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PERFORMANCE EVALUATION OF A ROUTING PROTOCOL IN WIRELESS SENSOR NETWORKS

by

Cheng Kiat Amos, Teo

December 2005

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13. ABSTRACT (maximum 200 words)

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In this thesis, the evaluation of a routing protocol developed by Crossbow Technologies called XMesh, is presented. The main components of the routing protocol are described and the routing algorithm explained. Experiments were conducted to determine the connectivity ranges of motes in different transmission power settings. The relationship of mote transmission power and network connectivity is presented. An energy efficiency study looked at the means of extending the lifespan of the network. Although, packet losses during the period of a node failure were significant, the routing protocol showed that it was able to adapt and reorganize to provide reliable and stable routing in a network.

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PERFORMANCE EVALUATION OF A ROUTING PROTOCOL IN WIRELESS SENSOR NETWORKS

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ABSTRACT

The ability to sense and monitor a variety of environmental conditions using un-tethered sensors offers a significant change over traditional sensing systems that need to be strategically positioned and have topologies engineered. Recent research into wireless sensor networks has attracted great interest due to its diversity of applications, ranging in areas such as home, health, environmental and military applications.

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EXECUTIVE SUMMARY

Wireless sensor networks consist of small nodes with sensing, computational and wireless communications capabilities that can be deployed randomly or deterministically in an area from which the users wish to collect data. Typically, wireless sensor networks contain hundreds or thousands of these sensor nodes that are generally identical. These sensor nodes have the ability to communicate either among each other or directly to a base station (BS). The network is highly distributed and the nodes are lightweight. Intuitively, a greater number of sensors will enable sensing over a larger area. As the manufacturing of small, low-cost sensors become increasingly technically and economically feasible, a large number of these sensors can be networked to operate cooperatively unattended for a variety of applications. Such applications include military and civil applications like intrusion detection, target field imaging, tactical surveillance and inventory control.

This study evaluates a routing protocol developed by Crossbow Technologies called XMesh. The routing problem for sensor networks differs from that of traditional ad-hoc wireless networks because sensor nets can be constrained by limited battery power, communication bandwidth, processing power and on-board memory. The nodes are connected by low power radios and operate in aggregate over multi hops to achieve some application-specific communication. The hardware platform used in this study was the MICA2 motes running TinyOS. The RF transmission power was adjusted through software.

The main components of the XMesh routing protocol are described and the routing algorithm explained. Before studying the routing protocol, experiments were conducted to characterize mote connectivity ranges in different transmission power settings. These experiments provided a better understanding of the loss behavior of a link that enabled a practical network topology to be designed. It was observed that for any given power setting, there were three regions of communications, the effective, transitional and unreliable regions; and the number of motes required for connectivity in a given area is proportional to the amount of transmitted power of the motes.

An energy efficiency study looked at the means of extending the lifespan of the network. It was determined that to prolong the network lifetime, a duty cycle must be implemented so that the motes can conserve power by staying asleep. For a 1% duty cycle, the lifetime of a network is approximately 1.1 years.

To observe the XMesh routing protocol, eight MICA2 motes were deployed in a cluttered indoor environment. It was observed that the average time taken for the motes to establish connectivity when placed close to the base station was approximately five to seven minutes while the average time taken to establish connectivity if the motes were deployed before being switched on was between twelve and eighteen minutes. It was also observed that the packet delivery ratio drops significantly when a node is switched off to simulate node failure but returned to prior levels when the routing paths were reestablished. Although, packet losses during the period of a node failure were significant, the routing protocol demonstrated that it was able to adapt and reorganize to provide reliable and stable routing in a network.

The characteristics and performance of the XMesh routing protocol demonstrated its ability to maintain the network functionalities when sensor nodes fail. The routing protocol was able to establish new links and routes to the data collection base station.

I. INTRODUCTION

A. MOTIVATION

The ability to sense and monitor a variety of environmental conditions using un-tethered sensors offers a significant change over traditional sensing systems that need to be strategically positioned and have topologies engineered. Recent research into Wireless Sensor Networks (WSN) has attracted great interest due to its diversity of applications, ranging in areas such as home, health, environmental and military applications [1].

Wireless sensor networks consist of a large number of small, low-powered and multi-function sensors nodes that are able to sense, process and communicate through collaborative efforts. Their desired characteristics include: ease of installation; self-identification; self diagnostics; reliability, time awareness for co-ordination with other nodes; signal processing and standard control protocol and network interfaces [2]. The advantage of wireless sensor networks is their ability to gather useful information from the physical world and communicate that information to more powerful logical devices that can process it. From a military perspective, such priori information acquired through stealthy unmanned surveillance of enemy capabilities and positions would reduce the risk to human personnel in certain missions. In the near future, sensor devices will be produced in large qualities at a low cost and densely deployed to improve robustness and reliability. However, the characteristics of the wireless environment pose several challenges in wireless sensor networks; the most distinct being the random time-varying fading nature of the wireless channels. Additional difficulties and considerations include arbitrary network topology, resource contention (limited frequency allocation and multi-access), multi-path, co-channel interference, and hostile jamming issues. As such, wireless sensor networking protocols and algorithms must possess an inherent self-organizing ability.

The routing problem for sensor networks differs from that of traditional ad-hoc wireless networks because sensor nets typically involve resource[1] constrained nodes connected by low power radios and operate in aggregate over multi hops to achieve some

[1] Battery Power, Communication Bandwidth, Processing Power, On-board Memory

application-specific communication. Although there are several papers that model the networking performance of wireless sensor networks [3, 4, 5, 6], the practical evaluation of networking in wireless sensor networks are limited. This research will evaluate the performance of the XMesh routing protocol in wireless sensor networks using several MICA2 motes. The motes were developed by Crossbow Technology and offer low latency, low energy consumption with a low data rate. The Crossbow network claims to be scalable and reliable through multi hop and dynamic routing algorithms and possesses the ability to self-configure [7].

B. THESIS OBJECTIVE

The purpose of this research is to evaluate a sensor network made up of a group of MICA2 motes equipped with acoustic, infrared and magnetic sensors. Specifically, it will

- Evaluate the communications characteristics of the MICA2 radio. It will also determine the optimal connectivity of the motes.
- Evaluate the trade-off between energy efficiency and surveillance capability of the MICA2 motes; estimate the lifetime of the sensor network to determine the time to mote replenishment.
- Study the effect of mote failures on the wireless sensor network.
- Study the MICA2 routing infrastructure and determine if it can survive under adverse environments.

