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.

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

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

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

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:

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

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

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

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

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

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

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

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.

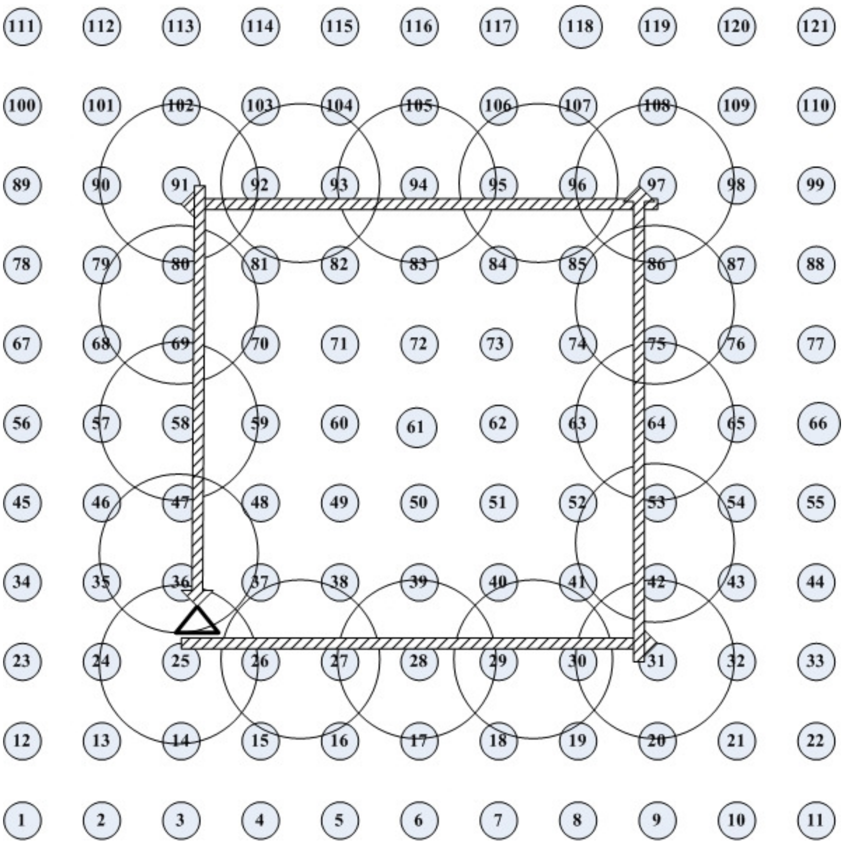

Figure 8.1: Path for a mobile node to follow in a 300mx300m application area.

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.

