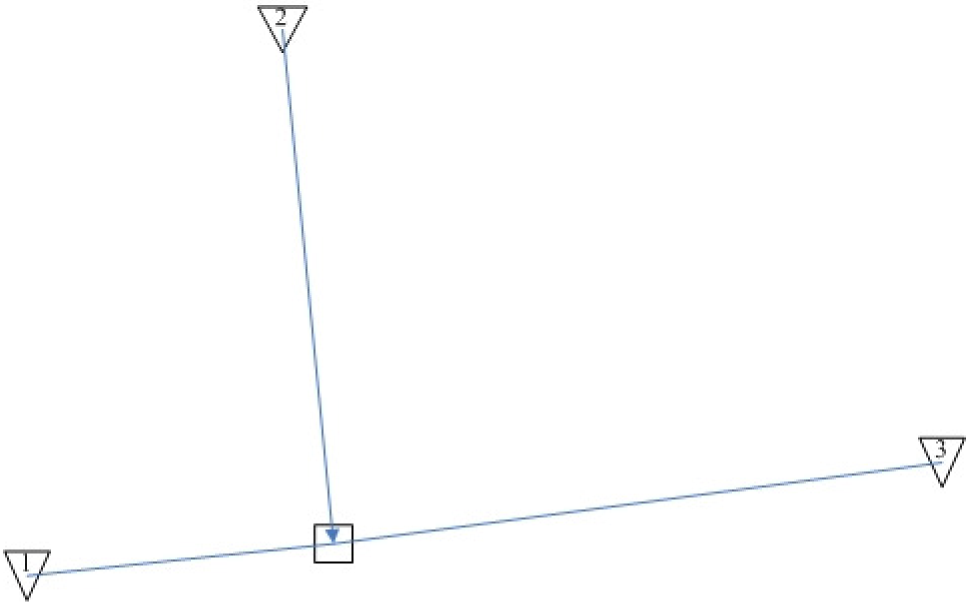

Figure 6.3: Calculating node location

The receiving sensor uses the three beacons' location to determine the distance each of the beacons is from the others. The algorithm then calculates the point of intersection of the radius (calculated as the node range times the number of hops from the node) from each beacon to determine the location of the node, as shown in Figure 6.3.

6.3 RELATED WORK

The iterative multilateration approach is used by Savvides et al. to determine the location of all unknown nodes in a network. On network initialisation a small number of nodes know their location. The unknown nodes determine their distance from their neighbours, using a node location technique such as time of arrival, and then use this information together with data about the known neighbourhood beacons to estimate their position (Savvides et al., 2001). This approach requires that the calculation of node position takes place at an unknown node and that each node broadcasts its position to all nodes within range, resulting in flooding and depletion of the power supply.

The solution presented in this chapter differs from this approach in that each node keeps a location table containing the virtual IDs of the beacon nodes and their distance from the beacon (i.e. number of hops). The node does not calculate its position but attaches the information in the location table to all messages it transmits. The receiving server calculates the node position using trilateration techniques. Also, a node will only re-transmit beacon data if it lies on the perimeter of the transmitting nodes range. This approach should reduce the number of messages present in the system and thus the amount of energy consumed in processing received messages.

Biswas et al. describe a set of semidefinite programming (SDP) algorithms to determine the location of nodes in a WSN (Biswas et al., 2006). The primary disadvantage of this approach is that SDP programs do not scale to larger densities very well.

Patwari et al. suggest a form of cooperative localisation whereby sensor nodes cooperate in a peer-to-peer manner to form a map of the network. They use statistical models to calculate localisation performance bounds on location estimation precision based on time of arrival, angle-of-arrival and received-signal-strength measurements (Patwari et al., 2005).

In describing solutions to the broadcast storm problem in ad-hoc networks, (Chen et al., 2002) and a comparison of broadcast techniques in mobile ad-hoc networks (Williams & Camp, 2002), the authors mention a distance-based scheme, where the distance between the transmitting and receiving nodes is used to determine if a message should be re-transmitted. These schemes were not tested in a WSN environment, and do not separate the radio signal into accurately decodable data and radio signal with corrupt and non-intelligent data.

6.4 EXPERIMENTAL SIMULATION

A simulation of WSN deployment was developed to test the algorithm. The simulation program was coded in Java on an Intel Pentium computer using the Windows XP operating system. As this is a simulation, the Euclidean distance between two nodes was calculated to determine if a node was on the perimeter. All nodes with a Euclidean distance greater than 0.8R, (where R is the range or radius of the transmitting node) and less than R are said to be on the perimeter of the transmitting nodes range and are flagged to re-transmit the message. In a practical application, the radio signal strength can be used to determine if the receiving node is on the perimeter of the transmitting nodes area. Two experimental scenarios were considered.

6.4.1 Scenario 1

Beacon or sink nodes (i.e. nodes with known location) were placed approximately equidistant from one another in a 500mx500m application area. Sensor nodes were randomly placed on the panel. The simulation was run for a range of nodes from 100 sensors to 5000 sensors. The number of beacon nodes is calculated as 10% of the number of sensor nodes. The purpose of scenario 1 is to evaluate the PEA on its own strengths without ascribing any additional advantages or disadvantages from the small world model on the algorithm. It is for this reason that the number of beacon nodes was calculated at 10% of the number of sensor nodes.

6.4.2 Scenario 2

To further expand on the work from Chapter 5, the number of hops required to reach a predefined number of sinks for an application area size varying from 100m to 5000m was evaluated. The number of hops to a given number of beacons (sinks) for a given application area size was calculated based on the previously described small world model. The beacons were placed within the application area at specific points that was calculated from the number of hops of a node on the perimeter of the application area. From chapter 5 (Figure 5.1), the number of messages decreases as the number of hops is greater than 4. Therefore, experiments were run with the number of hops ranging from 4 to 8.

6.5 RESULTS AND ANALYSIS

6.5.1 Scenario 1

The number of times a beacon node's location message was re-transmitted until each sensor node has received three beacon location messages is shown in Figure 6.4. The graph provides a comparison with flooding, (similar to iterative and collaborative multilateration). The PEA algorithm significantly reduces the number of messages required for all nodes to receive three beacon initialisation messages.

