CHAPTER 1
RESEARCH OVERVIEW

1.1 INTRODUCTION

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

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

The architecture of a wireless sensor node (as shown in Figure 1.1), is that of a small electronic device, comprising one or more transducers (for monitoring a specific physical phenomenon), a processing unit to convert the electrical signal received from the transducer into an intelligible message format and to perform simple computations, a communication unit for transmitting and receiving messages and a non-renewable power source to provide energy to the above units (Krishnamachari, 2005; Akyildiz et al., 2002; Pottie & Kaiser, 2000; Karl & Willig, 2005). Some nodes are also equipped with a location

finding system. Nodes can range in size from about the size of a grain of sand to that of a shoebox. The sensor nodes sense and react to changes within the application area. Sensors convert a physical phenomenon (such as heat, light, sound or motion) within the target environment into electrical signals (Zhao & Guibas, 2004).
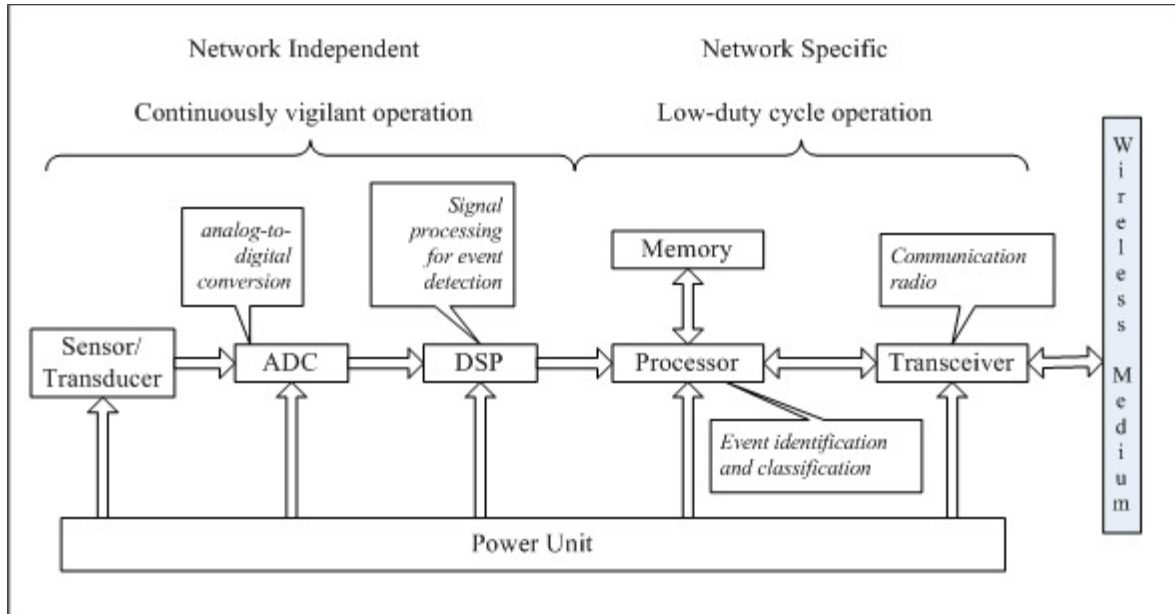

Figure 1.1: Wireless sensor node architecture

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

When an event that the WSN has been set-up to monitor is triggered, the neighbouring sensors that have detected the event aggregate their data and transmit a single message to the central data-capturing centre (sink node). The sink node re-transmits the information to a human interface device where the data can be evaluated. The sink transfers the message data over a wireless link to an external interface. The human or machine that receives the