C. THESIS ORGANIZATION

This chapter has presented the motivation for this study and the thesis objectives. Chapter II provides an overview of wireless sensor networks and presents the basic components of a sensor node and some sensor network applications. Prior related work is also discussed. Chapter III presents the routing challenges in wireless sensor networks and surveys the various networking algorithms found in wireless sensor networks. Chapter IV will specifically focus on the XMesh routing protocol, its components and algorithm. Chapter V presents an empirical characterization of the communications link in terms of the loss behavior at various levels of transmission power and also discusses the motes energy efficiency versus transmission power desired, and the connectivity ranges of the sensor network. This chapter also discusses the results and findings of the study of the routing algorithm's ability to handle node failures. Chapter VI summaries the research work and includes some proposals for future work.

II. WIRELESS SENSOR NETWORKS

A. CHAPTER OVERVIEW

This chapter introduces wireless sensor networks and the components that constitute a sensor network. The possible use of wireless sensor networks in industrial, commercial, health, environmental and military applications is presented. This chapter also compares wireless sensor networks with other wireless networks.

B. INTRODUCTION TO WIRELESS SENSOR NETWORKS

Wireless sensor networks consist of small nodes with sensing, computational and wireless communications capabilities that can be deployed randomly or deterministically in an area from which the users wish to collect data. Typically, wireless sensor networks contain hundreds or thousands of these sensor nodes that are generally identical. These sensor nodes have the ability to communicate either among each other or directly to a base station (BS). The network is highly distributed and the nodes are lightweight. Intuitively, a greater number of sensors will enable sensing over a larger area. As the manufacturing of small, low-cost sensors become increasingly technically and economically feasible, a large number of these sensors can be networked to operate cooperatively unattended for a variety of applications. Such applications include military and civil applications like intrusion detection, target field imaging, tactical surveillance and inventory control. This section introduces the general components in a single node, its operating system and the wireless sensor network topology.

1. Node Hardware Components

A basic sensor node consists of five main hardware components [8] namely: the processor; memory; sensor; communication device and power supply. Figure 1 shows the schematic diagram of the sensor node components. The figure also shows the communication architecture of a wireless sensor network.

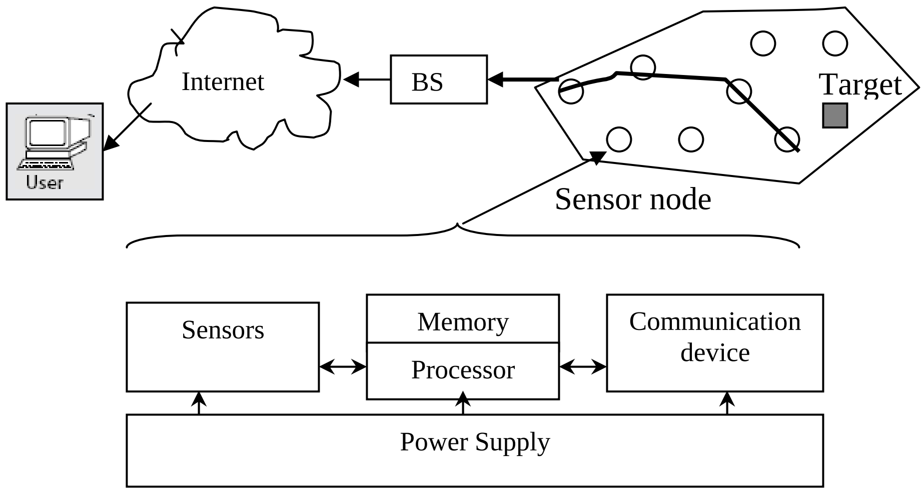

Figure 1. Components of a Sensor Node

a. Processor

The processor is the core of the wireless sensor node. It collects data from the sensor, processes the data, decides when and where to send it, receives data from other sensor nodes, and decides on the actuator's behavior. It has to execute various programs, ranging from time critical signal processing to communications protocols to application programs. Essentially, it is the heart of the node.

b. Memory

The memory component consists of Random Access Memory (RAM) to store intermediate sensor readings, packets from other nodes; and an Electrical Erasable Programmable Read-Only Memory (EEPROM) to store program code as RAM that loses its contents once the power supply is interrupted. Flash memory is EEPROM-like but enables data to be erased and written in blocks instead of bytes. It can also be used as intermediate storage if the RAM is insufficient but the long read/write access delays of flash memory and the high energy required must be accounted for when doing so.

c. Communications Device

The communications device is used to exchange data between individual nodes. The transmission medium of choice for sensor networks is Radio Frequency (RF) based communications. Although RF communications require modulation, filtering, and multiplexing circuitry, which make them more complex and expensive, it is preferred because it does not require visual line of sight between sender and receiver. Packets conveyed in the sensor network are small, data rates are low and frequency reuse is high due to the short communications distances. Typically, communications frequencies range between 433 MHz and 2.4 GHz.

d. Sensors

Sensors used in WSN can be categorized into three categories. The first is passive, omni-directional sensors that measure the quality at the point of the sensor nodes without actually manipulating the environment by active probing such as light sensors, microphones, thermometers, and vibration sensors. The second is passive, narrow beam sensors that have a well defined direction of measurement as in the case of cameras. The third is active sensors that actively probe the environment such as laser or sonar systems.

e. Power Supply

Once deployed, sensor nodes are usually inaccessible. As such, the lifetime of a sensor network is dependent on the power resources of the nodes. Hence, the nodes power supply is a crucial system component. The typical form of energy source are the traditional batteries which have a fixed lifespan. One way to extend the life of a node is by recharging the battery from the environment, i.e., energy scavenging [9]. Solar cells are an example of techniques used for energy scavenging.

2. Node Operating System

The task of an operating environment is to control and protect access to resources and manage their allocation to different users. It also supports the concurrent execution of several processes and communication between these processes [8]. These tasks are only partially required for wireless sensor networks as its executing code is more restricted. The execution environment for wireless sensor networks should support the specific needs of the system, in particular, the need for energy efficiency. There are several programming models such as concurrent programming, process based programming and events based programming. It was concluded in [8] that events based programming most suited the reactive nature of wireless sensor networks. It was also concluded that the operating system TinyOS, and the programming language nesC, are able to support the concurrency required for sensor node software while staying within the confined resources and running on top of the simple hardware provided by these nodes [7].