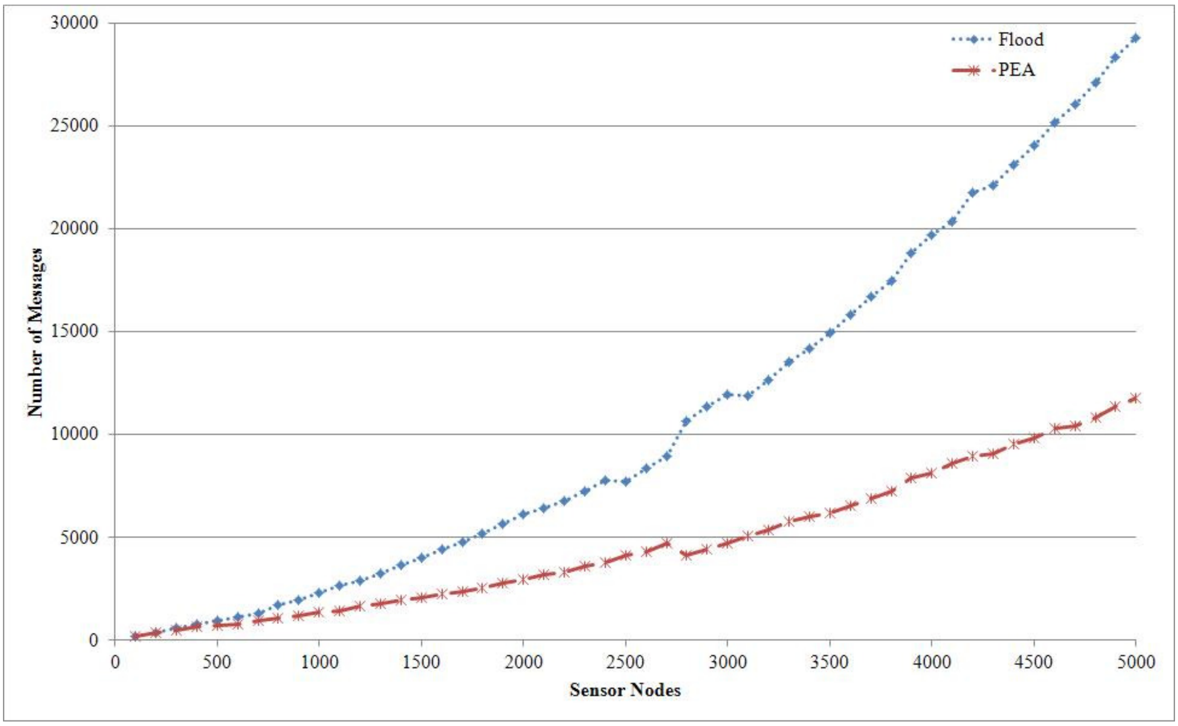

Figure 6.4: Number of beacon initialisation messages re-transmitted in WSN

There is a direct relation between the number of beacon nodes and the number of location messages re-transmitted. The number of hops to obtain the first beacon decreases to 0 as the number of beacons deployed within the specified area increases.

In addition, there is a significant advantage with PEA in the time required to obtain the IDs of three beacon nodes, as shown in Figure 6.5. While the time taken to obtain three messages is dependent on the simulation and supporting computer hardware, the difference between PEA and flooding indicate that initialisation of the WSN will be achieved faster using PEA for localisation.

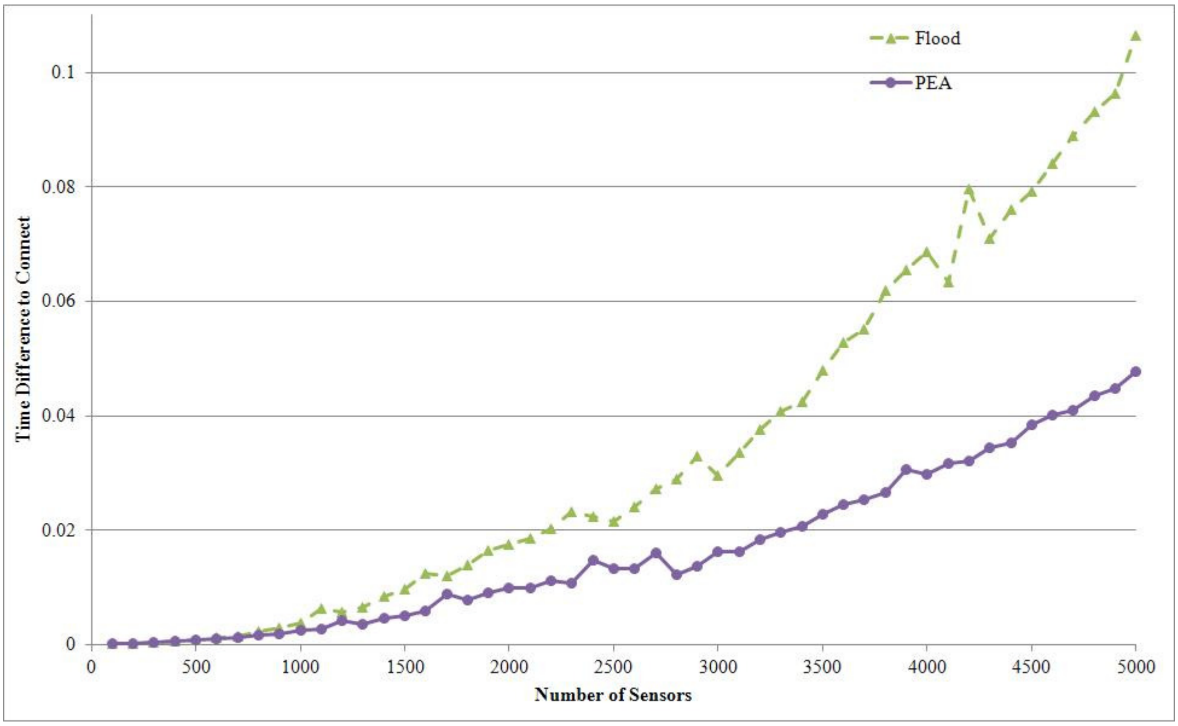

Figure 6.5: Time difference from start to end for each node to receive three beacon messages

6.5.2 Scenario 2

The number of hops required to reach a predefined number of beacons (i.e., 4, 5, 6, 7 and 8 beacons) for an application area size varying from 100mx100m to 5000mx5000m was calculated based on the small world model and is shown in Figure 6.6. Note; this is the number of calculated hops required to reach any **one** beacon from any furthest point within the application area. However for localisation calculations, the location of at least three beacons has to be known. In Figure 6.7 the number of hops from the three closest beacons to a node is shown as the application area size varies from 100m to 5000m. As expected the number of hops will be larger.

What is interesting is that for the three closest beacons the maximum number of hops is almost double the calculated number of hops from any node to a single beacon. This means that placing beacons at specific points according to the small world model guarantees that messages from at least three beacons can reach any node in a WSN from approximately twice the number of hops required to reach at least one beacon. As shown previously in chapter 5, the number of initialisation messages increases as the number of hops declines. Thus, a WSN application designer can make a decision based on calculated number of hops for the minimum number of required beacons to evaluate the impact of the initialisation message on the application.

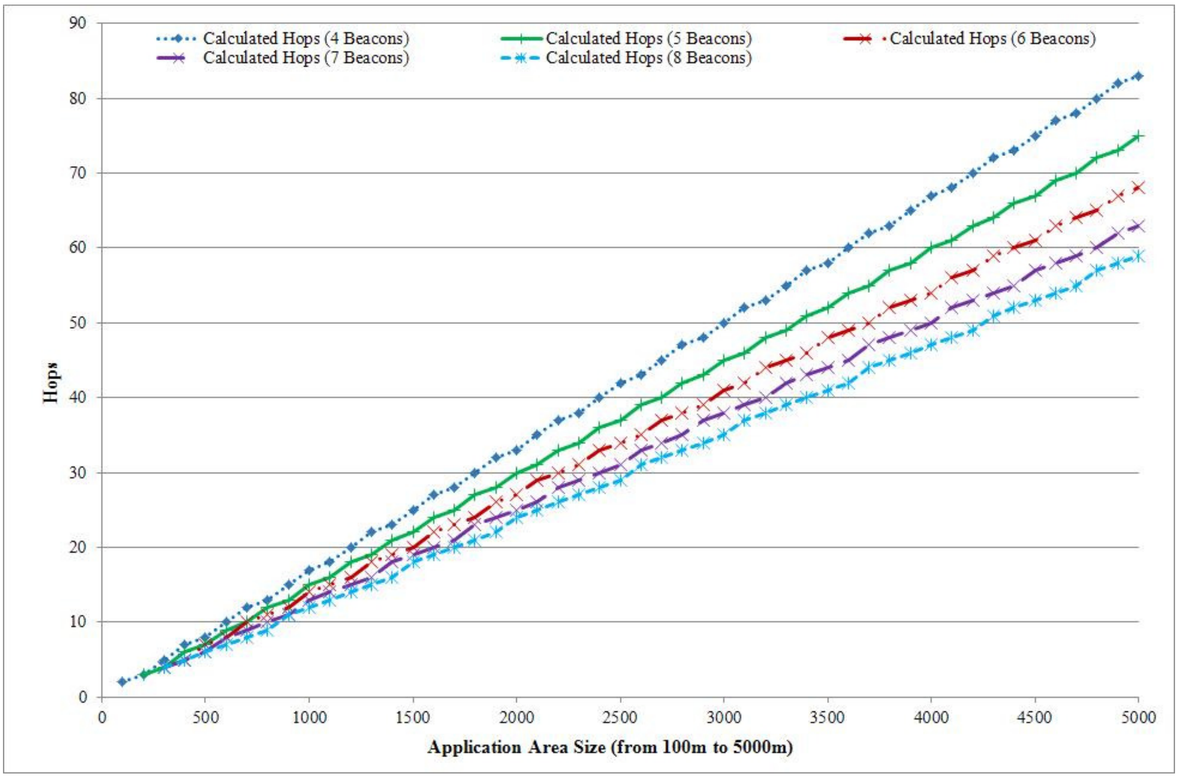

Figure 6.6: Number of hops for a specific number of beacons as application area size varies