message data processes this information and then records the event and determines if the event needs to be reacted to. The current architecture of many WSN applications is shown in Figure 1.2 adapted from (Akyildiz et al., 2002), with permission. The sensor nodes that will pass a message from the source node that detected an event to the sink node are the message's route (highlighted in Figure 1.2).
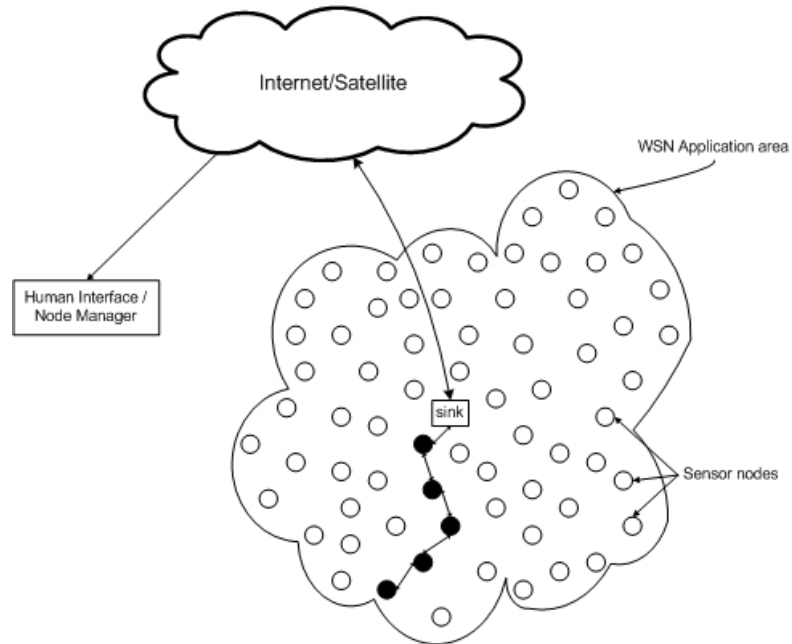

Figure 1.2: Single sink interfaces to external manager (Akyildiz et al., 2002)
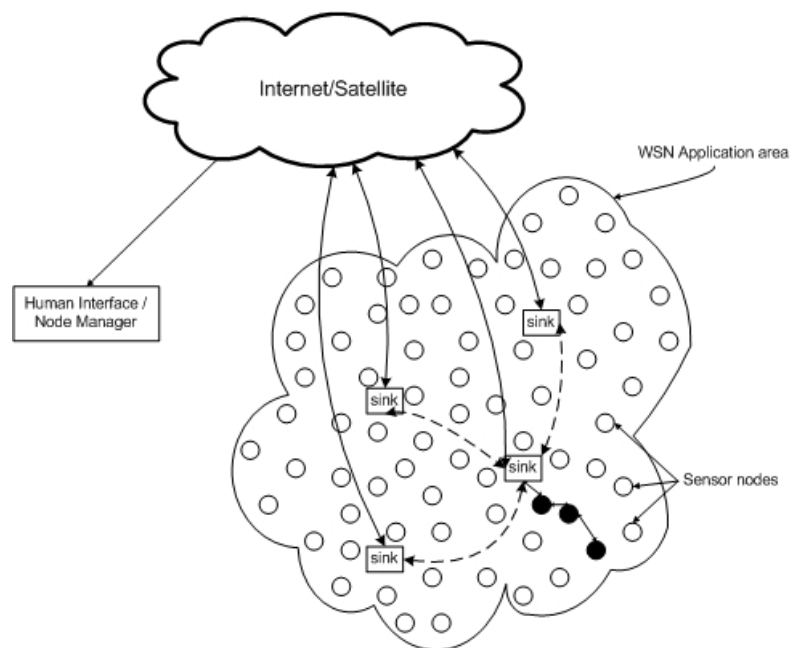

Figure 1.3: Multiple sink/actor interfaces to external manager (Akyildiz et al., 2002)

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

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

1. Each sensor node communicates with one or more base stations (sinks). Traffic is mainly between individual sensor nodes and a base station.

2. The network topology is a multi-hop star-tree that is either flat or hierarchical.

3. They are used in diverse applications, which may have different requirements for quality of service (QoS) and reliability.

4. Most network applications require dense deployment and physical collocation of nodes.

5. Individual sensor nodes have limited resources in terms of processing capability, memory and power.

6. Power constraints result in small message sizes.

7. The placement of nodes in a WSN is application-dependent and may not be pre-determined.

A WSN also differs from other wireless networks, such as cellular networks and mobile ad hoc networks (MANETS) because these networks are linked to a wired or renewable energy supply. In cellular networks and MANETS, the organising, routing and mobility management tasks focus on optimising QoS and ensuring high bandwidth efficiency. There is a large amount of network traffic and the data rate is high to cater for the demand for multimedia-rich data. These networks are designed to provide good throughput/delay characteristics under high mobility conditions. Sensor nodes mainly use broadcast, while most MANETs are based on the peer-to-peer communication paradigm. Energy consumption is of secondary importance in cellular networks and MANETS as the battery packs can be replaced or re-charged as needed, whereas WSNs are limited in power,

computational capacity and memory, and may not have global IDs (Rentala et al., 2002; Yoneki & Bacon, September, 2005)**.** Also, sensor nodes have short ranges. It is not feasible for sensor nodes to try to transmit a message over a large distance because the required transmission power increases as the square of the distance between source and destination (Lewis, 2004).