3. Network Topology

The basic network topologies are shown in Figure 2. They include star, ring, tree, bus, fully connected and mesh. A wireless sensor network employs a mesh topology. Mesh networks are regularly distributed networks that allow transmission only to the node's nearest neighbor [10]. They are good for large-scale networks of wireless sensors that are distributed over a geographic region. The regular structure for mesh topology reflects the communication topology; the actual geographic distribution of the node need not be a regular mesh.

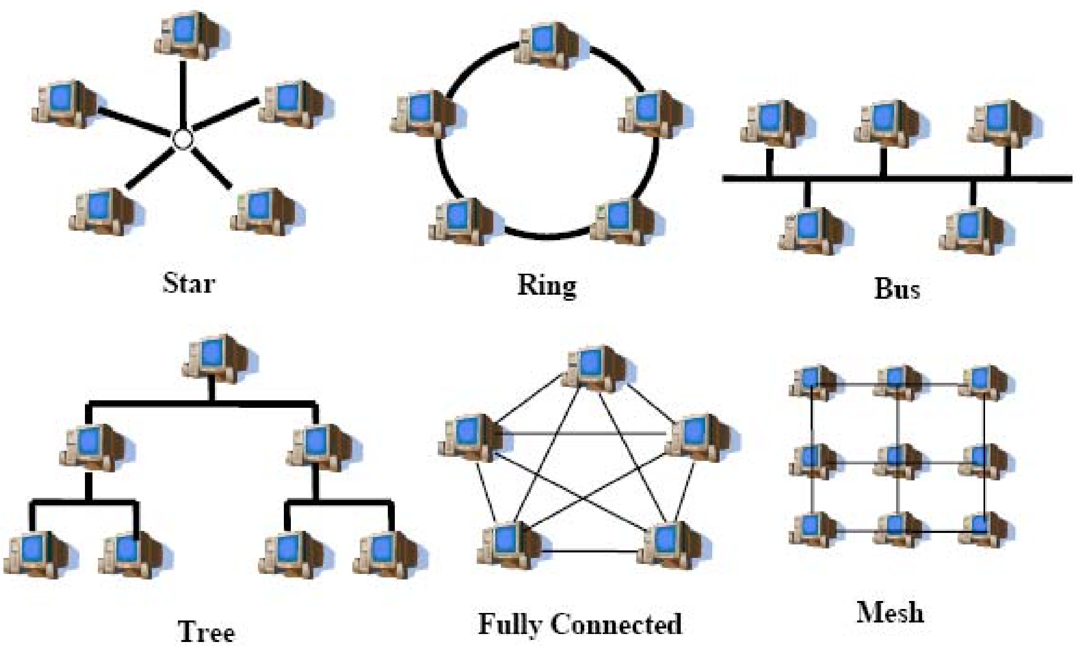

Figure 2. Basic Network Topologies (From Ref [10])

C. WIRELESS SENSOR NETWORKS AND OTHER WIRELESS NETWORKS

The characteristics of a sensor node can be categorized as low power consumption, small physical size, concurrency of operations and diversity in design and usage [11]. As such, wireless sensor networks differ from other wireless networks like mobile ad-hoc networks and cellular networks in the following areas.

First, the number of sensor nodes in a sensor network can be several orders of magnitude higher than in a traditional ad-hoc network. As such, it is not possible to build a global addressing scheme as the overhead of ID maintenance would be high given the large number of sensor nodes. Thus, traditional IP-based protocols may not be applied to wireless sensor networks.

Second, sensor nodes are constrained by limitations in energy, computational resources and storage capacities. As such, careful resource management is vital to extend the lifespan and optimize the efficiency of processing and memory in the sensor node.

Third, the nodes in wireless sensor networks are generally static after deployment except for a few mobile nodes. Nodes in other traditional wireless modes are free to move, which results in unpredictable and frequent topological changes.

Fourth, sensor nodes operate in a hazardous environment and are thus prone to failures. Hence, the topology of the network may require reconfiguration as nodes fail.

Fifth, wireless sensor networks require the flow of sensed data from multiple sources to a particular base station. This, however, does not prevent the flow of data in other forms such as peer-to-peer or multicast.

Sixth, position awareness of sensor nodes is important, whether the nodes are deployed deterministically or randomly, since data collection is normally based on location. Currently, it is not feasible to use the Global Position System (GPS) due to the power requirements and cost. Methods based on triangulation [12] allow the sensor to approximate their position using the radio strengths for a few known points.

Finally, data collected are from many sensors that are in close proximity. Hence, there is a good probability that the sensed phenomenon is the same and that there will be some redundancy in the data collected. Such redundancy needs to be exploited to improve bandwidth and energy utilization.

D. APPLICATIONS OF WIRELESS SENSOR NETWORKS

Sensor networks may consist of different types of sensors such as thermal, infrared, acoustic, magnetic, visual and seismic, to monitor a wide variety of conditions such as temperature, lighting conditions, noise levels, vehicle movement, presence or absence of objects and soil movement. The range of use of sensor nodes vary from event detection to continuous sensing to local control of actuators. This section provides an overview of some applications of wireless sensor networks.

1. Commercial and Industrial Applications

a. Monitoring an Industrial Plant

The control room in a large industrial plant has indicators that display the state of the plant (temperature, pressure of storage tanks, condition of equipment, state of values, etc.) as well as input devices that control actuators that affect the observed state of the plant. The sensors used to monitor the state of the physical plant, the control device and the actuators are relatively cheap when compared to the cost of shielding required in a wired environment. Cost savings can be achieved through inexpensive wireless means. The states of the plant often change slowly, and as such, the required data throughput of the network can be relatively low but the required reliability is high. Wireless sensor networks providing multi message routing paths can meet these requirements.

b. Environmental Control in Buildings

The heating ventilation and air-conditioning (HVAC) of buildings are centrally controlled, typically by a small number of thermostats and humidistats. The number of humidistats and thermostats are limited by the cost of their wired connection to the rest of the HVAC system. The result may be that a room could be warmer than another because there are only one or two controls in that section of the building. The cause of such unsatisfactory HVAC is that the control systems lack information about the environment in the building to maintain a suitable environment for everyone. A distributed wireless sensor network, not requiring the expense of wired sensors and actuators, can be used to monitor the temperature in different parts of a room through several thermostats and humidistats placed around each room. Air flow to each room can be regulated through wireless control of the vents. Also, such sensors can be placed in air ducts to determine the quality of air or performance of heat exchangers without requiring maintenance personnel to make manual measurements. Such a system will enable close monitoring of the system performance that may lead to cost savings, which may amount to $55 billion a year and reducing 35 million tons of carbon emissions [9].

c. Inventory Control

Each item in a warehouse can be tagged with a sensor node. This will enable the users to track the exact location of the items as well as inventory the stock on hand. Inserting new items can be achieved by attaching the appropriate sensor nodes to the item. If the items are perishable, the senor node can also report the state of the items such as days in storage or temperature.

