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.

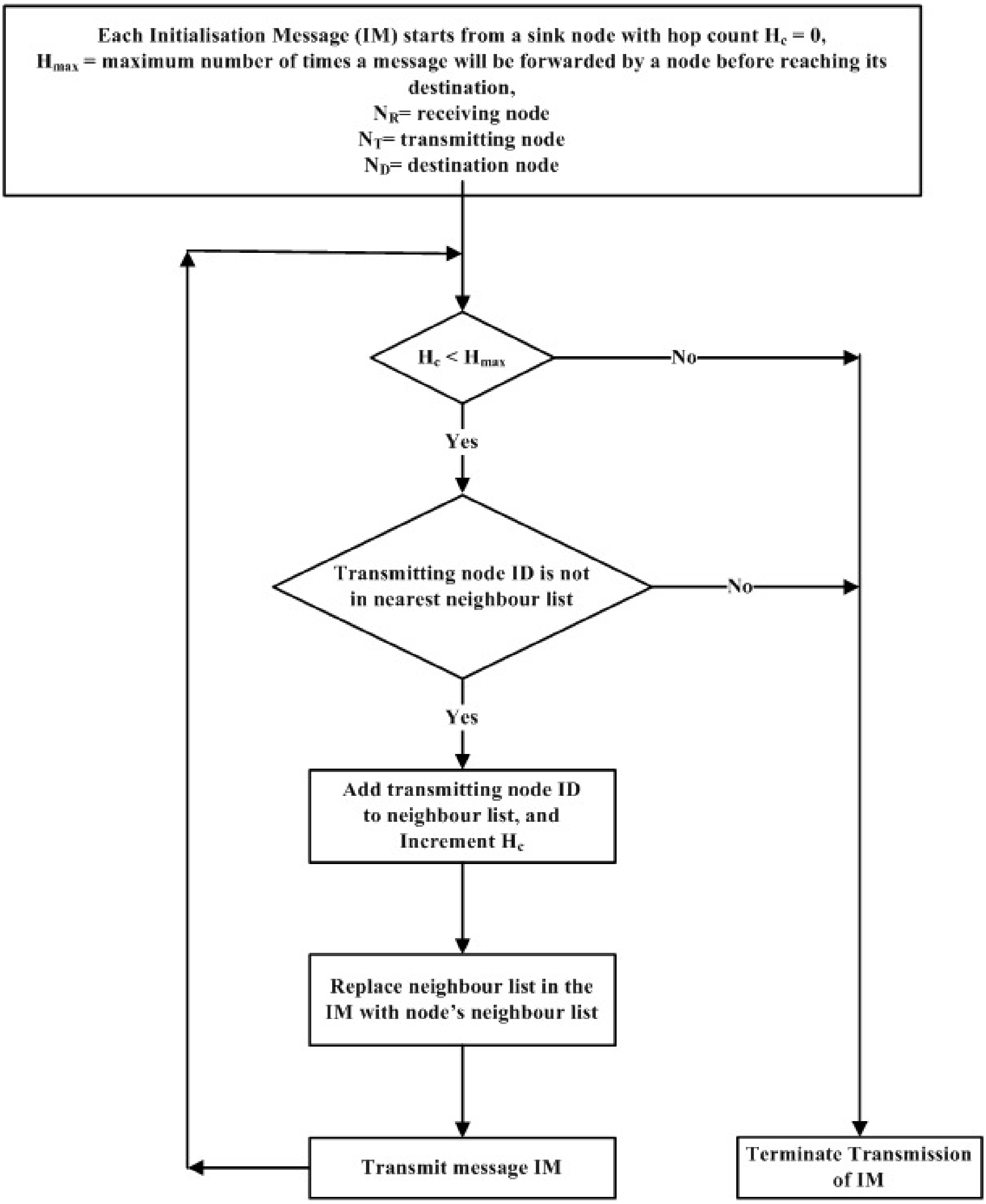

Figure 4.1: Creating route paths with an initialisation message

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 μ*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.

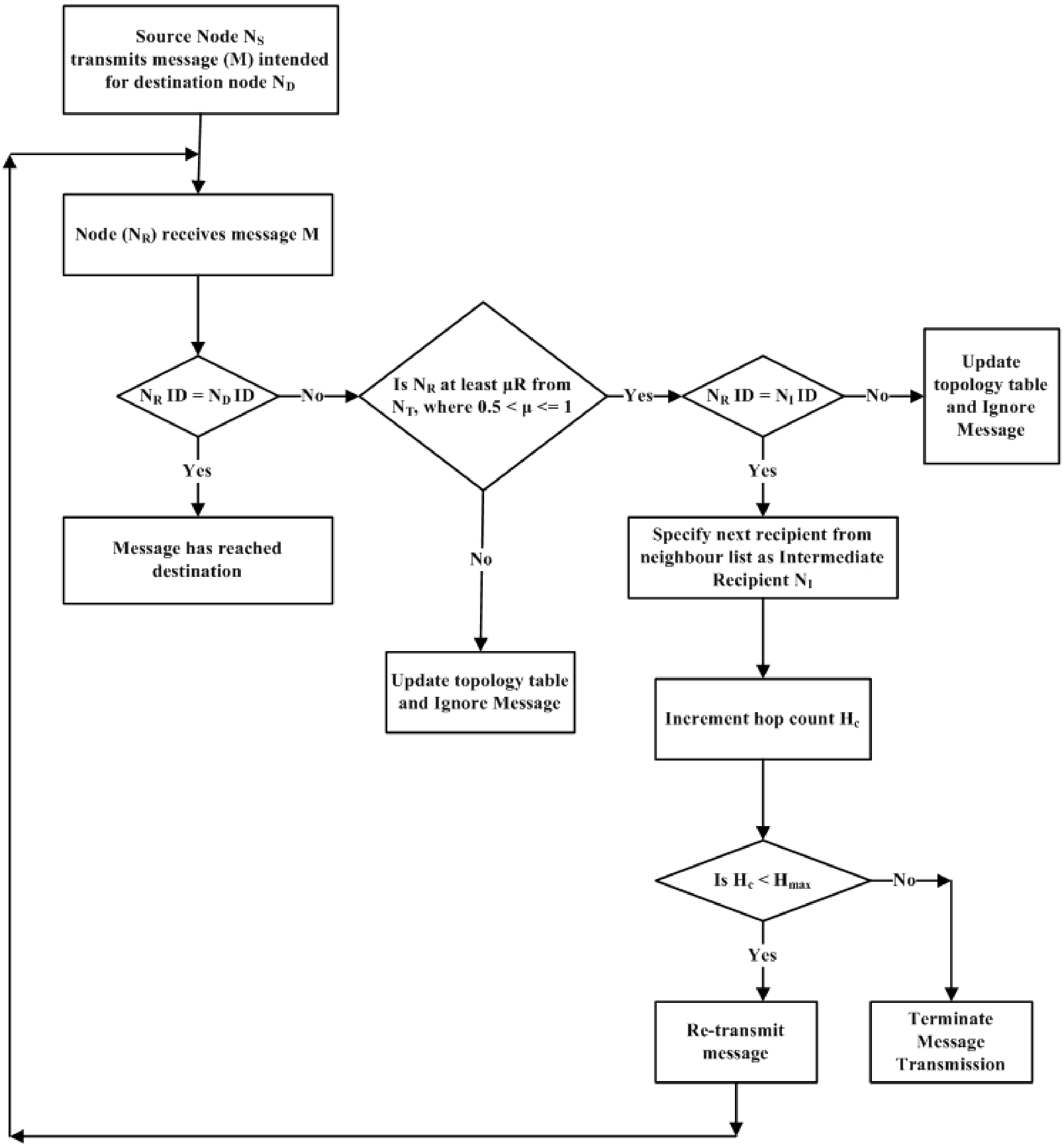

Figure 4.2: Message routing via the nearest neighbour table

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).