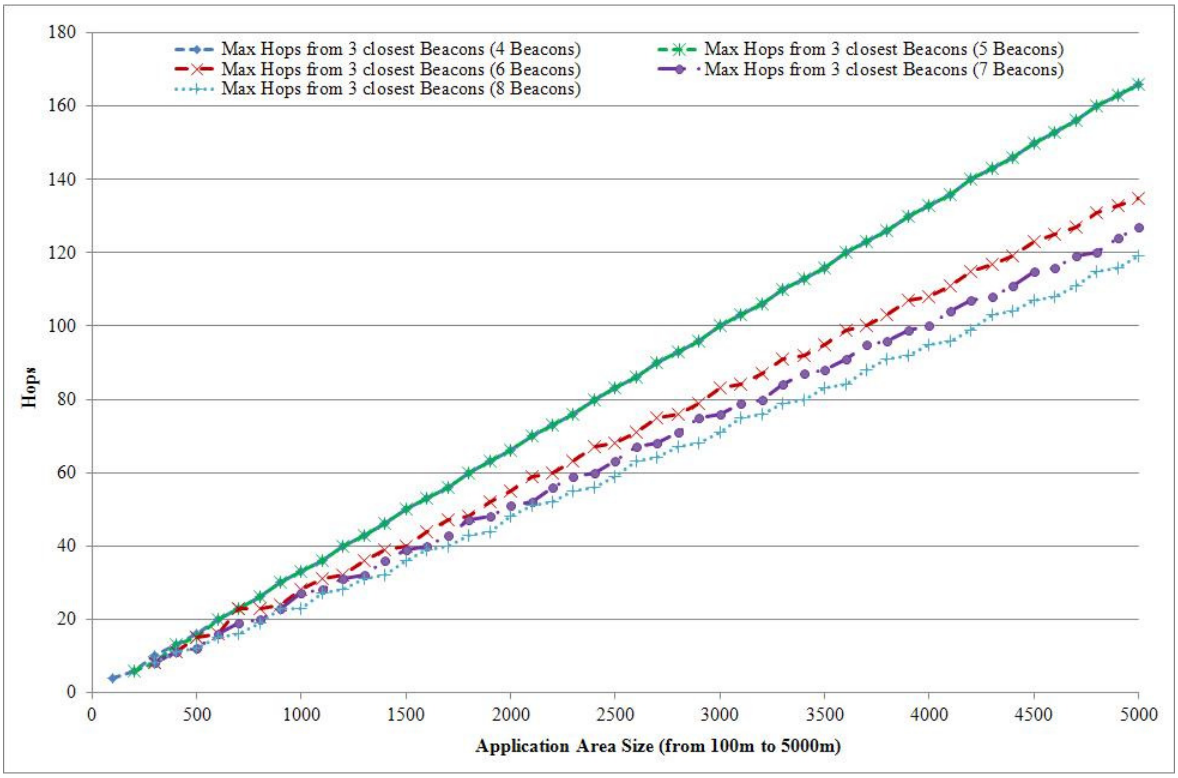

Figure 6.7: Number of hops from 3 closest beacons as application area size varies

As can be seen in Figure 6.7 the maximum hops to any three beacons when there are only for 4 and 5 beacons in a WSN are the same.

6.6 CONCLUSION

It has been shown that the PEA results in a significant reduction in the number of messages required to obtain three beacon localisation messages, as well as a reduction in the time taken for this initialisation. This means that there will be power savings as the number of times a node receives and/or re-transmits a message decreases. The control centre will be able to calculate the location of an event reasonably accurately using the three beacons' IDs supplied in the event-sensing message.

When the WSN is modelled as a small world network and a specific number of beacons were calculated, the number of hops from any three beacons is at most twice the minimum number of hops required by a node to reach the nearest beacon. Thus, the cost of sending the additional three beacons' data in an initialisation message is at most twice that of sending an initialisation message from only one beacon.

Using the PEA, a WSN irrespective of whether it has been modelled as a small world network or not, should be able to localise all nodes in the network within a short time while prolonging node lifetime.

6.7 DECLARATION

The work in this chapter has been published at the following Conference:
IEEE Africon 2009.

CHAPTER 8

OPTIMUM PATHS FOR MOBILE SINKS/ACTORS

As stated previously, one key factor to prolonging node lifetime is to reduce the number of messages each node is required to receive, transmit, re-route or process. Locating the sink close to the centre increases the number of messages nodes close to the sink are expected to receive and re-transmit. The use of mobile nodes has been proposed previously. However, the path these mobile sinks should travel has not been actively researched. Chapters 3, 4 and 5 discussed mechanisms to reduce the number of messages sent within the application area and reduce the number of messages seen per node, by placing multiple sink nodes within the application area. These sink nodes were stationary and placed a specified number of hops from the furthest node. However, nodes close to the sink node received more messages than nodes furthest from the sink. In this chapter an optimum path for mobile sinks to move around is proposed.

8.1 INTRODUCTION

In previous chapters algorithms are proposed to reduce the number of messages transmitted within a WSN application by (1) placing static sinks at specific points within the application area to reduce the number of times a message should be re-transmitted before it reaches its intended destination, (2) using an IM at network start-up to create one or more routes to one or more sinks, so that the number of times a message is re-transmitted by a node is limited to the nodes specified in the route table, (3) determining if there is an optimum number of hops from a static sink node that would result in reduced numbers of messages being sent and received per individual node in the application area, and (4) analysing existing uncertainty about a mobile actors location and energy levels to coordinate which set of actor(s) can reliably react to an event without flooding the WSN application area with a large number of messages.

In this chapter the idea of using mobile sinks to reduce the number of messages transmitted within a WSN application area is broadened. Initial message routing protocols assumed the sink or destination node was in a fixed location, and that network nodes had no or limited knowledge of the network topology (Akkaya & Younis, 2003). The researcher proposes the use of mobile sinks to interact with sensor nodes to determine optimum routing tables for each sensor node. An investigation is conducted into the route a mobile sink can travel that will reduce the number of messages transmitted within a network, allow equitable usage of all nodes to transfer an event message and still allow an event to be reported in real-time. A model for optimum path movement of mobile sinks to reduce the number of messages transmitted and received by an individual sensor node is proposed.

In the following sections a brief discussion of current research using mobile sinks and/or nodes to improve the energy efficiency of routing protocols is provided. The algorithm to transmit data from a sensor node to a mobile sink is discussed and the results analysed.

8.2 ALGORITHM DESIGN

To reduce the number of messages received and re-transmitted by nodes closest to the sink, it is proposed that one or more mobile sinks follow a path in the application area based on the calculated number of hops from a sink. If the sinks are mobile actors, then the model described in Chapter 7 can be used to coordinate which actor(s) should respond in real-time to an event.