2. Health Applications

a. Gym Workout Performance Monitoring

A gym member enters the club and registers with his/her trainer at the kiosk or desk. The relevant cardio and weights machines are reserved and programmed in accordance to the users exercise plan. The users pulse and respiratory rate can be monitored via wearable sensor nodes and transmitted to a personal computer for analysis. The club can monitor the members exercise behavior and intervene when members need help reaching their goals.

b. Monitoring of Human Physiological Data

Physiological data collected can be stored over a period of time to study human habits and behavior. Sensor nodes allow greater freedom of movement and allow physicians to either monitor an existing condition or pre-empt a possible condition.

3. Environmental Applications

a. Soil Condition Monitoring

Sensor nodes can monitor soil temperature and moisture for a given area. If the moisture of the soil falls below a threshold, the irrigation system turns on to provide the necessary moisture for optimal crop growth. The sensor nodes can also be fitted with a variety of chemical and biological sensors so as to enable the farmer to determine the level of fertilizer or herbicide required. This application is most suited for vineyards as minor changes in the environment can greatly affect the value of the crop and how it is subsequently processed.

b. Seismic Activity Detection

The detection of seismic activity may mark the onset of earthquakes, volcanic eruptions or a tsunami. Timely analysis of such information will enable cities to be evacuated. Sensor nodes placed in regions of seismic activity (such as the San Andreas fault-line) will enable geologists to monitor and predict the onset of an earthquake, volcanic eruption or a tsunami.

4. Security and Military Applications

A wireless sensor network can be an integral part of military command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting (C4ISRT) systems. They can be quickly deployed and are fault tolerant, which makes them an ideal sensing technique for reconnaissance and surveillance.

a. Monitoring of Force Movement and Inventory

The location and status of friendly forces and the condition and availability of equipment and ammunition can be monitored by the use of wireless sensor networks. This will enable the military commander to maneuver his forces or equipment to where it is needed most.

b. Battlefield Reconnaissance and Surveillance

A wireless sensor network can be small, unobtrusive and camouflaged to resemble rocks trees or even litter. These networks have distributed control and routing algorithms, which make them difficult to destroy in battle. As such, critical terrain and approaches routes can be covered with sensor nodes to monitor enemy activity. Deployed wireless networks can be used in place of guards or sentries; and can also be used to locate and identify targets for potential attacks or to support an attack by friendly forces.

E. PRIOR WORK

In a recent study by Tingle [13], communication and sensor ranges of the MICA2 with fixed radio transmission power were evaluated over four types of terrain, namely open terrain, outdoor wooded, urban outdoor and indoor and two heights, namely six and 12 inches. The study found that the radio ranges varied between five to 19 meters. It was noted that communication at ground level was never greater than six meters and the longest connectivity recorded was 19 meters with the mote at 12” off the ground in the indoor environment. The study also gave an account of the protocol stack (physical-datalink-network-application) used in sensor networks, layered and clustered network architectures; and the characteristics of the different types of sensors that can be used in wireless sensor networks.

A concurrent study by Koh [14] provides a detailed study on the mote antenna performance and the antenna radiation characteristics.

F. SUMMARY

This chapter presented the components of a generic sensor node and its operating system. It discussed the difference between wireless sensor networks and other wireless networks such as mobile ad-hoc networks and cellular networks. Some possible applications were introduced. As MEM technologies mature, it can be precluded that wireless sensor networks will be employed in a large number of situations.

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III. ROUTING PROTOCOLS IN WIRELESS SENSOR NETWORKS

A. CHAPTER OVERVIEW

The basic issue in communication networks is the transmission of data with a prescribed throughput and Quality of Service (QoS) such as the cost of transmission over a link, packet loss, congestion over a link, message delay, network lifetime, etc. Since wireless sensor networks consist of multiple nodes and may require multiple services, routing methods in wireless sensor networks must be able to adapt to the dynamic nature of the network. This chapter describes the challenges in the design of a routing protocol in wireless sensor networks. This chapter also presents some of the routing protocols that are used in wireless sensor networks. They are classified into three categories: flat-based routing, hierarchical based routing and location based routing [15]. In flat-based routing, all nodes are assigned equal roles and functions. In hierarchical-based routing, nodes are assigned different roles, such as cluster heads, in the network. In location based routing, the node locations are used in routing the data in the network. These schemes are described in greater detail in the following sections

B. ROUTING CHALLENGES IN WIRELESS SENSOR NETWORKS

Wireless sensor networks are usually deployed in inaccessible or remote locations and are often unattended. Despite the numerous applications of wireless sensor networks, these networks have several limitations such as limited energy supply, limited bandwidth of the wireless link and limited processing power. The ability to execute data communications while trying to prolong the lifetime of the network and also prevent connectivity degradation is a difficult task. The design of routing in wireless sensor networks has to overcome many factors before efficient communications can be achieved. Some of the routing challenges are presented in this section.

1. Transmission Medium

In a sensor network, communicating nodes are linked by a wireless medium. These links can be formed through radio, infrared or optical methods. Each method has its own advantages and disadvantages. For example, infrared and optical communications require line-of-sight whereas radio communications do not. As such, infrared and optical communications methods are not ideal choices for a sensor network. However, in radio communications, problems associated with a wireless channel such as fading and high error rates, affect the routing operation of the sensor network. The choice of frequency is an important factor in the system design as well. According to [16], certain hardware constraints and the trades-offs between antenna efficiency and power consumption limit the choice of carrier frequencies to the UHF range. [8] provides an in-depth discussion of wireless channel and communication fundamentals.