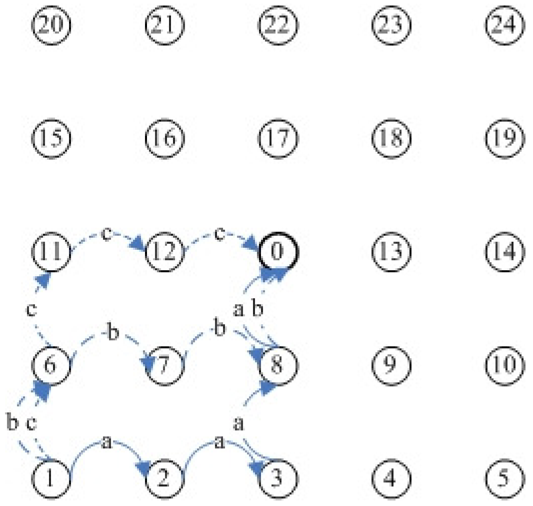

Figure 4.3: Possible routes from sensor to sink

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.

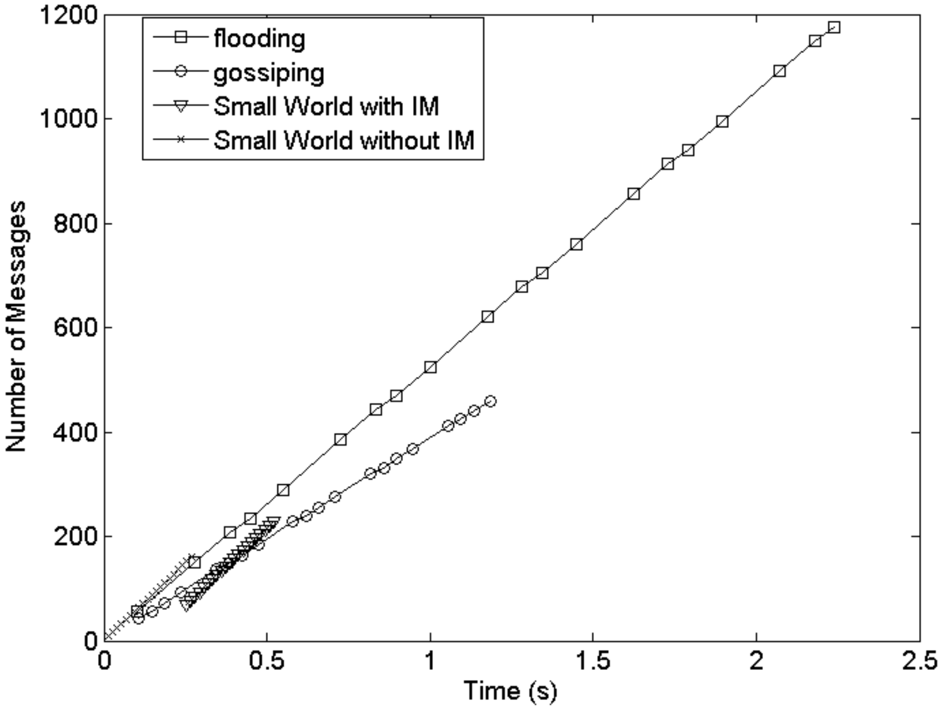

Figure 4.4: Messages vs. time (Nodes [1,5,20,24] to [0])

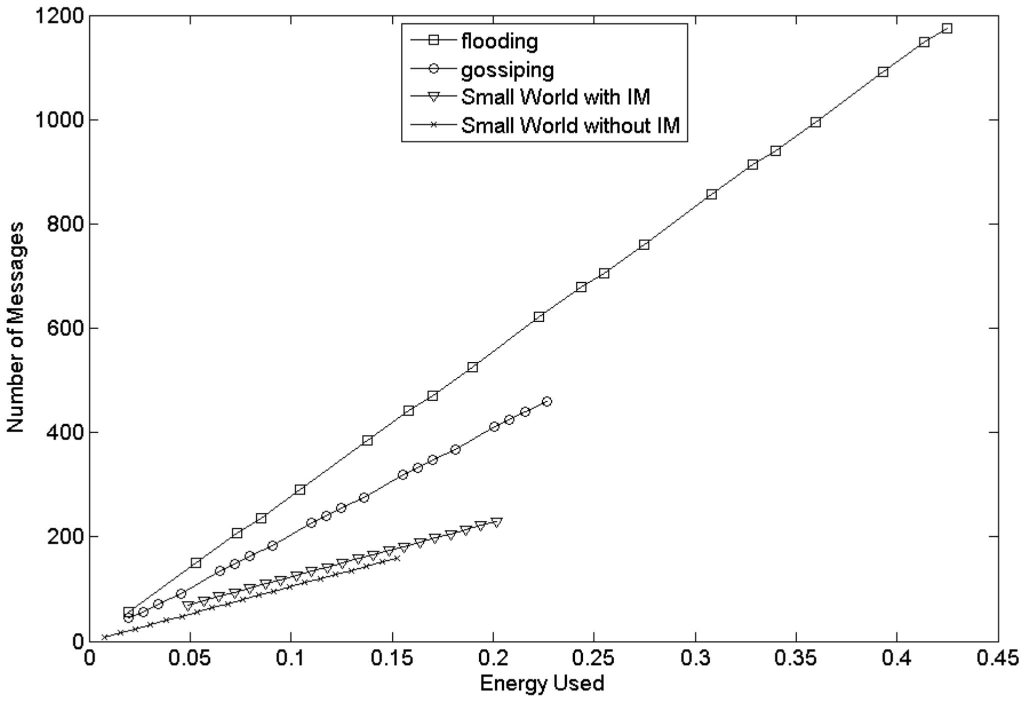

Figure 4.5: Messages vs. energy (Nodes [1,5,20,24] to [0])

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.

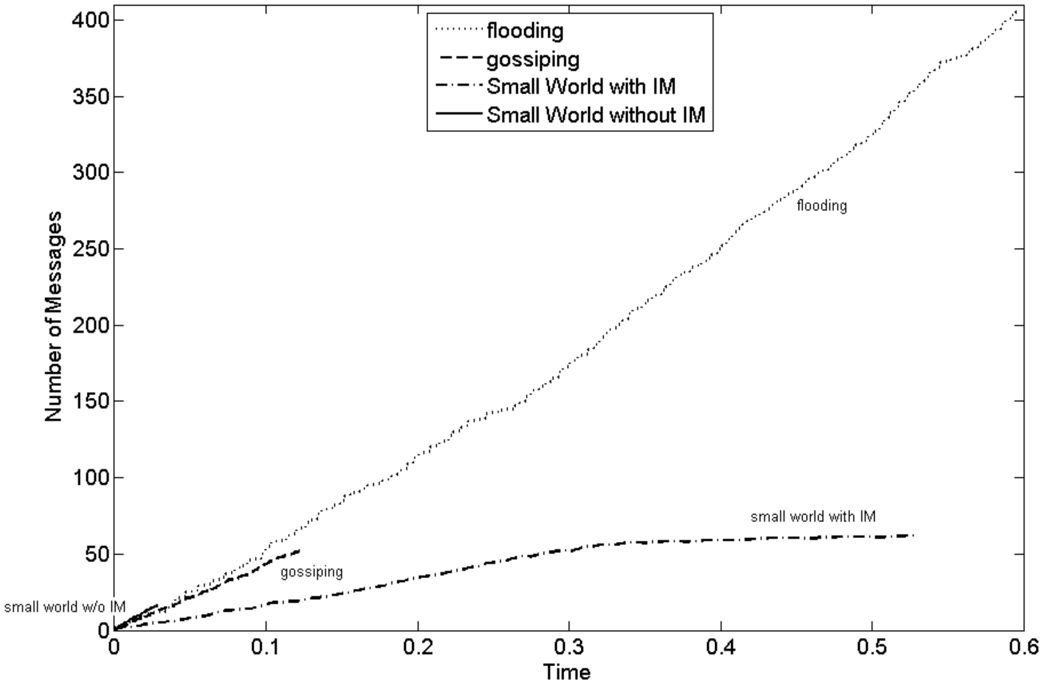

Figure 4.6: Messages vs. time (Node[1]to[24])