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

1.2   WIRELESS SENSOR NETWORK APPLICATIONS

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

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

1. *monitoring space*, e.g. habitat monitoring, precision agriculture, indoor climate control, surveillance, treaty verification, and intelligent alarms;

2. *monitoring things*, e.g. structural monitoring, ecophysiology, condition-based equipment maintenance, medical diagnostics, and urban terrain mapping; and

3. *monitoring the complex interactions of things with one another and the encompassing space*, e.g. monitoring wildlife habitats, disaster management, emergency response, ubiquitous computing environments, asset tracking, healthcare, and manufacturing process flow.

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

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

2. Ad-hoc deployment requiring that the system should be able to cope with the resultant distribution and form connections between the nodes.

3. Dynamic environmental conditions requiring the system to be adaptive in nature to changing connectivity and node failure.

4. Unattended operation requiring configuration to be done automatically and repeatedly.

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

1.2.1   Application design space and design challenges

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

1. *Lifetime*: a WSN must operate for long periods of time, but a typical sensor node has limited energy (battery). This constraint influences the required degree of energy efficiency and robustness required of sensor nodes. In the quest to reduce energy consumption, most components, including the radio in a sensor node, are switched off at periodic intervals. The death of a node due to power failure can cause significant topological changes and may require re-routing of packets and reorganisation of the network.

2. *Deployment*: affects properties such as expected node density, node locations as well as regular patterns in node locations, and the expected degree of network dynamics. Sensors can be manually placed and data routed through pre-determined paths, or randomly scattered resulting in an ad-hoc routing structure.

3. *Mobility*: may apply to all or only a subset of nodes in a network. The type of mobility (active or passive), the degree (duration) of mobility and node speed, influence the network protocols and algorithms used.

4. *Quality of service*: may include real-time constraints on reporting of an event (responsiveness). To extend network lifetime, nodes may switch between sleep and wake-up modes, which may negatively affect the responsiveness of the sensor nodes to an event.

5. *Cost*: must be low in view of large number of sensors deployed in an application. There is a correlation between cost per node and resources available to a node. Need to design synergistic protocols that share the nodes' storage, computation and communication resources to optimise performance of WSN. Also, node deployment and maintenance must remain inexpensive.

6. *Size*: varies according to application and whether it is intended not to be easily visible.

7. *Resources*: limited by size and cost constraints. Size and cost affect available power, processing ability, storage space and communication range.

8. *Energy*: power can be stored via a battery (non-renewable energy source), or scavenged from the environment, e.g. by solar cells (renewable energy source).

9. *Heterogeneity*: nodes deployed within a WSN may differ from one another according to application requirements. Some nodes may have a global positioning system (GPS) for location determination, or more computational power etc., which affects the complexity of computer algorithms that can be executed on a node. The number of nodes that differ from one another in a WSN directly influences the management of the WSN and may result in a two- or more tiered, cluster-based network architecture.

10. *Transmission media (communication modality)*: the different types of wireless communication mechanisms include among others infra-red, sound (underwater), radio, laser or other types of optical media. The design of medium access and communication protocols is dependent on the communication modality used.

11. *Infrastructure*: whether nodes communicate directly with one another (ad hoc) or with base station devices (infrastructure). Hybrid mix of infrastructure and ad hoc communication may also be used.

12. *Network topology*: it is impractical to configure each node in large WSNs manually. Nodes in a WSN must be able to configure their own network topology; localise, synchronise and calibrate themselves, coordinate inter-node communication and determine other important operating parameters as an ensemble network of nodes. The diameter of the network (i.e. the maximum number of hops between any two nodes in

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

13. *Coverage*: this is the degree of coverage by sensor nodes in an application area. Network coverage can be sparse, where only areas of interest are covered by sensor nodes or dense where the area is (almost) completely covered by sensors, or redundant, where multiple sensors cover the same location. The degree of coverage is determined by the required observation accuracy, redundancy and robustness of the system.