2. Coverage and Connectivity

A sensor's view of the environment is limited by its sensing range; it can only cover a limited physical area of the environment. According to [17], the node has coverage of an area when the area can be monitored by its sensors. When the sensor network is connected so that information collected by the nodes can be relayed back to the base station, it is said to have connectivity. It is proven that if the radio range is at least twice that of the sensing range, complete coverage of an area implies connectivity among a set of working nodes. As such, sensor networks should be deployed in high density to preclude them from being isolated and also to prolong network lifetime. However, it cannot be assumed that the network topology and size will be static as node failures will inevitably cause the network to shrink and the network topology to change.

3. Node Deployment

Node deployments in wireless sensor networks are application dependent [1] and are either randomized or deterministic. Whether deployed deterministically or randomly, sensor nodes are deployed in large numbers in high density. As such, transmissions ranges are usually short and routing would consist of multi-hops. In deterministic deployment, nodes are manually placed and data is routed along a pre-determined path. In random deployment, the nodes are scattered randomly creating a distribution that may not be uniform and an ad-hoc infrastructure [18]. In this situation, clustering will be necessary to allow connectivity and enable energy-efficient network operations.

4. Power Consumption

Sensor nodes are generally of a small form factor, implying that they are equipped with a limited power supply. In a multi-hop sensor network, nodes have a dual role of data originator and data router. Sensor nodes can use up their limited energy performing computations and transmitting information in a wireless environment. The sensor node lifetime greatly depends on battery lifespan [19]. Power consumption in the nodes can be attributed to three main areas: sensing, data processing and communication [1]. Of the three domains, data communications expends the most energy. This has led to the use of power efficient modulation schemes such as M-ary Frequency Shift Keying (MFSK) and energy efficient routing protocols such as energy-aware routing [20, 21].

5. Scalability

A sensor network can comprise several to several hundred nodes, each of which has its own computing power and can transmit and receive data over wireless communication links. Routing algorithms must be able to work with such a large number of nodes. In normal operations, most nodes are usually dormant, less a few that provide a coarse sensing quality, until an event occurs. The routing algorithm must be scalable enough to respond when multiple events are triggered from the environment.

6. Fault Tolerance

Nodes may fail due to a lack of power, physical damage, environmental interference such as rain or man-made interference such as electronic jamming. The failure of sensor nodes should not affect the overall task of the sensor network. Fault tolerance is the ability to sustain sensor network functionalities without interruption when sensor nodes fail [22]. If many nodes fail, the routing protocols must be able to establish new links and routes to the data collection base station. This may require varying signal rates and transmit powers on existing links to reduce energy consumption, or rerouting packets through areas in the network where more nodes are available. This means that several layers of redundancy may be required in a fault tolerant sensor network.

7. Data Aggregation

Due to the close proximity of deployment, several sensor nodes are likely to sense the same event which results in redundant data. These packets from multiple nodes can be aggregated to reduce the number of transmissions. Data aggregation is the combination of data from different sources according to a certain aggregation function (e.g., minima, maxima, average) [4]. Recognizing that data processing would require less energy than communications, substantial energy savings can be obtained through data aggregation. This technique has been used to achieve energy efficiency and data transfer optimizations in several routing protocols. Data aggregation can also be employed through signal processing techniques. Referred to as data fusion, a node is capable of producing a more accurate output signal by using techniques such as beamforming to combine the incoming signals and reduce the noise in the signals [19].

C. FLAT BASED ROUTING

In flat based routing, all nodes are assigned the same roles and nodes collaborate to perform the sensing task. Due to the large number of nodes in sensor networks, assigning global identifiers to each node will not be feasible. With such a lack of global identification, data is usually transmitted from every sensor node in the region with much redundancy. This is very inefficient in terms of energy consumption. As such, routing protocols need to be able to select and query a set of nodes and utilize data aggregation during the relay of data. This has led to data-centric routing where the base station sends queries to certain regions and waits for data from sensors located in the selected region. This has necessitated the use of attribute-based naming to specify the properties of the data. This section introduces some of these protocols and highlights their advantages and key concepts.

1. Sensor Protocols for Information via Negotiation (SPIN)

SPIN [23, 24] is a family of adaptive protocols that disseminate the information at each node to every node in the network assuming that all nodes in the network are potential base stations. These nodes use the assumption that nodes in close proximity of each other have similar data and as such, only data that other nodes do not posses need to be distributed. Nodes assign a high level name to describe their data completely (called meta-data) and perform metadata negotiation before any data is transmitted. This ensures that no redundant data are sent throughout the network. The semantics of the meta-data format is application specific and not specified in SPIN. In addition, SPIN has access to current energy levels of the node and adapts the protocol it is running based on how much energy is remaining.

The SPIN family of protocols is based on two basic ideas. First, to operate efficiently and conserve energy, sensor applications need to communicate with each other about the data that they already have and the data they still need to obtain. Exchanging data about the sensor data requires less energy than exchanging all the sensor data.

Secondly, nodes in the network monitor and adapt to the changes in their own energy sources to extend the operating life of the network.

Conventional protocols like flooding and gossiping waste energy by sending unnecessary data by sensors covering overlapping areas. Drawbacks of flooding include implosion which is caused by duplicate messages sent to the same node (as illustrated in Figure 3a), overlap when two nodes sensing the same region send similar packets to the same neighbor (as illustrated in Figure 3b), and resources consuming large amounts of energy without considering energy constraints. Gossiping avoids the problem of implosion by selecting a random node to send the packet rather than broadcasting the packet blindly. This, however, causes delays in the propagation of data in the network.

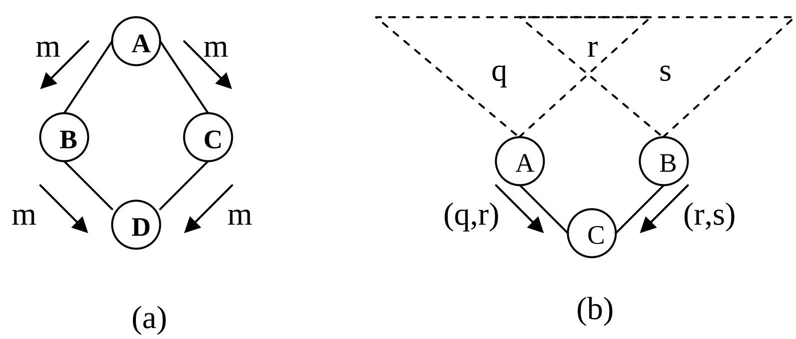

Figure 3. Problems with Flooding: (a) Implosion (b) Overlap (From Ref [23])

The problem of flooding is resolved by SPIN's meta-data negotiation, which also achieves significant energy efficiency. SPIN uses a three stage protocol as sensor nodes use three types of messages: ADV, REQ and DATA. The ADV message allows the sensor to advertise a particular meta-data, REQ to request a specific data and DATA to carry the message itself. As illustrated in the figure below, the protocol starts when a node obtains new data that it is willing to share. It starts by advertising (a) this to its neighbors. If a neighbor is interested in the data, it responds by sending a request (b) for the data and the data (c) is sent to the neighbor node. This process repeats with other nodes (d,e,f), which results in the entire sensor area receiving a copy of the data.