8.2.1 Calculation of optimum path for one or more mobile sinks

The assumption is that a WSN application will have one or more mobile sinks moving within the application area, collecting data from nodes within communication range in its path. The path these mobile sinks follow should be optimal to (1) ensure reliable communication between nodes and sink(s), (2) ensure the even distribution of messages received and transmitted within the application area to reach a sink destination to improve node longevity and network lifetime, and (3) enable real-time processing of event messages. Consider the following definitions in Table 8.1:

Variable	Description
X	Width of application area
Y	Length of application area
R	Node and mobile sink communication range
X_{m_start}	Minimum starting X point on the mobile path
X_{m_end}	Maximum ending X point on the mobile path
Y_{m_start}	Minimum starting Y point on the mobile path
Y_{m_end}	Maximum ending Y point on the mobile path
H	Number of hops from node to nearest node that is within communication range of the mobile sinks path.
d	Distance between each time the sink node broadcasts a “hello” type message as the sink moves along a pre-calculated mobile path
N_{hello}	Number of times the “hello” message will be broadcast by mobile sink to complete one loop around the calculated path
a	The constant acceleration of the mobile sink
d_{stop}	The constant deceleration of the mobile sink
v_i	Initial velocity of mobile sink
v_f	Final constant velocity of mobile sink
s_{av}	Distance the mobile sink has to traverse after accelerating from zero velocity to when the sink reaches the required velocity
s_{dv}	Distance the mobile sink has to traverse after decelerating from constant velocity to when the sink stops (zero velocity)
s_{cv}	Distance the mobile sink has to traverse moving at constant velocity before next “hello” type message is broadcast
t_{av}	Time it takes the mobile sink to accelerate from zero and reach constant velocity
t_{dv}	Time it takes the mobile sink to decelerate from constant velocity to zero
t_{cv}	Time it takes the mobile sink moving at constant velocity to traverse the required distance before next “hello” type message is broadcast
T_{total}	Total time it takes a mobile sink to complete one loop of its calculated path transmitting messages at required intervals
t_{stop}	Time a mobile sink will stop, broadcast a “hello” type message and wait for responses from surrounding nodes

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

Assumptions

- The application area a mobile sink travels in must be a **square**, i.e. X=Y.
- The mobile sink will have constant acceleration until it reaches the required constant velocity.
- The mobile sink will have constant deceleration until it reaches zero velocity and stops.
- There are no obstacles that will prevent a wireless message (transmitted from a node within communication range), from reaching the sink reliably.

Optimum path for one mobile sink

For one sink, the optimum path must be equidistant from any furthest node in the application area. Therefore, the maximum distance a message from a node on the perimeter of the application area travels before reaching a node within communication range of the mobile node must be the same as the maximum distance from a node at the centre of the application area to a node within communication range of the mobile node. This is shown mathematically in the equation below.

$$X = R * H_{(perimeter)} + R * H_{(maximum\ centre)} + R * H_{(perimeter)} + R * H_{(maximum\ centre)} \qquad [8.1]$$

$$where,\ \ H_{(maximum\ centre)} = H_{(perimeter)} = H$$

$$Therefore, \qquad Y = X = 4 * R * H \qquad [8.2]$$

Since the application area dimensions (X and Y) and the range of the nodes are known, the maximum number of hops a message has to be re-transmitted before reaching a node that is within communication range of the mobile sink's path can be calculated as follows:

$$H = \frac{X}{4 * R} \qquad [8.3]$$

$$where,\ H_{(outer)} = low(H) = floor(H)$$
$$and,\ H_{(inner)} = high(H) = ceil(H)$$

Once the number of hops has been calculated, the optimum path is calculated as follows:

$$X_{m\_start} = R * H \qquad [8.4]$$

$$X_{m\_end} = X - R * H \qquad [8.5]$$

$$Y_{m\_start} = R * H \qquad [8.6]$$

$$Y_{m\_end} = Y - R * H \qquad [8.7]$$

Consider the nodes placed in a 300mx300m WSN application area as shown in Figure 8.1 with the optimum path for the mobile sink. If the sink was centrally located, (at approximately node 61), then it is either nine or ten hops from nodes 1, 11, 111 and 121. The path of the mobile node is calculated based on equations [8.4], [8.5], [8.6] and [8.7].

Nodes on the perimeter of the mobile sink's path that is located within the immediate communication range of the mobile sink node act as temporary stores for any message destined for the sink. As the sink passes along the path, these nodes pass the message to the sink. This results in a short delay between the time an event occurs and the time the sink receives the message. If the sink needs to be notified immediately, the node can calculate where in the mobile path the sink currently is and re-route the message to the sink.

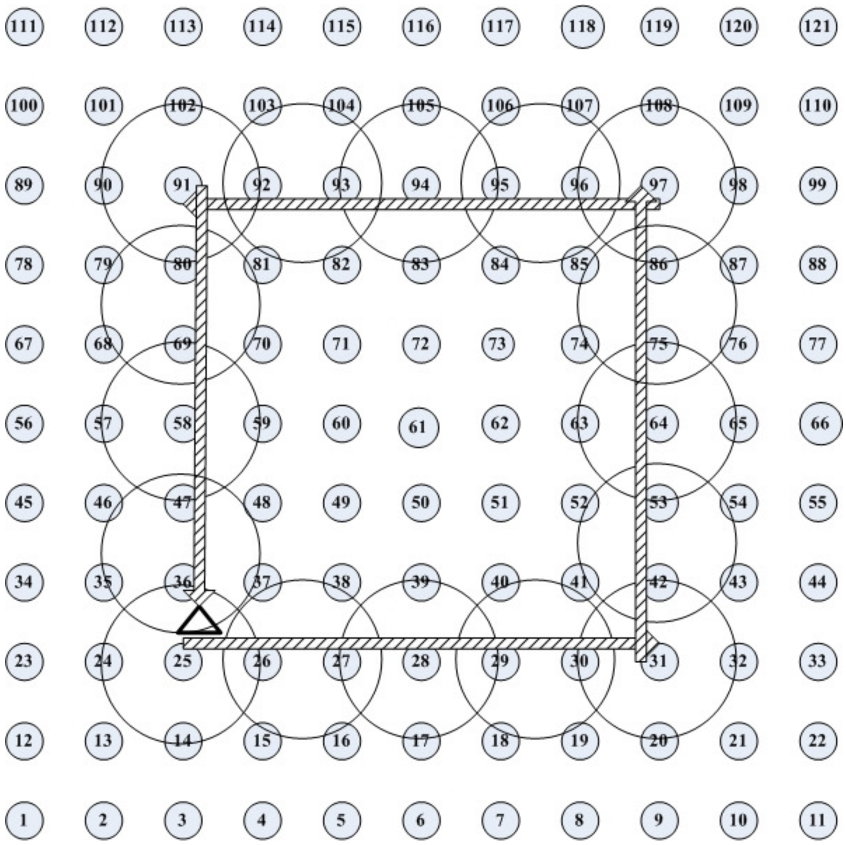

Figure 8.1: Path for a mobile node to follow in a 300mx300m application area.

Optimum path for multiple mobile sinks

If there are multiple sinks, then the actual load is spread among more nodes, as shown in Figure 8.2. The number of sinks and the optimum mobile path can be calculated to ensure that all nodes are within communication distance of a mobile sink's path, with the possible exception of nodes at the perimeter of the WSN application area. For example, nodes 1, 6, 11, 56, 61, 66, 111, 116 and 121 may require an intermediate node to pass the message on in Figure 8.2. To ensure connectivity, this set of nodes can be moved closer to the sink node's path, as shown in Figure 8.3. The path each sink has to travel is even shorter and hence the calculated time to complete one loop is less.

The assumption is that the application area for a mobile sink must be a square. Therefore, for multiple sinks, each section of the WSN application area that has a mobile sink must be a square. Thus the number of sinks and number of squares must be a square of a positive integer number, i.e. $N_{sink} = \{1^2, 2^2, 3^2, 4^2 \ldots\}$. The size of each square is calculated as follows:

$$x = \frac{X}{\sqrt{N_{sink}}} \; and \; y = \frac{Y}{\sqrt{N_{sink}}} \qquad [8.8]$$

Using equations [8.4], [8.5] [8.6], [8.7] and [8.8], the mobile path for each sink can be calculated. Figure 8.2 shows the number of sub-divisions and mobile paths calculated for the same 300mx300m WSN application area shown in Figure 8.1 for one mobile sink. The size of the application area is small, so for four square sub-divisions, each node in the WSN application area will be within communication range of the mobile path.