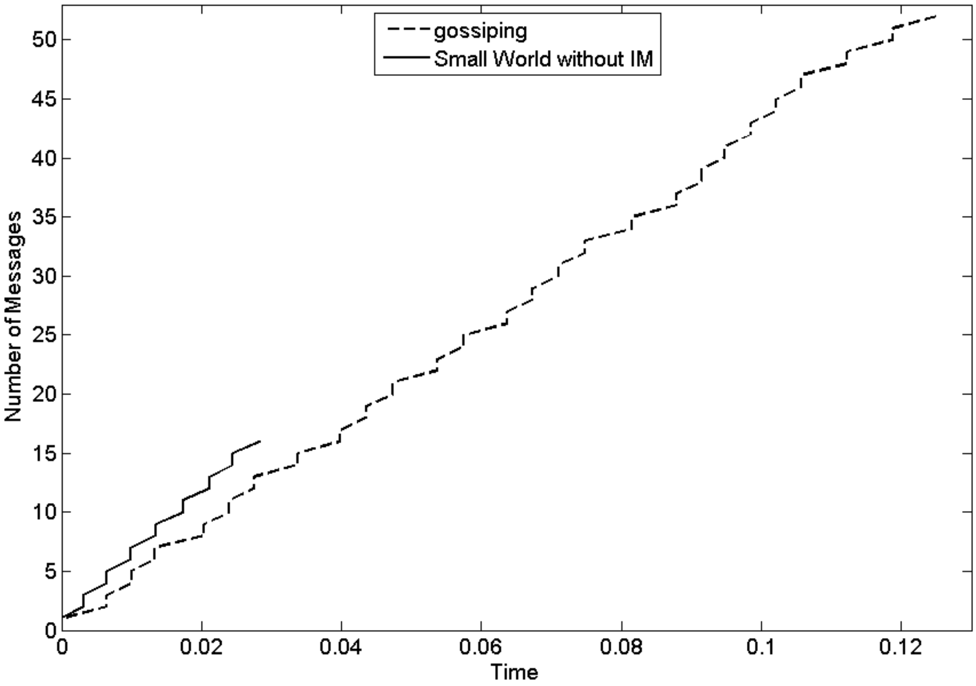

Figure 4.7: SWR without IM vs. gossiping

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.

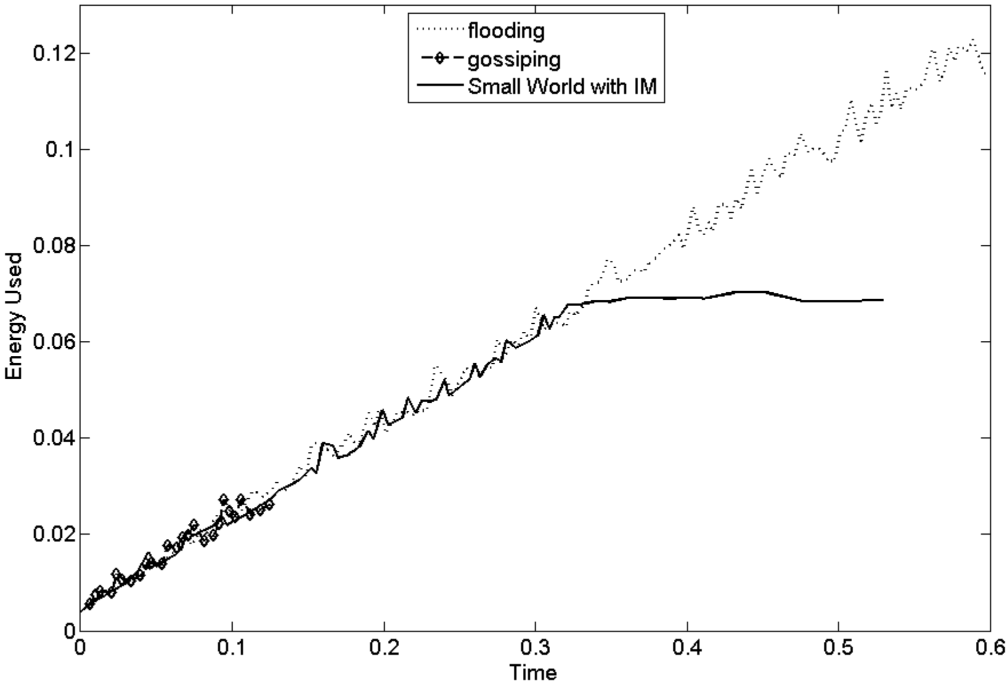

Figure 4.8: Energy usage to send message (Node[1] to [24])

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.

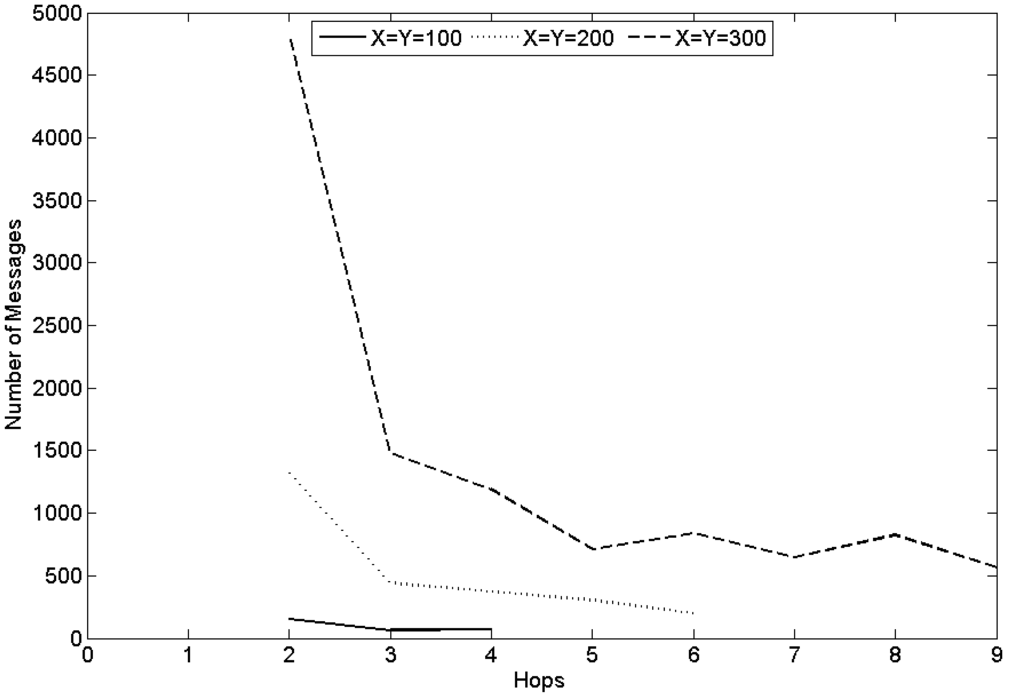

Figure 5.1: Total number of IMs versus number of hops/sinks

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.