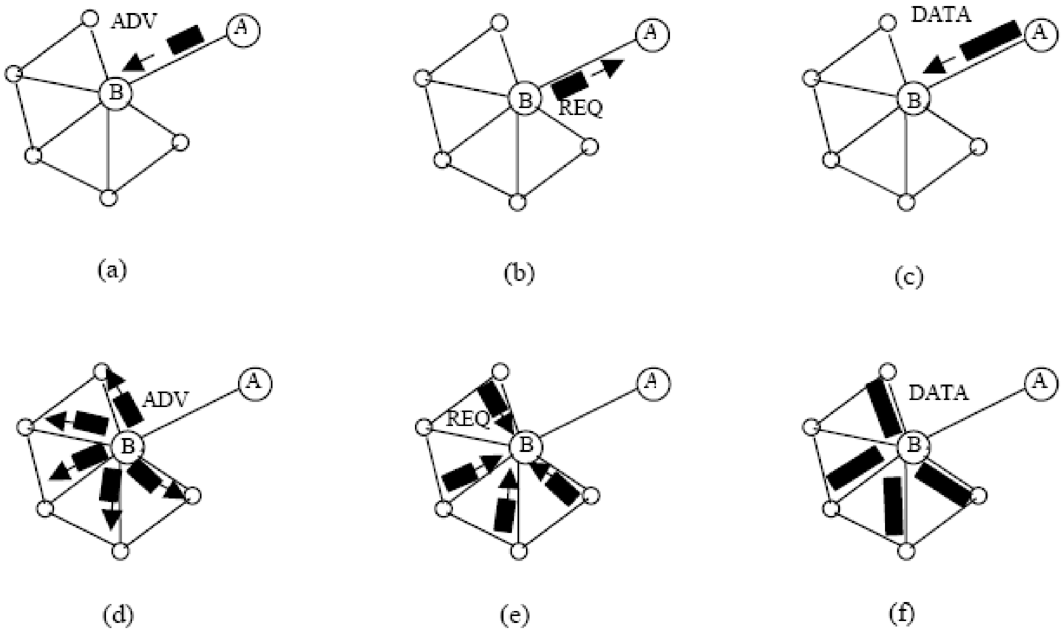

Figure 4. SPIN Protocol (From Ref [23])

One advantage of SPIN is that topological changes are localized since each node only requires knowledge of its single-hop neighbors. SPIN provides more energy savings than flooding and meta-data negotiation almost halves the redundant data. SPIN's advertising mechanism does not provide guaranteed data delivery. Consider that if the nodes are interested in data located far away from the source nodes and the nodes between the source and destination nodes are not interested in that data, such data will not be delivered to the destination at all. Hence, SPIN may not be a good choice for applications such as intrusion detection where reliable data delivery over periodic intervals is required.

2. Directed Diffusion

A data aggregation model for a wireless sensor network called directed diffusion was proposed in [25, 26]. The main idea of this model is to dispose of unnecessary network operations through combining the data coming from different sources en route, eliminating redundancy, minimizing the number of transmissions, thereby saving energy and prolonging the network lifespan. Directed diffusion is a data-centric and application aware model in the sense that all data generated by sensor nodes is named by attribute-value pairs such as name of objects, interval, duration, geographic location etc. (e.g., ID =

12, type = seismic, location = NE, footprint = vehicle/wheeled/>40 tones). A base station (i.e., sink) may request data by broadcasting interests (e.g., type = seismic, location = NE). Each node receiving the interest can cache the interest for later in-network data aggregation. The interests in the caches are compared with the received data with the values of the interest. This enables diffusion to achieve energy savings later by selecting empirically good paths. As the interest propagates through intermediate nodes in the network, gradients[2] are set up to draw data satisfying the query toward the requesting node (e.g., NE). Each sensor node that receives the interest establishes a gradient toward the sensor node from which it received the interest. This process continues until gradients are built from the source back to the base station. Figure 5 shows an example of the workings of directed diffusion (sending interest, building gradients, and data dissemination). When the interest fits gradients, paths of information flow are formed from multiple paths and then the best paths are reinforced to prevent further flooding. To reduce communication costs, data is aggregated on the way back to the base station. The base station may periodically resend interest when it receives data from the source(s) as interests may not be reliably transmitted through the network.

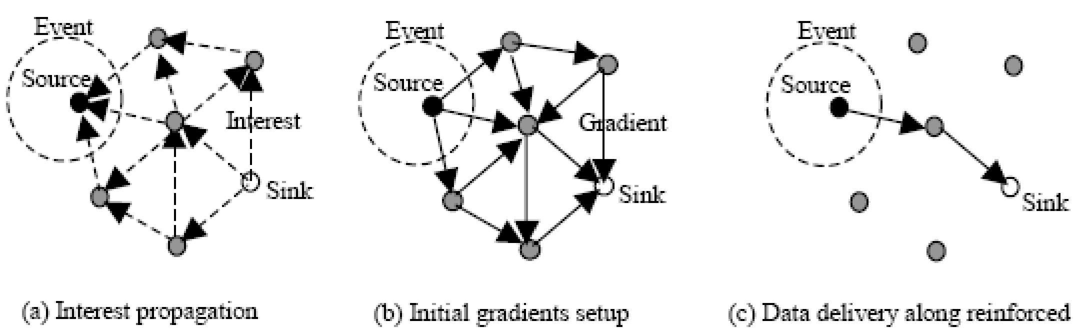

Figure 5. Simplified Schematic for Directed Diffusion (From Ref [25])

Directed diffusion differs from SPIN in two aspects. The first being that directed diffusion issues data queries on demand as the BS sends queries to the sensor nodes. In SPIN, nodes advertise the presence of data allowing the interested node to query that data. The second is that all communication in directed diffusion is neighbor to neighbor

[2] A gradient is a reply link to a neighbor from which the interest was received. The strength of the gradient may be different towards different neighbors resulting in different amounts of information flow.

with each node having the capability to perform data aggregation and caching. There is no need to maintain a global network topology, unlike SPIN. However, directed diffusion may not be applied to applications that require continuous data delivery such as habitat monitoring since it is a query driven system. The naming schemes are application dependent and need to be defined a priori. It may also require some additional overhead at the sensor nodes when matching data to queries.