14. *Connectivity*: sensor nodes are closely coupled to a changing physical environment and the network connections are determined by the sensors' location and range. The nodes forming the network will experience wide variations in connectivity and will be subject to potentially harsh environmental conditions. Networks can be always connected or intermittent if occasionally partitioned or sporadic where the nodes are isolated most of the time. Network connectivity has an influence on data gathering and the type of communication protocols used.

15. *Network size*: networks must be scalable from a few nodes to tens, or hundreds, or thousands of sensor nodes. Network size is influenced by network connectivity, throughput and coverage requirements and the network algorithms and protocols used will have to be distributed.

16. *Fault tolerance (robustness)*: the network remains functionally operational and survives if certain nodes or sets of nodes fail.

17. *Security*: the wireless medium creates additional security risks such as preventing eavesdropping and ensuring message integrity, as well as being unobtrusive in the application area. Security influences network coverage and connectivity.

18. *Self-optimisation and adaptation*: uncertainty about initial operating conditions, as well as a changing operating environment, implies that a WSN is not operating efficiently at start-up, and needs to monitor sensor and network measurements continuously to improve performance.

Analysis of these factors and their inter-relatedness indicate that the main goals of WSN application design is prolonging network lifetime and preventing connectivity degradation through aggressive energy management. There is a trade-off between a node's cost, energy, size and node range.
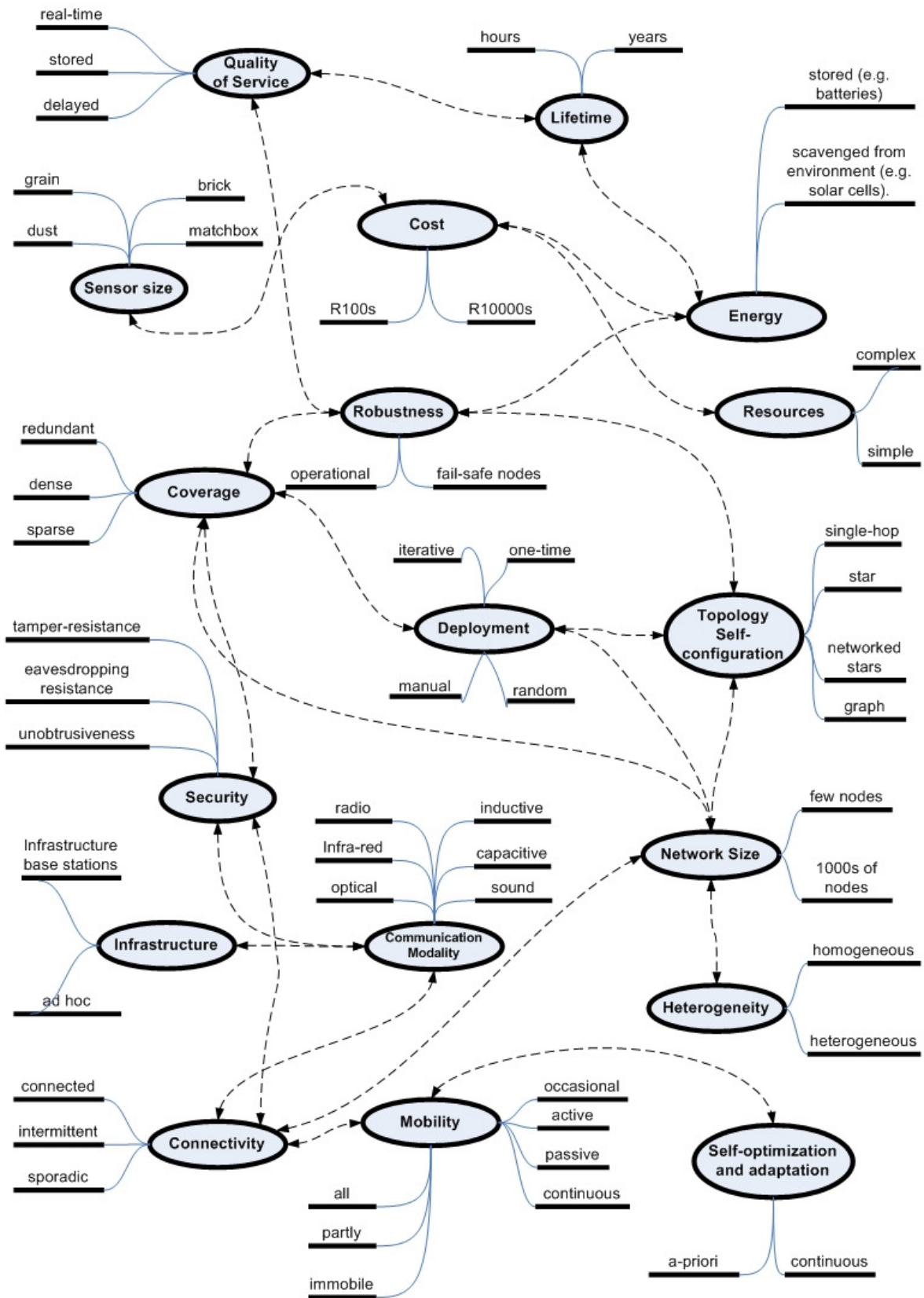
Figure 1.4: Factors to consider when designing WSN applications