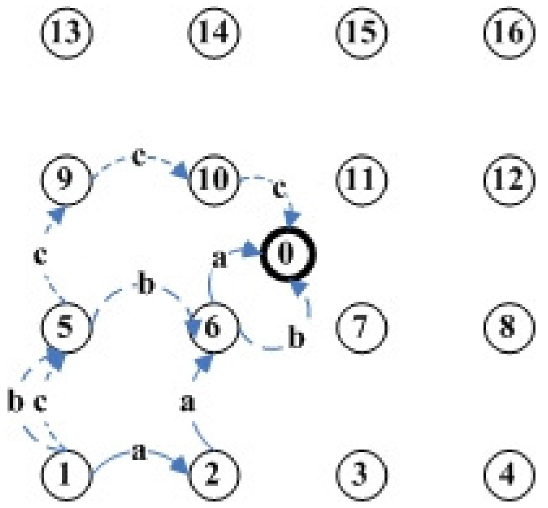

Figure 5.2: Application area 100mx100m

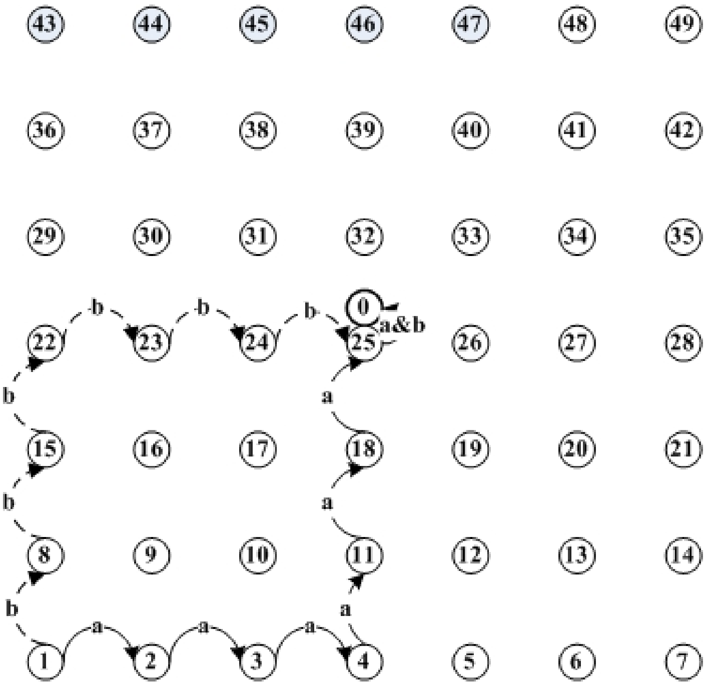

Figure 5.3: Application area 200mx200

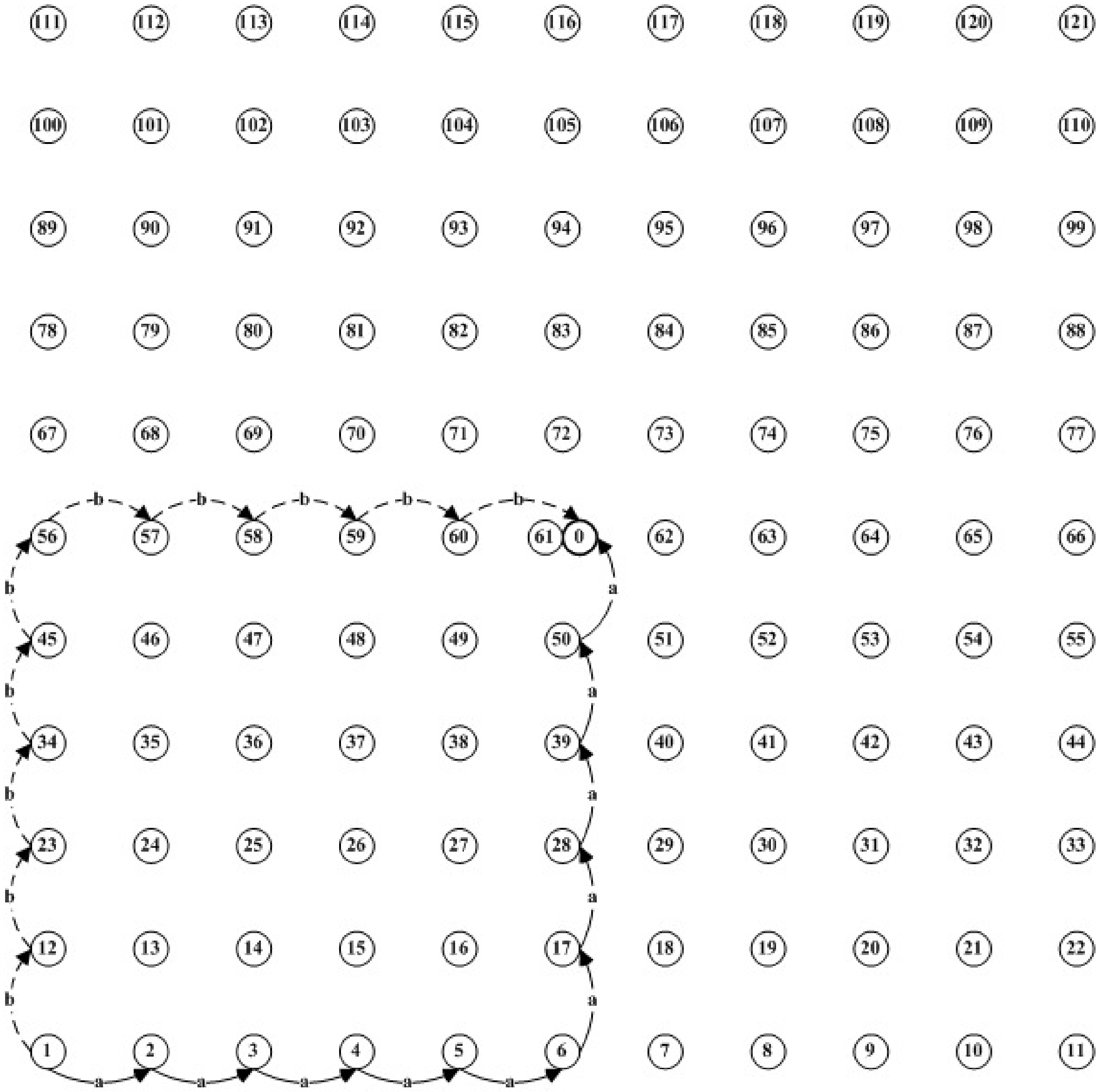

Figure 5.4: Application area 300mx300m

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.

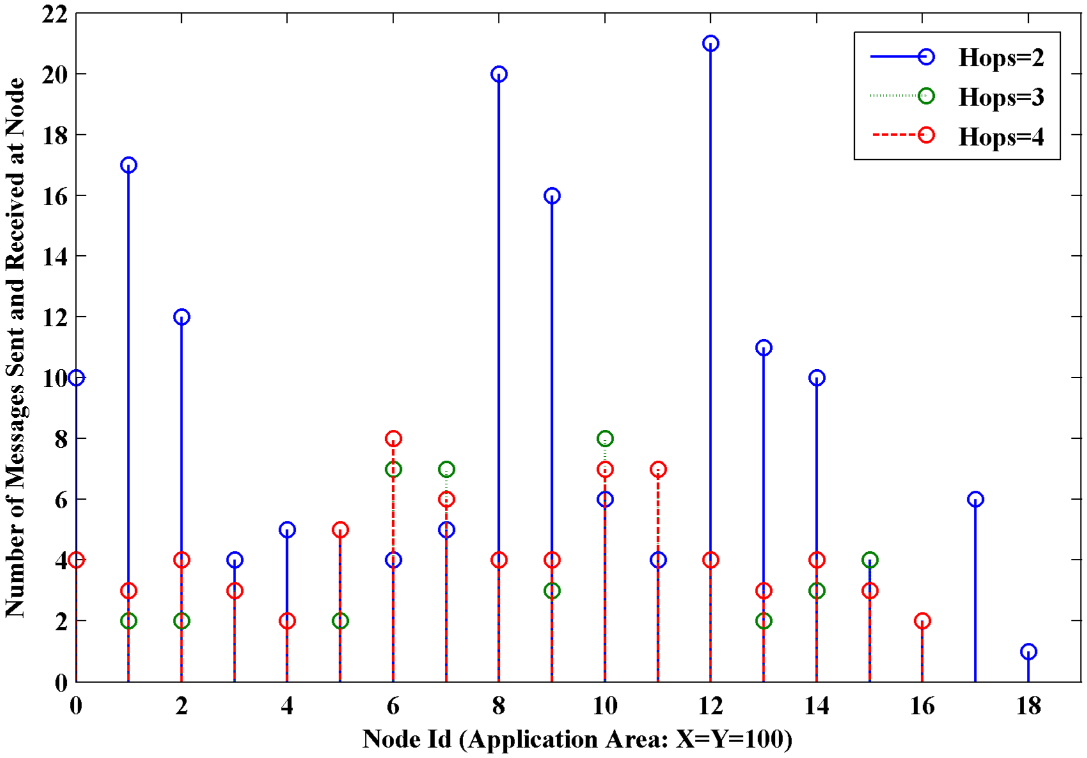

Figure 5.5: IMs per node [area 100mx100m]

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.