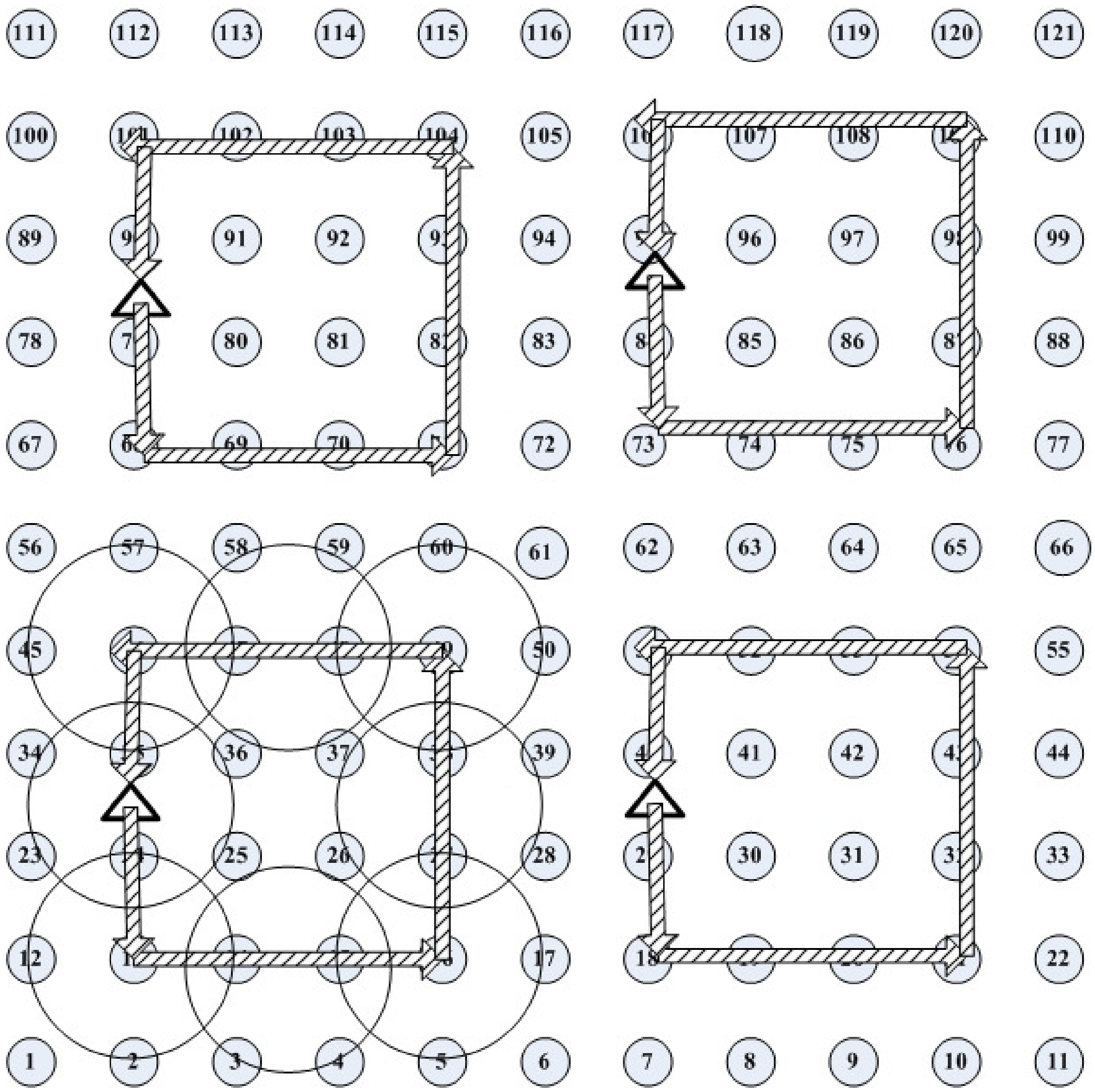

Figure 8.2: Four mobile sinks and each sinks path in a 300mx300m application area.

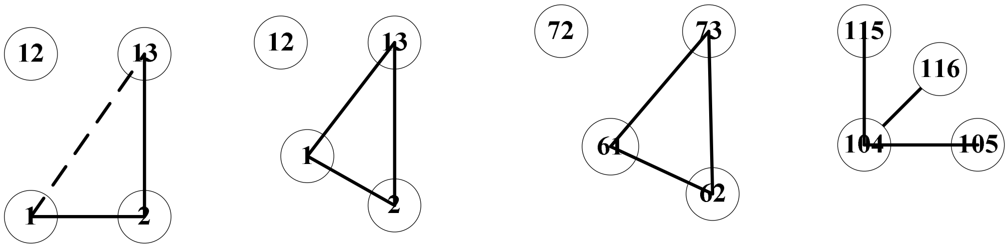

Figure 8.3: Moving corner nodes within communication range of mobile sink path

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:

$$s_{dv} = \frac{1}{2}at_{dv}^2 \qquad [8.14]$$

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:

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

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

$$t_{cv} = \frac{s_{cv}}{v_f} \qquad [8.15]$$

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:

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

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.