3. Energy Aware Routing (EAR)

Energy aware routing [27] is a variant of directed diffusion and is intended to increase the lifetime of the network. It differs from directed diffusion in that it maintains a set of sub-optimal paths instead of maintaining or enforcing one optimal path at a higher rate. These paths are maintained and chosen by a certain probability. The value of this probability is determined by how low an energy consumption each path can achieve. Always using the minimum energy path all the time will deplete the energy of the nodes on that path. Hence, by having multiple paths that are chosen at different times, the energy of any single path will not be depleted quickly. This can achieve longer network lifetime as energy is dissipated equally among the nodes. The protocol assumes that each node is addressable through class-based addressing that includes locations and types of the nodes.

The protocol initiates a connection through localized flooding, which is used to discover all routes between source and destination pairs and their costs, building routing tables. High cost paths are discarded and a forwarding table is built by choosing neighboring nodes in a manner proportional to their cost. Node selection is done according to the closeness to the destination and each node assigns a probability to each of its neighbors in the forwarding table which corresponds to the formed paths. Each node randomly selects a neighbor node from its forwarding table to send data to the destination with the probability inversely proportional to the node cost. Route maintenance is achieved through periodic localized flooding to keep the paths alive. This approach provides an overall improvement in energy saving, and thus, increasing network lifetime. However, this approach requires the gathering of location information and setting up the addressing mechanism for the nodes, which complicates route set up compared to directed diffusion.

4. Direct Sequence Distance Vector (DSDV)

DSDV [28] is an adaptation of the classical Bellman-Ford routing protocol for use in ad-hoc networks. Routing is achieved by using routing tables maintained by each node. The bulk of complexity in DSDV is in generating and maintaining these routing tables.

In DSDV, packets are routed between nodes of an ad-hoc network using routing tables stored at each node. Each routing table, at each node, contains a list of the addresses of every other node in the network. Along with each node's address, the table contains the address of the next hop for a packet to take place in order to reach the node. In addition to the destination address and the next hop address, routing tables maintain the rout metric and the route sequence number.

When network topology changes are detected or when there are no changes over a time period, each node will broadcast a routing table update packet. The update packet starts out with a metric of one. This signifies to each receiving neighbor they are one hop away from the node. The neighbors will increment this metric and then retransmit the update packet. This process repeats itself until everyone in the network has received a copy of the update packet with a corresponding metric. If the node receives duplicate update packets, it will only pay attention to the update packet with the smallest metric and ignore the rest.

DSDV requires nodes to transmit routing table packets periodically, regardless of network traffic. These update packets broadcast throughout the network so every node in the network knows how to reach every other node. As the number of nodes grows, the size of the routing table and the bandwidth required to update them also grows. This is the main weakness of DSDV.

D. HIERARCHICAL BASED ROUTING

Hierarchical or cluster based routing methods are well known routing methods with a special advantage related to scalability and efficient communications. Hence, they are used for energy efficient routing in wireless sensor networks. In hierarchical routing, higher-energy nodes can be used to process and send the information, while low-energy nodes can be used to perform the sensing in the vicinity of the target. The creation of clusters and the assignment of special tasks to cluster heads contribute to the overall systems scalability. Nodes within a cluster lower the energy consumption by performing data aggregation and fusion, lowering the number of transmitted messages to the base station, thus prolonging network lifetime. Hierarchical routing is mainly comprised of two levels: one for the selection of cluster heads and the other for routing.

1. Low Energy Adaptive Clustering Hierarchy (LEACH)

LEACH [19] is a cluster based routing algorithm in which self-elected cluster heads collect data from all the sensor nodes in their cluster, aggregate the collected data by data fusion methods and transmit the data directly to the base station. These self-elected cluster heads continue to be cluster heads for a period referred to as a round. At the beginning of each round, every node determines if it can be a cluster head during the current round by the energy left at the node. In this manner, a uniform energy dissipation of the sensor network is obtained. If a node decides to be a cluster head for the current round, it announces its decision to its neighbors. Other nodes which choose not to be cluster heads determine to which cluster they want to belong by choosing the cluster head that requires the minimum communication energy. LEACH was proposed for routing data in wireless sensor networks which have a fixed based station to which recorded data needs to be routed. All the sensor nodes are considered static, homogenous and energy constrained. The sensor nodes are expected to sense the environment continuously and thus have data sent at a fixed rate. These assumptions make it unsuitable for sensor networks where a moving source needs to be monitored.

The operation of LEACH is separated into two phases: the setup phase and the steady state data transfer phase. In the set up phase, the clusters are organized and cluster heads selected. The means of selection ensure that every node that advertises to be a cluster head chooses a random number between 0 and 1. If the generated number is less than a threshold, the node will be the cluster head for the current round. After receiving all the messages from the nodes that would like to be included into the cluster and based on the number of nodes in the cluster, the cluster head creates and announces a TDMA schedule, assigning each node a time slot when it can transmit. Each cluster communicates using different CDMA codes to reduce interference from nodes belonging to other clusters The CDMA code to be used in the current round is transmitted along with the TDMA schedule. In the steady state phase, the actual data transfer to the base station takes place. The cluster head node upon receiving all the data, aggregates it before sending it to the base station. After a certain time, determined a priori, the network goes back to the set up phase and enters another round of selecting new cluster heads.

LEACH uses single hop routing and assumes that all nodes can transmit with enough power to reach the base station and that each node has the computational power to support a different MAC. It is, therefore, not applicable to networks deployed in large regions. It is also assumed that the cluster heads will be evenly distributed throughout the network. This may not be the case and there is a possibility that cluster head may be concentrated in one part of the network. Lastly, it assumes that being a cluster head consumes approximately the same amount of energy for each node. As such, it assumes that all nodes have the same amount of energy at the beginning of each election round.

2. Threshold Sensitive Energy Efficient Protocol (TEEN)

TEEN [29] and Adaptive Periodic TEEN (APTEEN) [30] was proposed for time critical applications. Responsiveness is important for time critical applications, in which the network operates in a reactive mode.