When an event occurs, the sensing nodes aggregate the data and elect a single node to forward the message to the sink. In Figure 8.2, as each node is one hop from the path of the mobile sink, the message will be stored by the elected node until the sink passes by and requests messages. In Figure 8.1, the message is stored by any node in direct communication range of the mobile sink as it moves along the path. Most nodes in the WSN application area of Figure 8.1 are two hops away from the path of the mobile sink. Nodes at each corner are at most three hops from the path of the mobile sink because it is assumed that the corner nodes are moved slightly into the application area as shown in Figure 8.3 to be within communication range of at least three nodes.

Only nodes which have a minimum of four immediate neighbours will re-transmit the event message. This ensures that nodes on the perimeter of the application area do not unnecessarily re-transmit the message. The event message is only re-broadcast until it is received by an intermediate node that is in direct communication range of the path of the mobile node. The message is stored and when the mobile node passes the intermediate node, all stored messages are transmitted to the mobile sink. Real-time event messages can be forwarded to nodes that will be closer to the sink's path based on the calculations described at the end of this section.

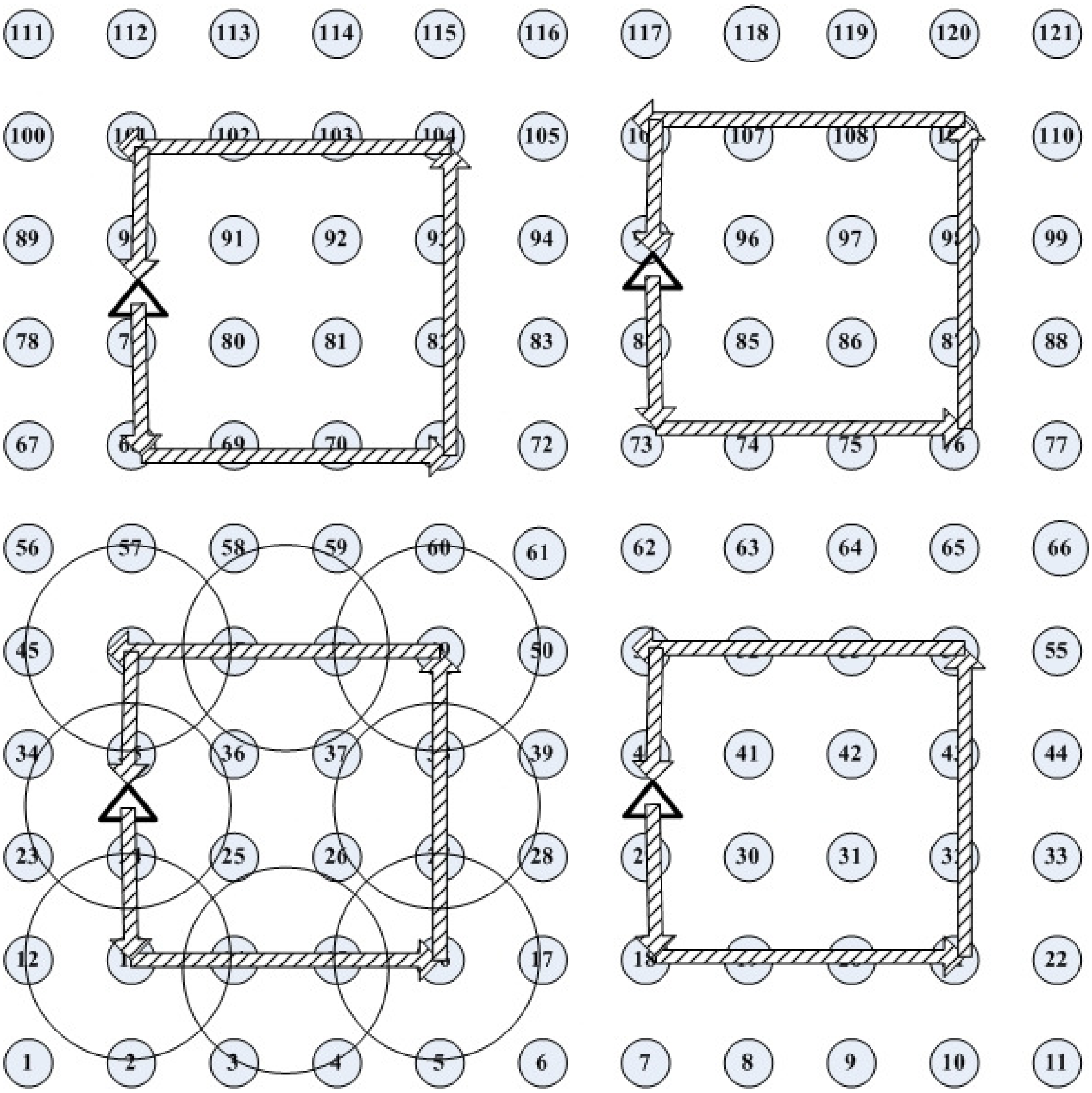

Figure 8.2: Four mobile sinks and each sinks path in a 300mx300m application area.

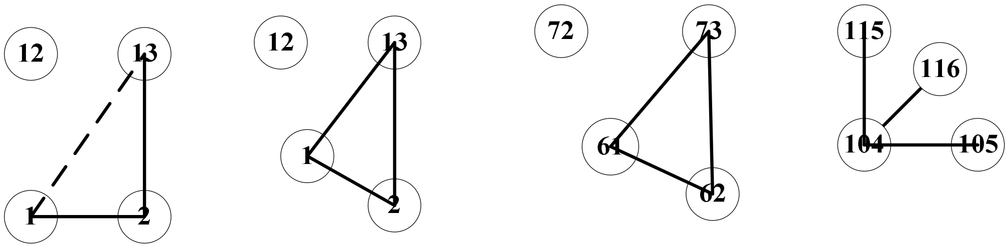

Figure 8.3: Moving corner nodes within communication range of mobile sink path

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

The calculation of the distance between transmitting a “hello” broadcast message and waiting for responses from surrounding nodes is shown below:

$$d = R + \frac{R}{2}$$

$$d = \frac{3*R}{2} \qquad [8.9]$$

The number of times the sink stops and broadcasts a “hello” type message is given by the following formula:

$$N_{hello} = \frac{2*\left(X_{m\_end} - X_{m\_start}\right) + 2*\left(Y_{m\_end} - Y_{m\_start}\right)}{d} \qquad [8.10]$$

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

The mobile node first moves along the path and greets all nodes within communication range. The mobile node transmits a greeting message at every d m. To ensure reliable data communications, the mobile sink briefly stops and transmits a “hello” type message requesting any of the surrounding nodes to return any data messages they may have temporarily stored while waiting for the sink to return. The message contains the mobile sink’s ID, velocity and acceleration, sink direction, its intended path, and when it calculates it will return to its current position as well as a list of all nodes that have responded to its greeting thus far. Initially, during the first loop of the mobile sink, the path list will be incomplete, as the sink is not yet aware of all nodes in its path range. When the mobile sink completes its first loop, it will have obtained a reasonably accurate network topology of all nodes within communication range of its path and their locations. The mobile node will re-broadcast this list as it continues to loop around its path, so that even if some nodes were asleep during previous cycles, these nodes can still obtain the list to update their records.

In the event that a real-time event message needs to be reported to the mobile sink, the initial node that is elected to receive the event message, as it is within communication range of the sink or the actual node that detected the event, can transmit the message to the sink, using this list and its knowledge of the mobile sink's velocity and intended path, to determine the optimum nodes to use to route the message to the sink.