1.2.2   Examples of WSN applications

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

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

1.3   RELEVANCE OF WIRELESS SENSOR NETWORKS

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

1.3.1   Multiple connected sensors versus a large single sensor

For some applications the gathering of information about the surrounding environment can be obtained from a set of distributed sensors or a single large sensor. A distributed set of sensor nodes generate a networking cost not found within a single-sensor environment. There is a trade-off between using a single large, resource-rich, long-range sensor and multiple sensors in a distributed network. Using a resource-rich sensor with long range to

cover the application area is not always an optimal solution because of the following physical effects (Pottie & Kaiser, 2000; Lewis, 2004):

1. ***Signal propagation laws***: In free space, electromagnetic waves decay in intensity as the square of the distance, and they are subject to absorption, scattering or dispersion effects in other media that can cause even steeper declines in intensity with distance, as well the possibility of being blocked by an obstruction. For a large single node, the distance from the target may be large. Therefore, a set of networked nodes distributed around an application area can provide a larger signal-to-noise-ratio (SNR) than a single, large, powerful node.

2. ***Detection and estimation theory fundamentals***: There are fundamental limits of estimation accuracy. To compute a good estimate of any particular feature, either a long set of independent observations or high SNR is required.

3. ***Communication constraints:*** Propagation is influenced by reflections off multiple objects and antenna elevation. For low-lying antennas, intensity drops as the fourth power of distance due to partial cancellation by a ground-reflected ray. The combination of Maxwell's Laws (governing propagation of electromagnetic radiation) and Shannon's capacity theorem (establishing fundamental relationships among bandwidth, SNR and bit rate) together dictate that there is a limit on how many bits can be conveyed reliably, given power and bandwidth restrictions. Multipath propagation losses can be improved by employing some combination of frequency-hopped spread spectrum, interleaving and channel coding. By increasing node density, clear line-of-sight paths to at least a few other nodes are created, which reduces losses.

4. ***Energy consumption in integrated circuits:*** There are limits on the power required to transmit reliably over any given distance. The power-amplifier stage typically burns at least four times the radiated energy, and so, in time, dominates the energy cost of radios.

5. ***Transmission power***: The required transmission power increases as the square of the distance between source and destination. Therefore, multiple short message transmission hops require less power than one long hop. In fact, if the distance between source and destination is defined as R, then the power required for single-hop transmission is proportional to R^2. If nodes between source and destination are taken advantage of to transmit in short hops instead, the power required by each node is

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

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

1.3.2   Wired versus wireless

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

1. *Superfluous message reception:* all transmitted messages will be detected by any listening device within receiving range, which then has to decide whether to accept, forward or ignore the message. This signal transmission and reception has a power cost.

2. *Ad hoc deployment*: WSN applications do not have a pre-planned network topology and nodes are only aware of their immediate neighbours. There are no pre-defined routing tables specifying the optimum shortest path to the sink.

3. *Finite energy*: the sensor has a finite amount of energy, which once depleted, disables the sensor and hence reduces network lifetime. This need to conserve energy, because of the lack of a continuous energy source, has an impact on communication between nodes. It costs energy to transmit and receive messages, and the wireless medium means that all nodes within range receive a message. Hence, a significant proportion of current research on WSNs is focused on energy preservation, by reducing the number of messages transmitted within a WSN, to ensure longer node and hence network lifetime.