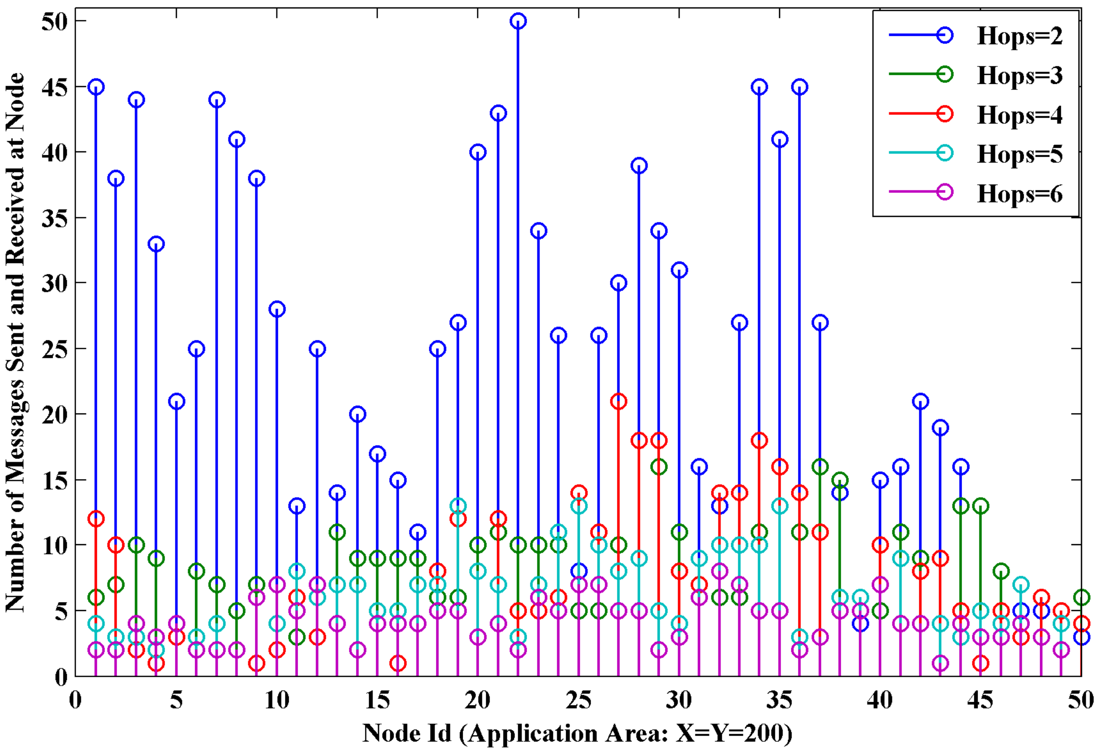

Figure 5.6: IMs per node [area 200mx200m]

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.

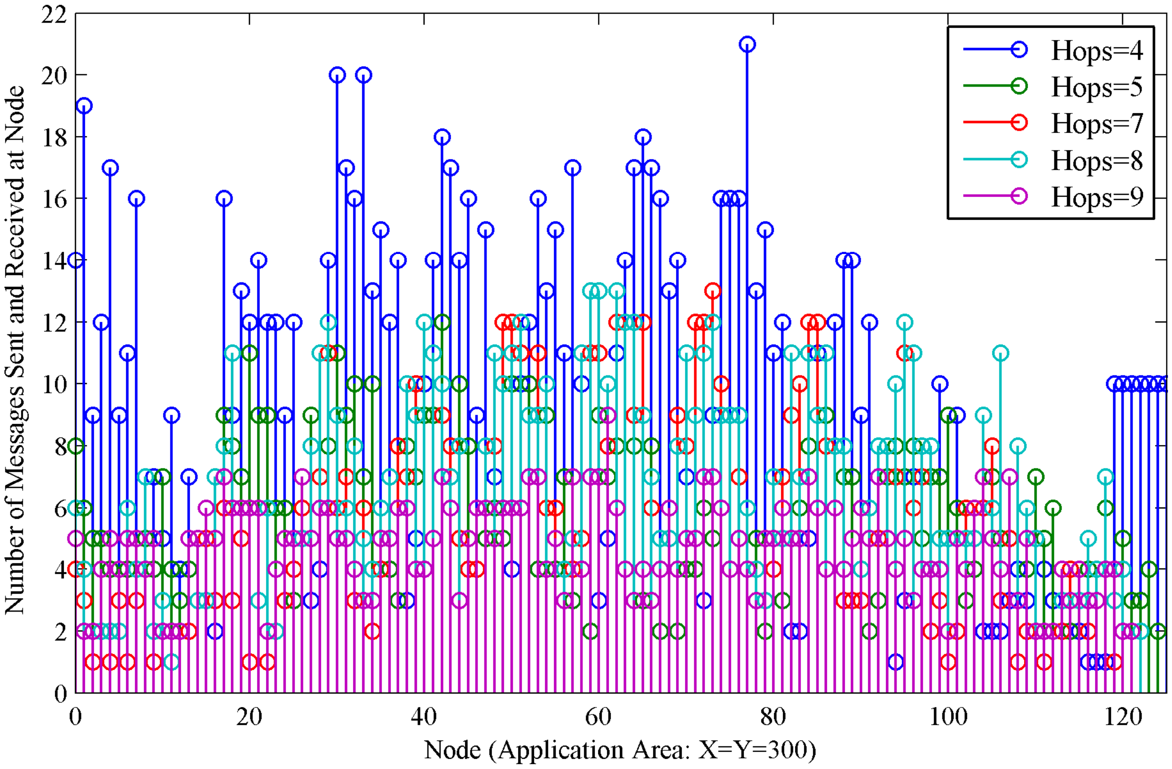

Figure 5.7: IMs per node [area 300mx300m]

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.