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

8.2.4.1 Sink stop-start movement with non-uniform velocity

Initially the sink will have to move from a state of rest or initial velocity of zero to a constant, specified velocity. The time it takes a mobile sink to accelerate to a constant velocity can be calculated using the following equation:

$$a = \frac{v_f - v_i}{t_{av}}$$

Thus, the time it takes the mobile sink to accelerate from zero and reach constant velocity is:

$$t_{av} = \frac{v_f - v_i}{a} \qquad [8.11]$$

The distance the mobile sink has to traverse after accelerating from zero velocity to when the sink reaches the required constant velocity is:

$$s_{av} = \frac{1}{2} a t_{av}^2 \qquad [8.12]$$

The sink will have to decelerate to stop before it broadcasts another “hello” type message. The time it takes a mobile sink to decelerate to a stop is similar to equation [8.11], i.e.

$$t_{dv} = \frac{v_{zero} - v_f}{d_{stop}} \qquad [8.13]$$

The distance the mobile sink has to traverse after decelerating from constant velocity to zero velocity to when the sink stops can be calculated as follows:

$$s_{dv} = \frac{1}{2}at_{dv}^2 \tag{8.14}$$

Now, the time the mobile sink will spend at constant velocity can be calculated based on the distance between each time the sink node broadcasts a "hello" type message:

$$s_{cv} = d - (s_{av} + s_{dv}) = ut + \frac{1}{2}at_{cv}^2$$

$Since\ at\ constant\ velocity, a = 0,$

$$t_{cv} = \frac{s_{cv}}{v_f} \tag{8.15}$$

If t_{stop} is the time a mobile sink will stop, broadcast a "hello" type message and wait for responses from surrounding nodes, the total time for a node to complete one loop along the calculated path is given by the following formula:

$$T_{total} = N_{hello} * (t_{stop} + t_{av} + t_{cv} + t_{dv}) \tag{8.16}$$

Each node within communication range of the mobile sink's path must be able to perform the above calculations. When one of these nodes receives an event message that it has to re-transmit to the mobile sink, it can calculate the time delay before the sink will again pass by, based on the above equations. The node can then determine, based on the message status and urgency, whether to wait for the mobile sink to pass within communication range or whether to route the message to a node closer to the mobile sink. The sink path information contained in the previous "hello" message is used to determine which node to request to forward the message to the sink. As electromagnetic waves travel much faster than the mobile sink, this will ensure that the event message reaches the sink in real-time.

8.2.4.2 Sink movement with uniform velocity

The previous calculations are based on the mobile sink stopping before it broadcasts a "hello" type message. The stopping and re-starting by the mobile sink will increase the time it takes a mobile sink to complete a loop around the calculated mobile path. A variation on the above calculations is to assume that the mobile sink moves at constant velocity without stopping. When the mobile sink reaches a "hello" broadcast point it will transmit a "hello" type message to all nodes and continue moving at constant velocity. Because electromagnetic waves travel much faster that the mobile sink, the mobile sink should be able to send and receive all responses from surrounding nodes before it moves out of radio range. Then Equation [8.16] becomes:

$$T_{total} = \frac{2*\left(X_{m\_end} - X_{m\_start}\right) + 2*\left(Y_{m\_end} - Y_{m\_start}\right)}{v_f} \qquad [8.17]$$

Of course the mobile node will have to decelerate when it approaches a corner to turn, but within the experimental simulation it is assumed that this time to turn is negligible.

8.3 RELATED WORK

According to Akkaya, Younis and Bangad (Akkaya et al., 2005), finding an optimal location for the sink in a multi-hop network is a very complex problem, NP hard in nature. The complexity results mainly from two factors. The first factor is the potentially infinite possible positions that the gateway can be moved to. Secondly, for every interim solution considered during the search for an optimal location, a new multi-hop network topology needs to be established in order to qualify that interim solution in comparison to the current or previously picked location in the search. A mathematical formulation of the problem would involve a huge number of parameters, including the positions of all deployed sensors, their state information such as energy level, transmission range, etc., and the sources of data in the networks. The authors propose moving the sink to the top relay nodes location. The sink is assumed to know the geographical location of deployed sensors. In the solution proposed in this thesis an optimum location is not sought but an optimum path that will ensure equitable usage of all nodes to transport data messages.

Research undertaken by Somasundara et. al shows that the energy consumption in a network using a mobile base station is significantly less than that of a static network (Somasundara et al., 2006). The authors propose moving the base station around the application area. When the base station is within range of sensor nodes, it collects event data. This is not an optimum real-time solution, as the sensor nodes have to wait for the base station to arrive before transmitting event information, but it is feasible in delay-tolerant applications, such as environmental monitoring. A key difference between this researcher's proposed ideas and the model presented here is that in the model presented here an optimum path within the application area, along which one or more mobile sinks travel is calculated.

Huang, Zhai and Fang consider a wireless network where the sensors are mobile, (applications such as tracking free-ranging animals, both wild or farm livestock) (Huang et al., 2008). The problem focused on in this paper is on improving the robustness of routing when there are path breakages in the communication channel due to node mobility. The suggested solution is the use of a cooperative, distributed routing protocol to combat path breakages. The writers assume that the intended path or route between the source and destination is already known and neighbouring nodes can be used if the communication channel on the intended path fails. In this chapter, the primary research focuses on actually developing these routes, while reducing the number of non-event type messages required in the network. However, cognisance will have to be taken of possible path breakages that may occur during the development of optimal routes.

Vupputuri, et al. use mobile data collectors to achieve energy efficient and reliable data communication. When an event occurs, sensor nodes inform the nearest data collector. The data collector aggregates the event information and with a specified reliability factor (R) informs the base station (Vupputuri et al., 2010). The primary focus of the authors' investigation is determining a mobile strategy for the data collectors to ensure reliable and energy efficient event reporting. The mobility strategy does not consider how to optimise the changing locations of the data collectors. The authors focus on reducing the number of messages sent and received by nodes close to the base station to improve network lifetime and ensure that multiple paths are used to improve network reliability.

Gu et al. use a partitioning-based algorithm to schedule the movements of mobile sinks in order to reduce data loss due to buffer overflow while waiting for a sink to arrive (Gu et al., 2006). This aspect is ignored in solution presented in this chapter. Other recent research activity in this field, include the work of Marta and Cardei (Marta & Cardei, 23-26 June 2008) where mobile sinks change their location when the nearby sensors' energy becomes low, and determine the new location by searching for zones where sensors have more energy.

The use of a mobile relay to route all traffic passing through a static node for a specified period of time, is discussed by Wang et. al. The mobile relay traverses a concentric circle that stays within a two-hop radius of the sink. The authors show that the use of a mobile relay can improve a WSN's lifetime by 130%. Additional experiments show that a mobile sink, moving around the perimeter of a large and dense network, can best optimise WSN lifetime compared to a mobile relay or using resource rich static relays located close to a static sink (Wang et al., 2005). The results of this paper indicate that the mobile relay should be a maximum of two hops from a static sink and that only nodes within a maximum of 22 hops from the sink need to be aware of the location of the mobile relay. The use of both a mobile sink and a mobile relay prevent over-utilisation of static nodes located close to the sink to route messages to the sink and hence increase overall WSN lifetime. We do not consider the use of a mobile relay in the solution discussed in this chapter and focus exclusively on an optimum path for a mobile sink to follow within a WSN application area. In chapter 5 it was determined that the optimum number of hops from a static sink should be around 5 hops to limit the number of messages sent and received by individual nodes. In future experiments, an analysis of the optimal number of hops from the perimeter that a mobile sink should travel along to increase network lifetime will be conducted.