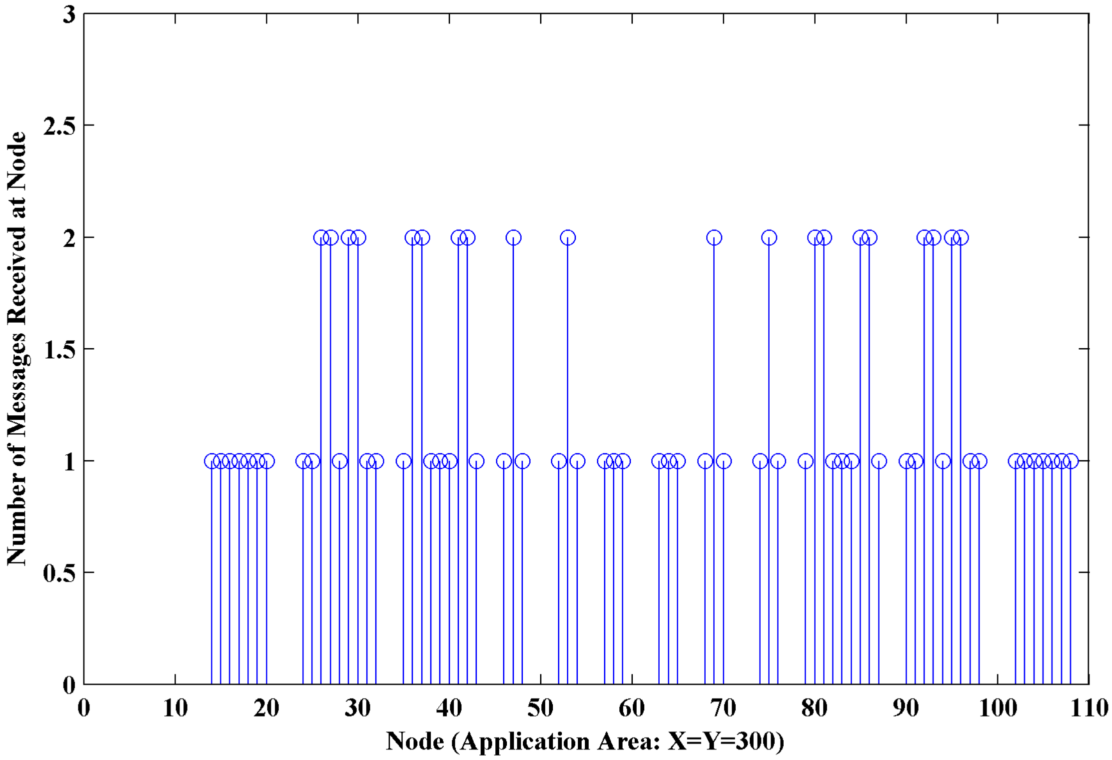

Figure 8.4: Number of messages received by nodes neighbouring mobile node's path

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.

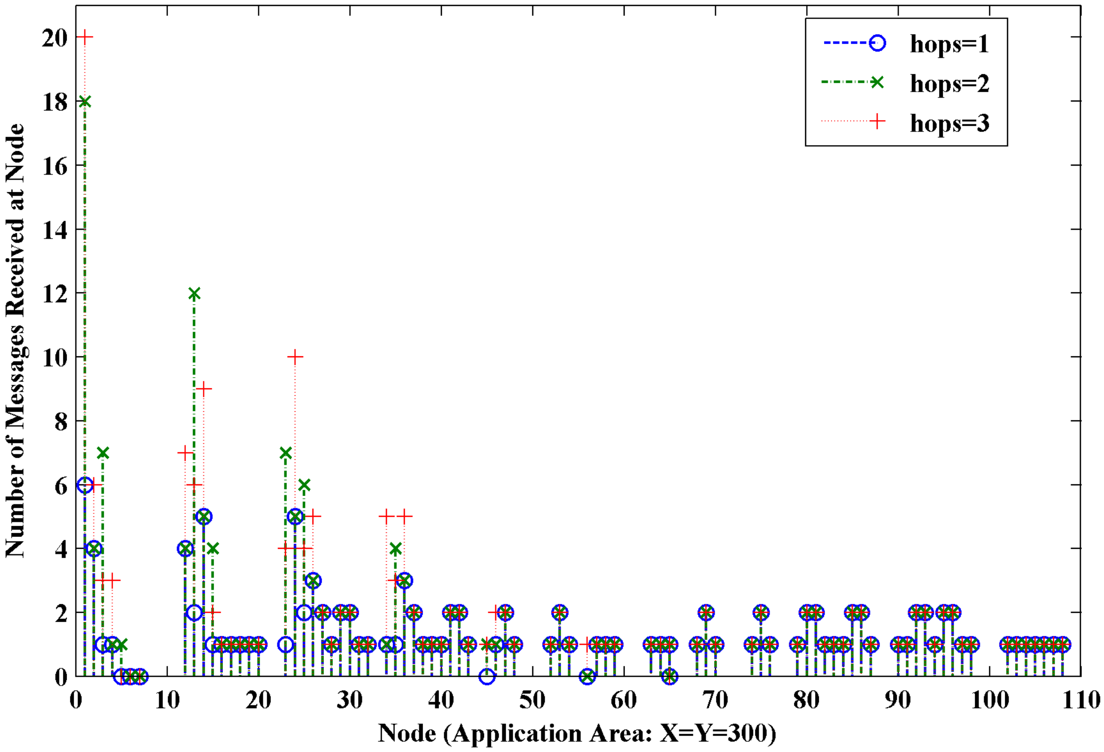

Figure 8.5: Number of messages per node when event message sent to node on mobile nodes perimeter

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.