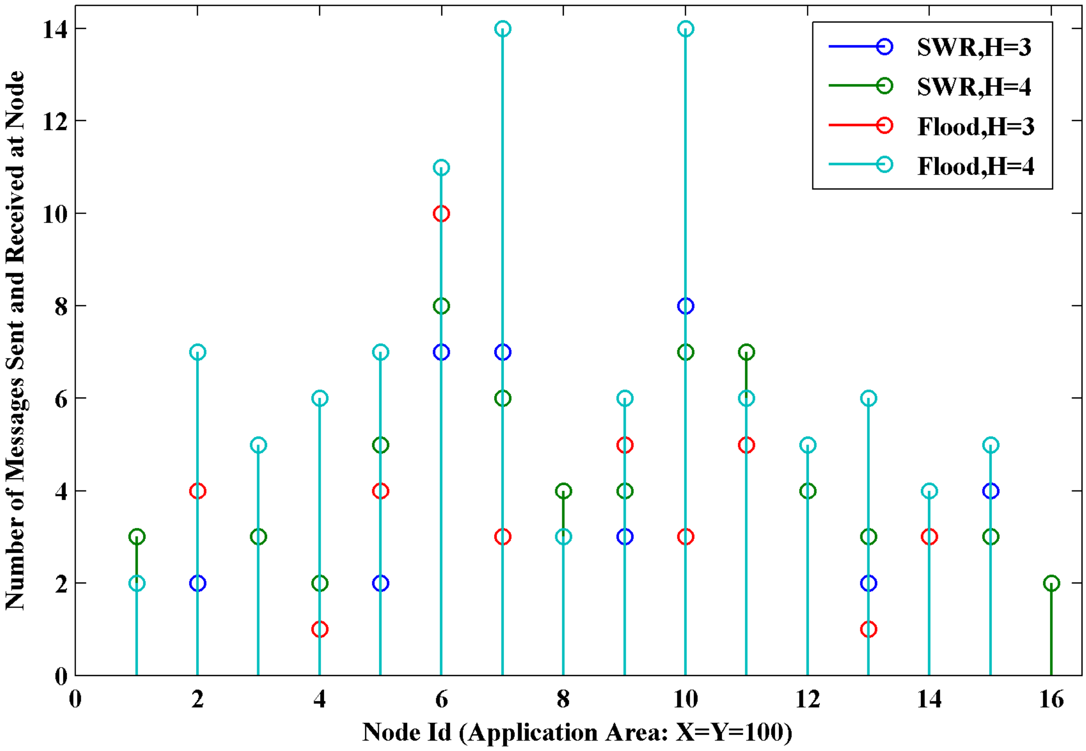

Figure 5.8: SWR and flooding (flooding restricted to same hop count as SWR)

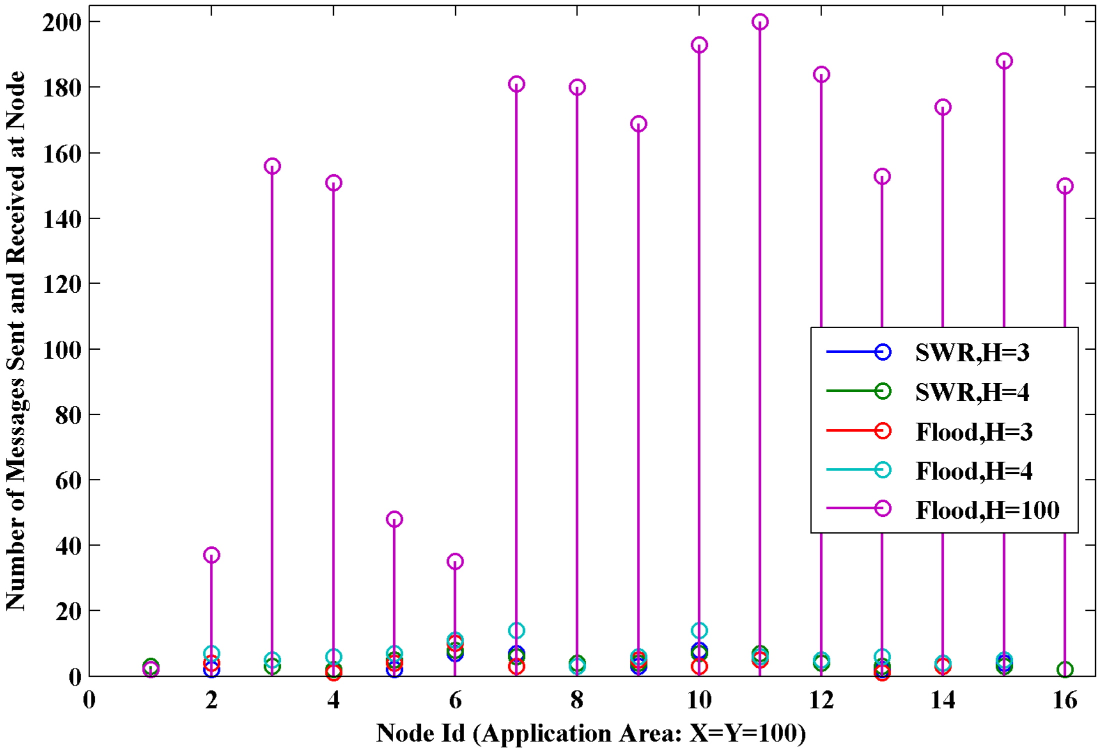

Figure 5.9: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction)

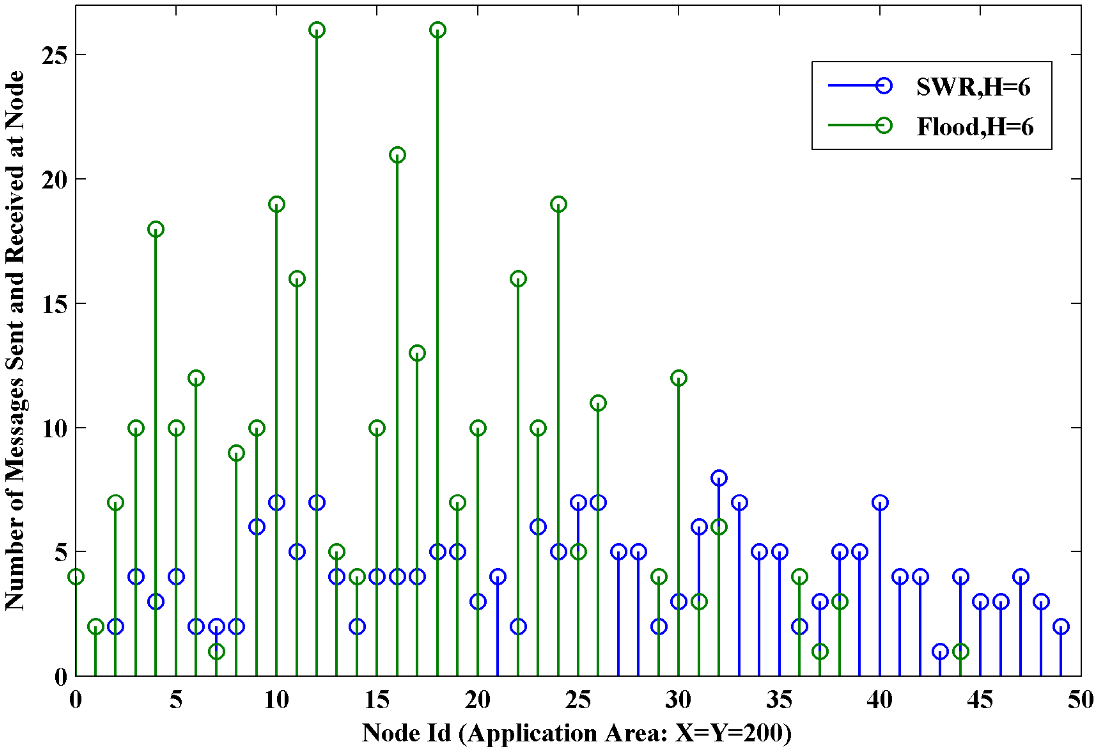

Figure 5.10: SWR and flooding (flooding restricted to same hop count as SWN)