A multi-sink heuristic algorithm (HOP) is proposed by Ben Saad and Tourancheau to find the best way to move mobile sinks in order to improve the lifetime of large scale sensor networks. Sinks are relocated to nodes located the maximum number of hops from a sink as it is assumed that these node will have higher residual energy as the nodes will not be required to re-transmit messages destined for a sink (Ben Saad & Tourancheau, 2009). The minimum amount of time a sink will spend at a specific location is 30 days. The proposed algorithm is compared against schemes using static sinks, sinks moving along the periphery of the network, sinks moving randomly and sinks moving according to an Integer Linear Programming algorithm, in terms of network lifetime and residual energy at each sensor node. The results of simulations indicate the HOP algorithm achieves significant improvement in network lifetime over the other algorithms and that there is more even distribution of residual energy per sensor node. The HOP algorithm differs from the solution proposed in this chapter, because HOP assumes that the sinks are not continuously mobile but are moved after a specified number of days to different locations within the building. It will be useful to do similar comparisons as those carried out by the authors to determine if there is an improvement in network lifetime by using the optimal path algorithm.

8.4 EXPERIMENTAL SIMULATION

The experimental setup used the Network Simulator (NS-2). In NS-2 mobile nodes move at constant velocity. As this was a simulation environment, the mobile node did not require time to accelerate to a constant final velocity or to decelerate when turning a corner. Therefore, the time calculations are based on the node moving at constant velocity around a square path.

Changes were made to certain C++ programs in the NS-2.3.5 version to enable the node to move along the specified path and periodically send “hello” type messages. A Tcl script defined the parameters of the path the node travelled on and stored the event messages received by nodes along the mobile node’s path. When a mobile node passed by a node with stored event messages, the node would pass these messages onto the mobile sink.

Experiments were run to determine the time it takes to complete one loop around the calculated path. This time was verified with the calculated time, using equation [8.17]. Thereafter an event message was broadcast from a node on the perimeter of the application area, and the effect on surrounding nodes was analysed. The velocity of the mobile sink was set at 10 m/s.

8.5 RESULTS AND ANALYSIS

Using Equation [8.17], the time it will take a mobile node moving at a constant velocity of 10m/s to complete one loop along the calculated path is calculated.

$$T_{total} = \frac{2 * (240 - 60) + 2 * (240 - 60)}{10}$$

$$T_{total} = 72\ seconds$$

The NS-2 Tcl script was run and the time taken for the mobile node to complete one loop around the calculated path as shown in Figure 8.1 is ***72 seconds***.

An analysis of the number of messages received by nodes neighbouring the mobile node's path is shown in Figure 8.4. As can be seen, certain nodes receive more than one message. These nodes are on the perimeter of two intersecting "hello" type messages sent from the mobile sink as shown in Figure 8.1. Thus nodes 36, 37, 26, 27 etc. receive a "hello" message from the mobile node twice. To prevent this duplication of received messages from the mobile node, the researcher suggests that the neighbouring nodes go into sleep mode for a specified time period after receiving the first "hello" type message from the mobile node. This should ensure that all nodes neighbouring the mobile node's path only receive one message per complete loop of the circuit.

To conserve energy further, the number of times a mobile node will circumvent the path can be application-specific. For example, if sensor nodes are required to send updates to a sink periodically, the mobile node can traverse the path only during this time period. However, if the application requires the mobile node to monitor the area continuously for events and respond in real-time, the mobile sink has to move along the path and send "hello" type messages continuously.

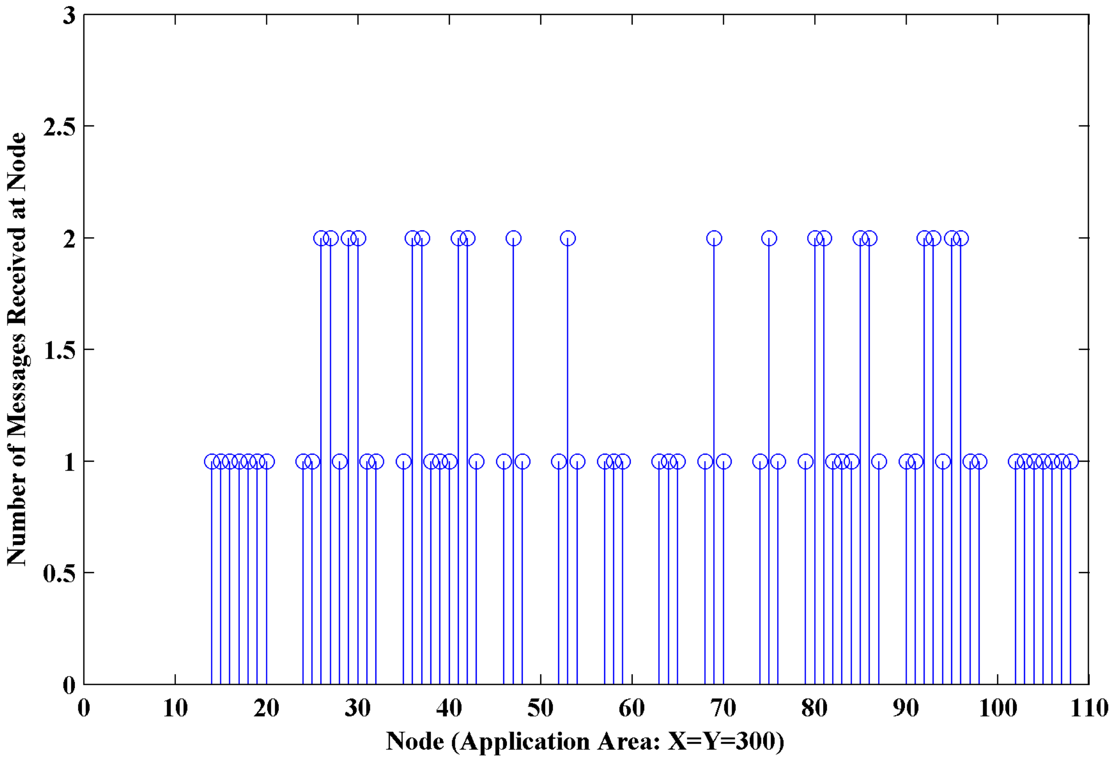

Figure 8.4: Number of messages received by nodes neighbouring mobile node's path

Next the effect of sending a message from a node on the perimeter of the application area to one of the nodes on the perimeter of the mobile node's path is analysed. For example, a message is sent from node ***1*** to nodes ***14*** and ***24*** (refer to Figure 8.1). As can be seen in Figure 8.5, only those nodes used to pass the event message receive more messages than those shown in Figure 8.4. A comparison of the number of messages received per node against that sent to a static sink placed in the middle of an application area is shown in Figure 5.12. The advantage of using a mobile path is obvious, as there is a significant decrease in the number of messages received per node compared to flooding and SWR even when the IM is taken into consideration.