If wireless networks pose so many problems, then why are researchers developing applications that communicate over a wireless medium? The primary constraint is cost. It costs money (in terms of the actual wires and labour) to install wired networks. The ease of

deploying wireless networks reduces the cost of the application significantly. Also, wireless applications provide greater flexibility in data gathering, as there is no fixed upfront cost. This means that WSNs can rapidly adapt to changing environmental conditions. Sometimes, the type of application specification means that it is not possible to use wired networks, for example monitoring mobile entities such as livestock. In these instances, the only possible solution is to use wireless sensor nodes to track and observe mobile entities.

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

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

1.4   SCOPE

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

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

1.5   PROBLEM STATEMENT

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

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

1. *T*ransmission of messages
2. *R*eceiving messages
3. *A*wake time, i.e. the time period a node is listening on the wireless medium.
4. *D*istance between nodes, as the energy expenditure is proportional to the square of the distance a signal is transmitted. Can also relate to the total distance a message has to travel between source and destination node.
5. *S*ize of message: larger message sizes imply more energy spent in transmitting and receiving the message.
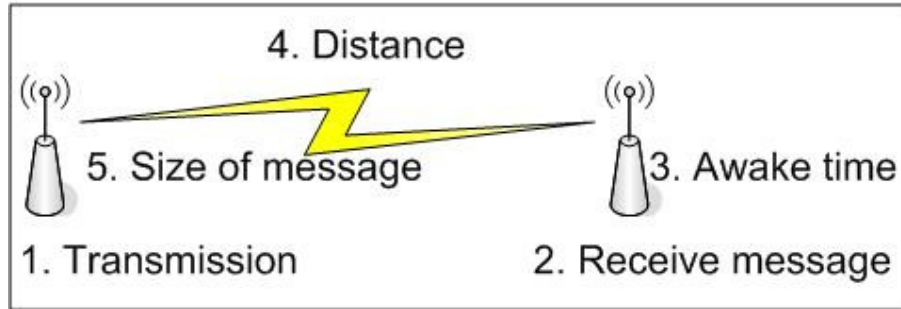
Figure 1.5: Main energy consuming activities in a WSN (TRADS)

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

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

In this thesis, a solution to these problems is proposed based on placing multiple sinks at pre-determined locations within the application area; *so that each node is at a maximum*

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

1.6   RESEARCH OBJECTIVE

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

1. Analyse the effect of only allowing nodes on the perimeter range of a transmitting node to re-transmit message data on reducing the number of messages re-transmitted as well as obtaining more accurate node location estimates.

2. Model uncertainty about an actor's energy and location as an information gap, and calculate the actor(s) set that should respond to the event, in order to determine if it is possible to select a few optimum actors that will adequately respond to an event, even when there is uncertainty about the other actors' energy and location.

3. Model a WSN as a small world network, by optimally placing sink nodes a specified number of hops from a sensor node, so as to determine if it is possible to place a number of sink nodes optimally in a WSN area, so that a message from any node within the application area will reach a sink node within a small predetermined number of hops.

4. Compare a WSN modelled as a small world network, against message routing using gossiping and flooding to determine if the small world model has significant advantages.

5. Determine the optimum route a mobile sink can travel that will reduce the number of messages transmitted within a network, allow equitable usage of all nodes to transfer an event message and still allow an event to be reported in real-time.

1.7   RESEARCH CONTRIBUTION

There are three contributions from this research, namely:

1. A WSN is modelled as a small world network by placing sink nodes at specific points within the application area. The sink nodes create long edges within the network, resulting in the total number of messages sent and received being significantly less. It is shown in chapter 3 of this thesis that modelling a WSN as a small world network is possible as long as the number of sinks are placed a specified distance from each other and irrespective of whether the sensor nodes are randomly scattered or carefully placed within the application area. The effect of modelling a WSN as a small world network on total number of messages sent and received within an application area is analysed in chapter 4. A comparison of the small world routing model and routing using flooding and gossiping indicates that the small world routing model reduces the total number of messages transmitted within a network when routing a message from a sensor node to a sink. The effect of using an initialisation message in a small world model to determine a route path versus routing using flooding at the individual node level in terms of the total number of messages sent and received by individual nodes is discussed and analysed in chapter 5. The results of the analysis in chapter 5 indicate that using an initialisation message does not negatively impact the energy resources of any node. The results of chapters 3, 4 and 5 indicate that routing using the small world model and initialisation message results in increased node longevity and hence increased WSN lifetime.