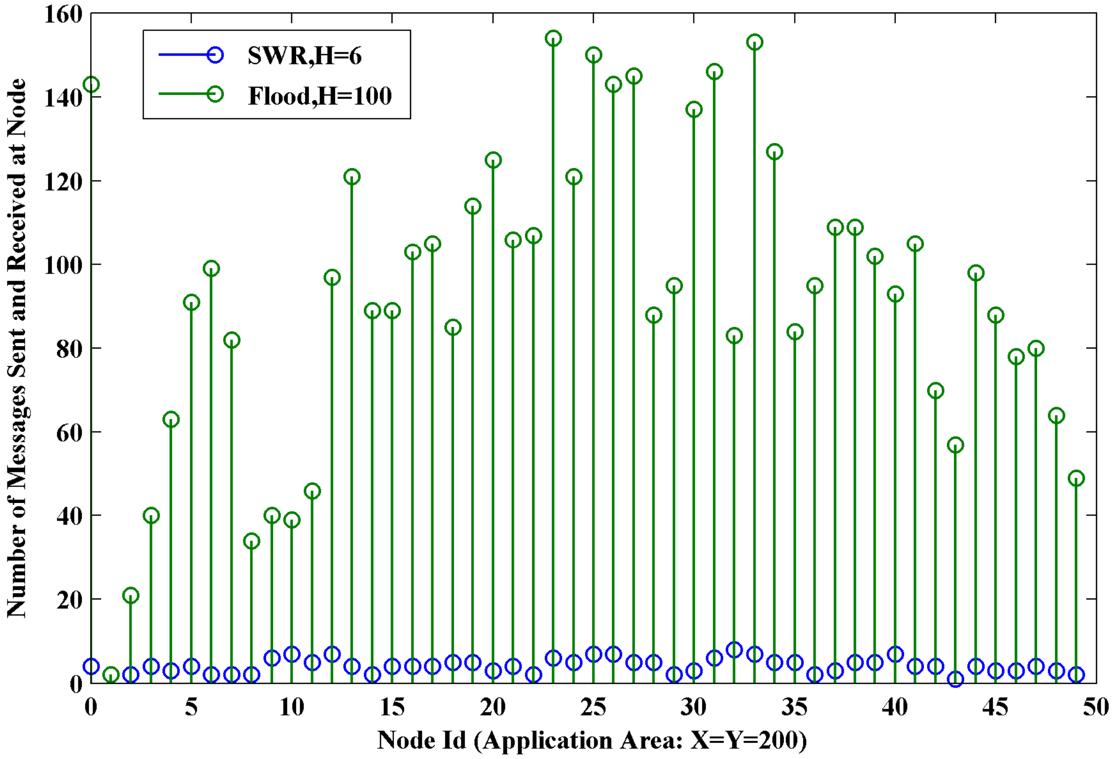

Figure 5.11: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction)

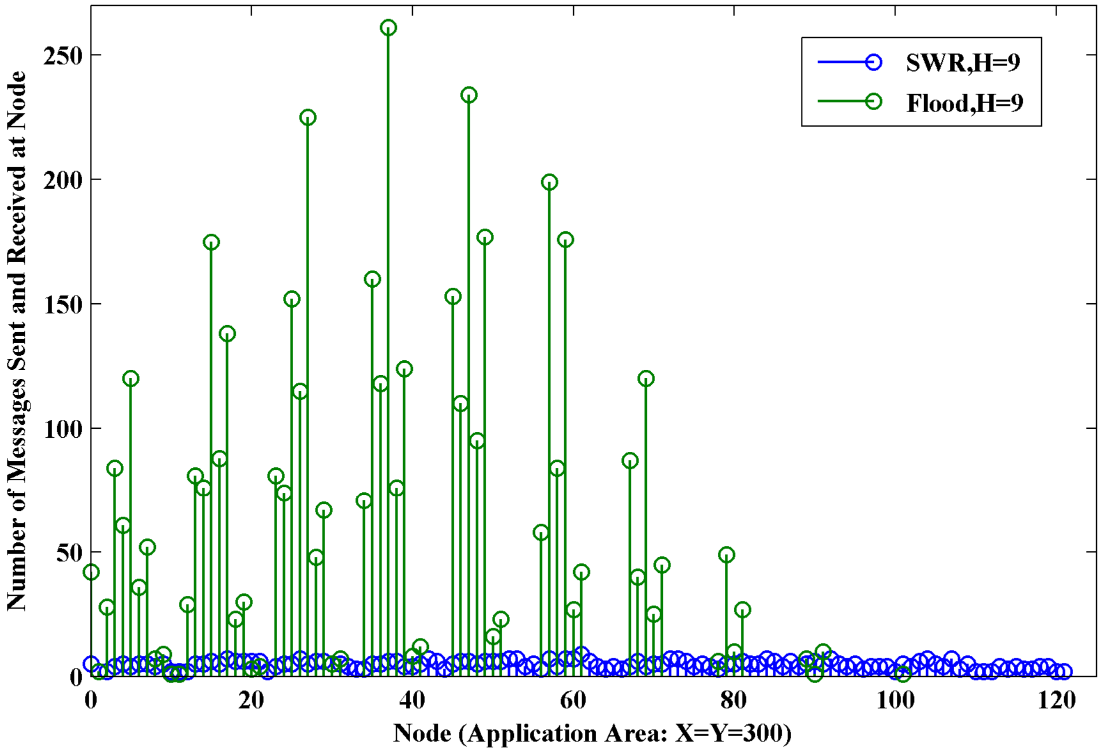

Figure 5.12: SWR and flooding (flooding restricted to same hop count as SWR)

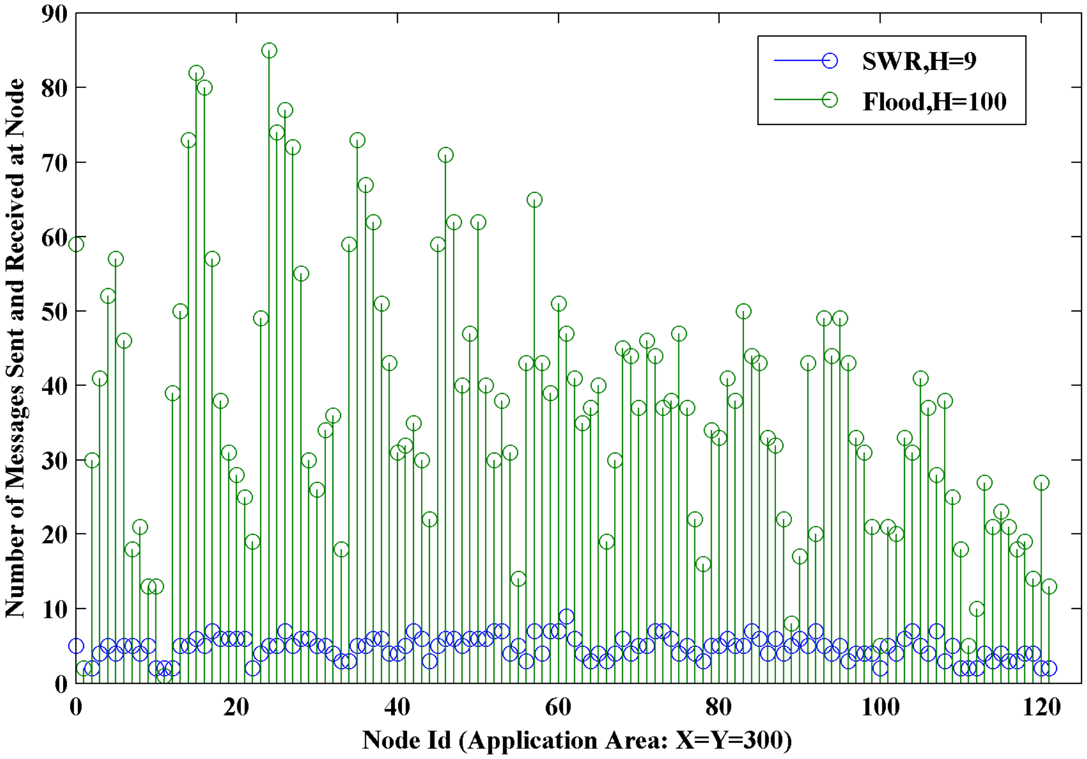

Figure 5.13: SWR and flooding (not restricting flooding hop count where 100 hops is equivalent to no restriction)

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).