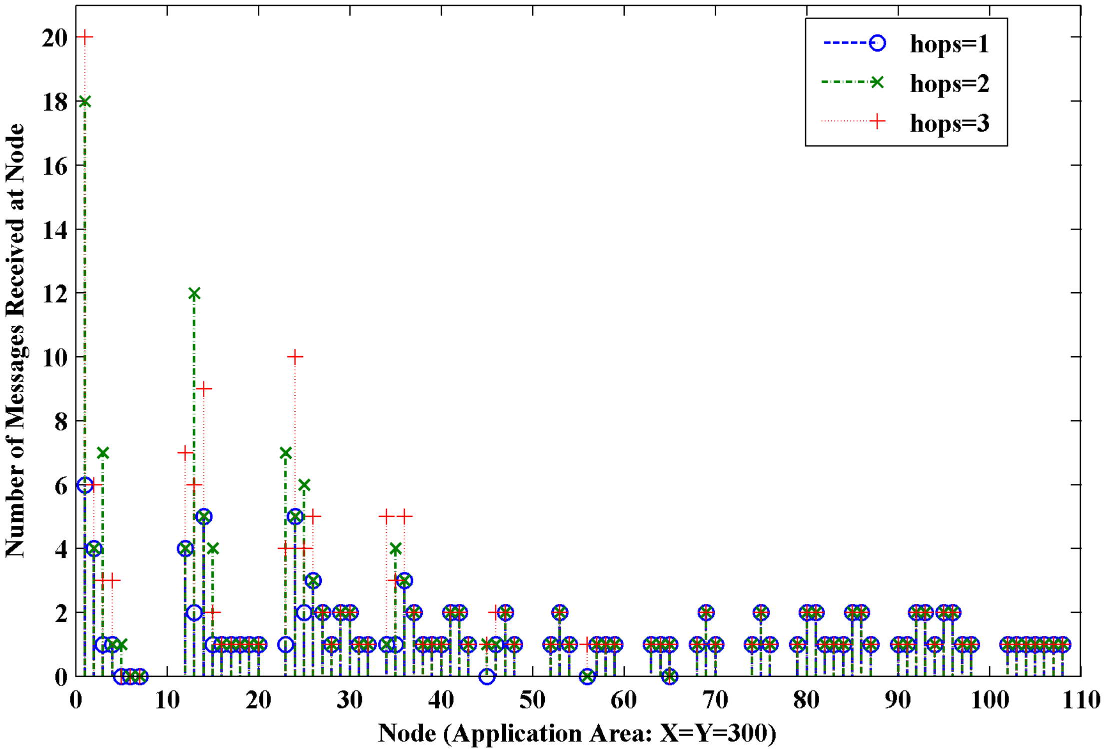

Figure 8.5: Number of messages per node when event message sent to node on mobile nodes perimeter

However, the continuous sending of “hello” type messages at periodic intervals by the mobile node, does incur a cost. To reduce the number of messages transmitted within the application area further, (depending on the type of WSN application); a “hello” type message can be sent once at initialisation when the mobile sink first completes a loop along the path. All nodes along the perimeter will be able to calculate when the sink will pass by again and ensure that the node is awake during that time, if the node has event messages to relay. At the calculated time the perimeter node can proactively send a message to the mobile node informing it that it will begin transmitting event messages.

8.6 CONCLUSION

It has been shown that the number of messages received per node can be reduced by using a specific path for the mobile node/sink to move along. All neighbouring nodes can store messages when an event occurs, and if the sensor detecting the event is not an immediate neighbouring node along the path of the mobile sink, the number of hops that the message has to be re-propagated is small. This means that even if a flooding type routing protocol is used, as long as the number of hops is small (that is, limited to the number of hops to reach a neighbouring node) the number of messages received per node is smaller. In addition, because all neighbouring nodes can pass an event message to the sink, no specific set of nodes is overloaded with the task of routing event messages to the sink. This ensures more equitable usage of all sensor nodes in the network and hence increased node lifetime.

CHAPTER 9

FINAL CONCLUSIONS AND FUTURE WORK

Sensor nodes have a limited non-renewable energy supply. This limit on sensor nodes energy imposes constraints in the design of WSN applications not currently considered as important in other wired and wireless networks. This cap on energy usage is not necessarily a bad thing. As engineers move away from a design philosophy that is based on unlimited energy and computing resources to one of optimising designs to utilise all resources more efficiently, other types of computing and networking technologies will consider similar issues currently faced by WSN application designers.

One of the central issues is that communication in a WSN must be highly energy efficient to prolong the longevity of sensor nodes and hence network lifetime. In a wireless environment two inconvenient consumers of a nodes energy is firstly, that neighbouring nodes of a transmitting node which are not the intended recipient node of the message also detect the wireless signal; and secondly the energy required to transmit a message increases as a square of the distance between source and destination. To enable energy efficient communication within a WSN, the number of messages sent and received by any node within the application area has to be restricted to only mandatory messages to notify sink(s) of events or to provide regular data updates of the monitored application.

In this thesis several strategies to minimise the total number of messages sent within a WSN and the total number of messages received and re-transmitted per individual node has been discussed and analysed. One of the solutions proposed is to model a WSN as a small world network whereby multiple sinks are placed within the application area. The idea of placing multiple sinks or cluster heads within a WSN application area has been considered before. There is general agreement that using multiple sinks (or cluster heads) reduces the total number of messages sent within a WSN and improves network lifetime. Where our proposed solution differs from previous proposals is that the placement of these sinks within a WSN cannot be random or even based on an election strategy between nodes to ensure all nodes get a chance to be a sink (or cluster head) as is the case with a routing protocol such as LEACH. It has been shown in this thesis that correct calculation of number and placement of multiple sinks within a WSN can result in significant reduction in the number of messages communicated within a WSN.

The total number of messages transmitted and received within a WSN can be reduced by ensuring that after a certain specified number of hops the message will reach its intended destination sink. However without a specific route all intermediate nodes will still re-broadcast the received message until the specified number of hops is exceeded. To further reduce unnecessary energy consumption and reduce message communication within a WSN, an initialisation message (IM) is transmitted from each sink node to all nodes within a specified number of hops from the sink. The use of the IM creates multiple route paths between a sensor node and one or more sink nodes. Now, when a sensor node transmits a message to a sink destination only those intermediate nodes that are specified in the route path need to re-transmit the message. All other nodes can ignore the message or enter sleep mode. The effect of the IM on an individual node within a WSN is small and negligible when the benefits of having multiple route paths to a destination sink is considered. The use of the IM further increases the energy efficiency of the WSN application.

The use of static sink nodes reduces the lifetime of those nodes in the immediate range of the sink node as these nodes are required to pass on messages from outlying nodes to the sink node. As these nodes are vital to ensuring communication with a sink node, the loss of a sink neighbour node severely affects the lifetime of a WSN application. To ensure more equitable usage of all nodes within the WSN, the use of mobile sinks has been proposed. A mobile sink has an additional advantage in that if it is properly equipped, the mobile sink can react to an event faster, i.e. the mobile sink can become a mobile actor that responds to an event in a similar manner that a human may respond. Having multiple mobile actors within a WSN still requires that communication must be optimised to reduce unnecessary message transmissions because of the wireless nature of the transmission medium. In addition, it does not make sense for all actors to respond to an event. This will result in wastage of all actors' resources. A method for optimising selection of which actors should respond to an event while ensuring that communication within the WSN is minimised has been proposed. The decision of which actor or set of actors to nominate to react to an event can be made using Info-Gap Decision Theory (IGDT). IGDT allows for robust decision making even when uncertainty about certain environmental factors (such as actor location of available energy) exists.

In this thesis an IGDT model for selecting the correct set of actors to respond to an event is discussed. The advantage of using IGDT versus actors in a cluster model is analysed. Various scenarios of where an event can occur within a WSN are discussed. It has been shown that IGDT enables the best placed actor(s) to respond to an event.

The use of actors or mobile sinks ensures that the same set of intermediate nodes is not continuously used to re-transmit messages to a central sink or actor. However a mobile sink randomly moving within the application area will not optimise message communication within a WSN and will result in excess numbers of unnecessary messages being transmitted within the application area and wasting all sensor nodes energy resources. In this thesis a calculated model to determine the optimum path a mobile sink (or actor) should travel is discussed. The impact of the mobile sink travelling along a predetermined path can still be considered to satisfy the soft real-time requirements of a WSN application because the small amount of time (for e.g. 72 seconds), it takes an actor to complete one loop around the path is still smaller that the time it would take a human to react to the event. The impact of using a mobile path in a WSN on network energy efficiency and reducing message communication has to be carefully evaluated because the use of continuous polling of the mobile sink of nodes along its path for messages can negatively affect these nodes lifetimes. It has been proposed that after the initial loop around the predefined mobile path, an actor refrains from sending further messages until communication is initiated by one to the nodes on the perimeter of the path that has a message to forward to an actor. This will reduce the amount of communication messages seen by all nodes within a WSN application area.

Currently only a square application area has been evaluated. In future research the application of the various proposed algorithms on more variable application area shapes and sizes will be analysed to determine if the proposed models are equally effective. Also, as all experiments have used simulation to determine their effectiveness, there is no real practical demonstration of the proposed algorithms energy efficiency. In future work, a small WSN application will be built and the small world routing strategy re-evaluated.

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