2. Actor-actor coordination needs to be able to choose an actor(s) to respond to an event as quickly as possible, even when there are uncertainties about an actor(s)'s resources. IGDT can be used where robust solutions are required in an uncertain environment. Uncertainty about an actor's energy and location is modelled as an information gap,

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

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

1.8   OUTLINE OF THE THESIS

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

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

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

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

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

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

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

In Chapter 8, a path for mobile sinks or actors is proposed to minimise the number of messages sent within the WSN application area.
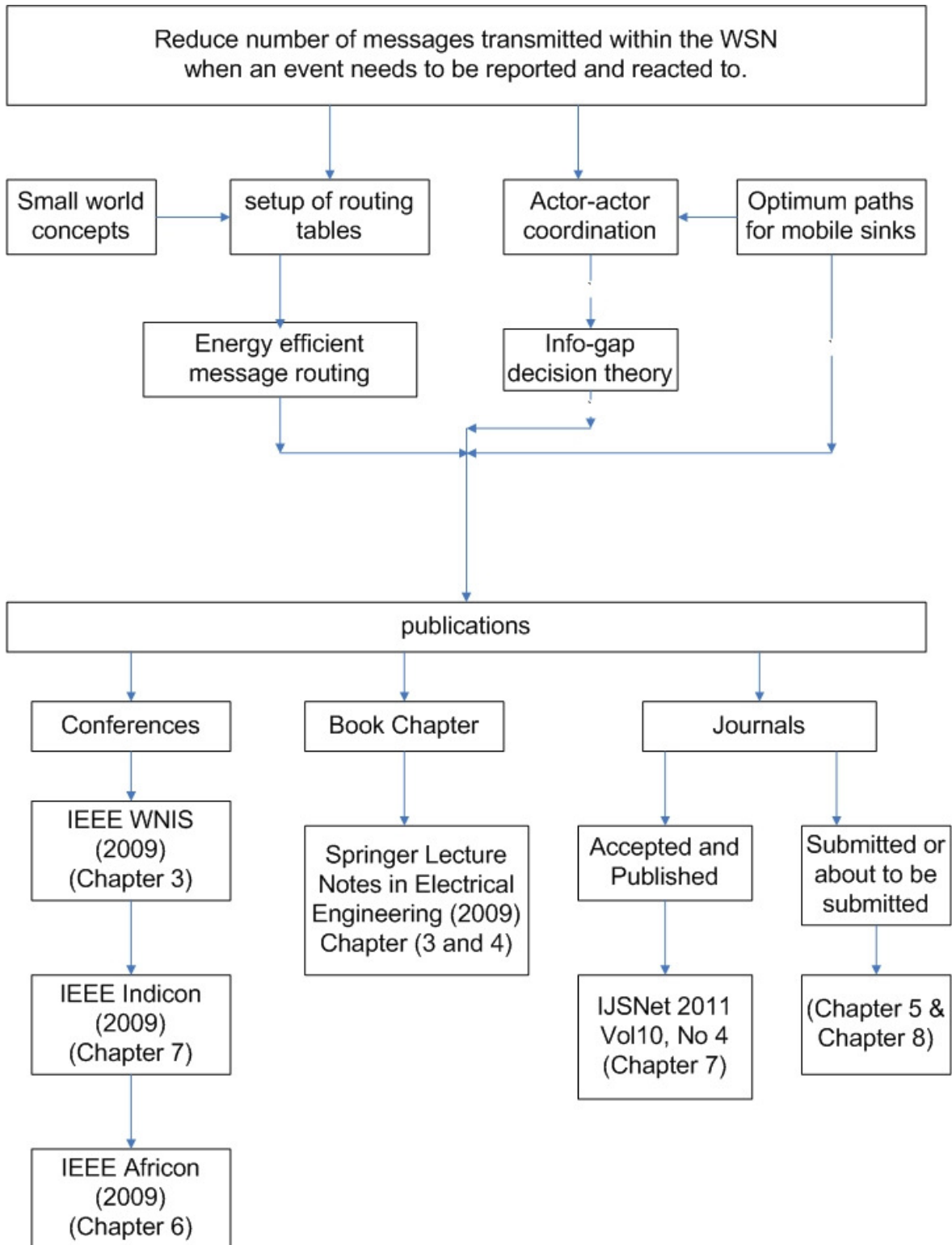
1.9   FLOW CHART: THESIS' THEMES AND PUBLICATIONS

Figure 1.6: Thesis flow chart