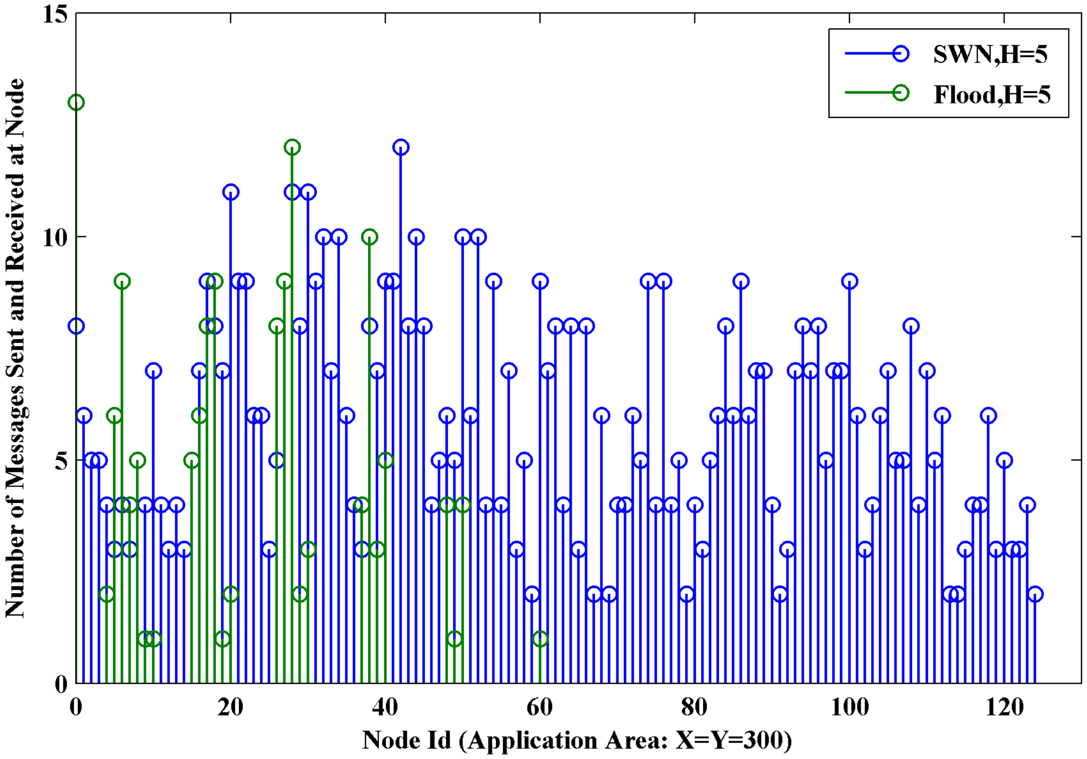

Figure 5.14: Number of messages per node for four sinks and five hops.

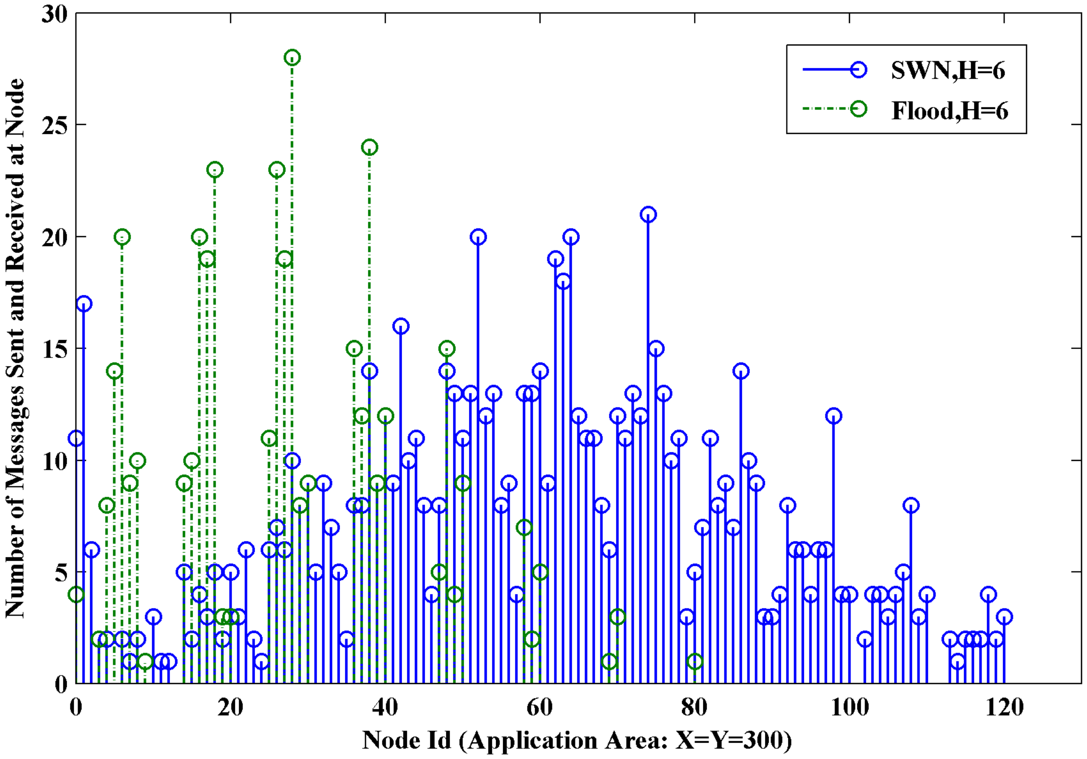

Figure 5.15: Number of messages per node for three sinks and six hops.

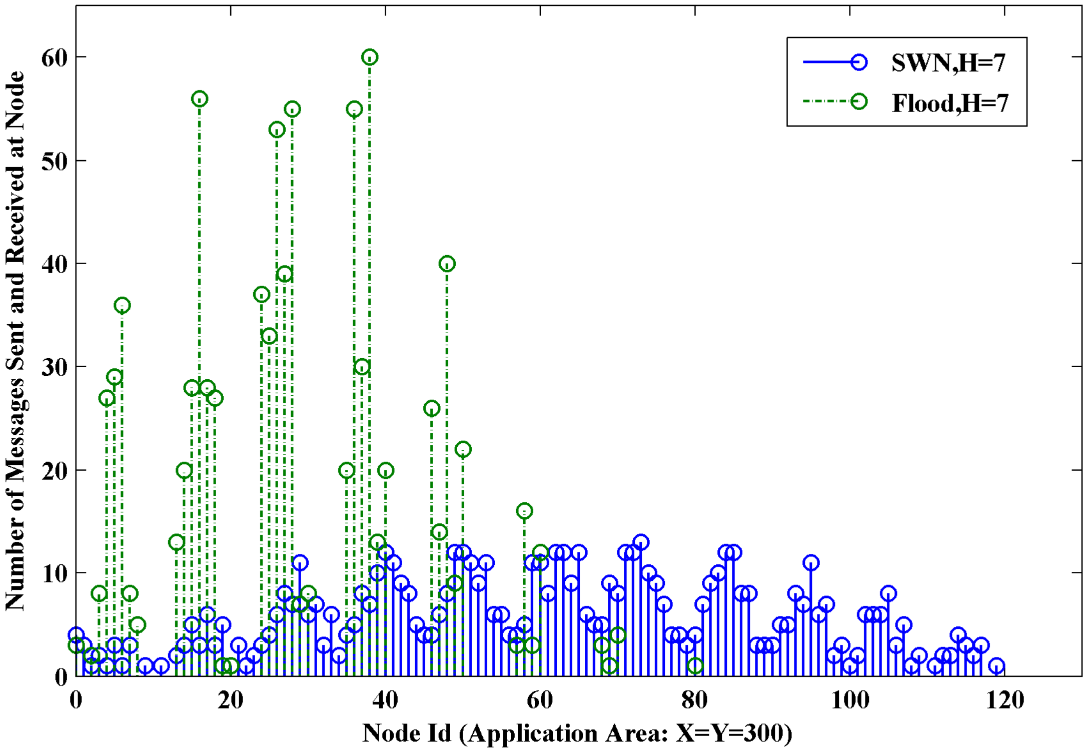

Figure 5.16: Number of messages per node for two sinks and seven hops.

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: $\text{Hops}_{\text{calculated}} + \text{Hops}_{\text{movedfromcalculated}}$, 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.