TEEN pursues a hierarchical approach along with the use of a data centric mechanism. The sensor network architecture is based on a hierarchical grouping where closer nodes form clusters and this process continues to a second level until the base station is reached as illustrated in Figure 6. In TEEN, the sensor nodes sense the medium continuously but data transmissions are done less frequently. After the clusters are formed, the cluster heads broadcasts two thresholds to the nodes, a hard and soft threshold for sensed attributes. The hard threshold is the minimum possible value of an attribute that will trigger a node to switch on its transmitter and transmit to the cluster head. Hence, only when the sensed attribute is in the range of interest, does the hard threshold allow the nodes to transmit, which reduces the number of transmissions significantly. Once a node senses a value greater or equal to the hard threshold, it transmits data only when the value of that attribute changes by an amount equal or greater than the soft threshold, reducing the number of transmission further if there is no or little change in the value of the sensed attribute. A smaller value of the soft threshold will provide a more accurate picture of the network at the expense of increased energy consumption. Hence, the soft and hard threshold can be adjusted to control the number of packet transmission, thereby controlling the trade off between energy efficiency and data accuracy. The disadvantage of TEEN is that the user may not get any data if the thresholds are not reached. As such, TEEN is not good for applications requiring periodic reports.

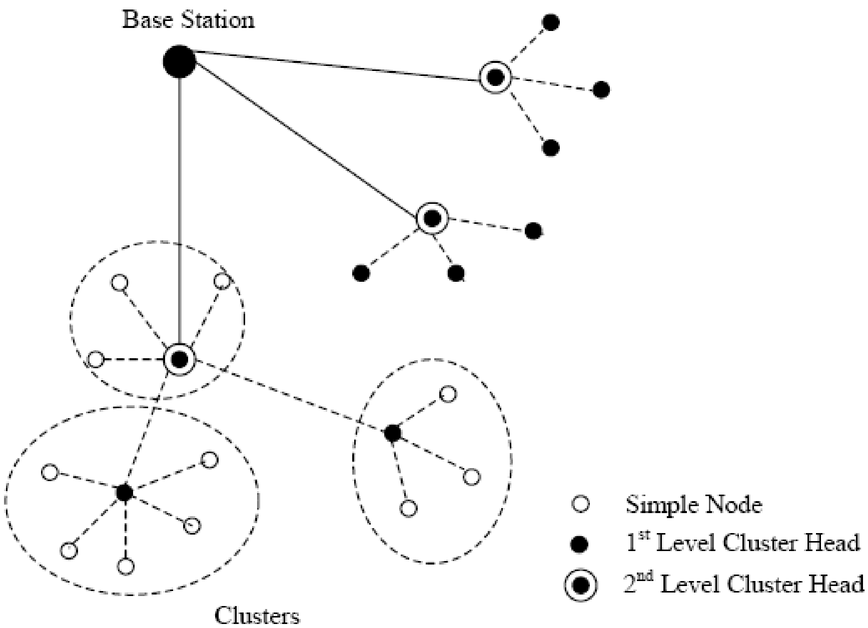

Figure 6. Hierarchical Clustering in TEEN and APTEEN (from Ref [30])

APTEEN is an extension of TEEN and aims to react to time critical events as well as capture periodic data collections. When the clusters are formed, the cluster head broadcasts the interest attributes (physical parameters of information of interest), soft and hard threshold values, the TDMA transmission schedule and a count value (maximum value between two successive report sent by a node) to all the nodes. Cluster heads also perform data aggregation in order to save energy. It shares the same architecture as TEEN. However, if a node does not send data for a time period equal to the count value, it is forced to sense and retransmit the data. The TDMA schedule assigns a transmission clot to each of the nodes in the cluster. As such, APTEEN combines both proactive and reactive policies enabling greater flexibility through the setting of count and threshold values by which energy consumption is controlled. APTEEN supports three different query types: historical – to analyze past data; one-time – to take a snapshot of the network; and persistent – to monitor an event over a period of time.

The main drawback of the two schemes is the added overhead and complexity associated with forming clusters at multiple levels, implanting threshold-based functions and dealing with attribute-based naming of queries.

3. Two-Tier Data Dissemination (TTDD)

TTDD [31] provides data delivery to multiple mobile base stations. In TTDD, each data source proactively builds a grid structure that is used to disseminate data to the mobile sinks by assuming that sensor nodes are stationary and location aware. Since sensors are assumed to know their location in order to tag sensing data and because a sensor's location is static, TTDD can use a greedy geographic forwarding to construct and maintain the grid structure with low overhead. Once an event occurs, sensors surrounding it process the signal and one of them becomes the source to generate data reports. To build the grid structure, a data source chooses itself as the start crossing point of the grid, and sends an announcement to each of its four adjacent crossing points. When the message reaches the node closest to the crossing point specified in the message, it will stop. During the process, each intermediate node stores the source information and further forwards the message to its adjacent crossing points except for the one from which it received the message. This recursive propagation of data announcement messages notifies those sensors that are closest to the crossing locations to become the dissemination node of the given source. After this process, the grid structure is obtained. Using the grid, a base station can use a flood query, which will be forwarded to the nearest dissemination point in the local cell to receive data. The query is then forwarded along other dissemination points upstream to the source. The requested data then flows down in the reverse path to the base station. TTDD does not specify how the algorithm obtains the nodes location information, which is required to set up the grid and may imply that the nodes are deployed deterministically. The overhead associated with maintaining and recalculating the grid as the network topology changes may be high. The length of the forwarding path is longer than the shortest path but the authors believe that the sub-optimality in the path length is gained in scalability.

E. LOCATION BASED ROUTING

In location based routing, sensor nodes are addressed by means of their locations. The distance between neighbors can be estimated through their signal strengths [32] and relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors. Alternatively, the locations may be available using GPS by communicating directly with nodes equipped with low-power GPS receivers. To save energy, some location based schemes demand that the nodes sleep when there is no activity.

1. Geographic and Energy Aware Routing (GEAR)

Since data queries often include geographic attributes, this geographic information can be used while disseminating these queries to appropriate regions. GEAR [33] uses energy-aware and geographically informed neighbor selection heuristics to route a packet toward the destination region. The idea is to restrict the number of interest messages in directed diffusion by only considering the target region rather than sending the interests to the whole network. GEAR compliments directed diffusion in this way to conserve more energy.

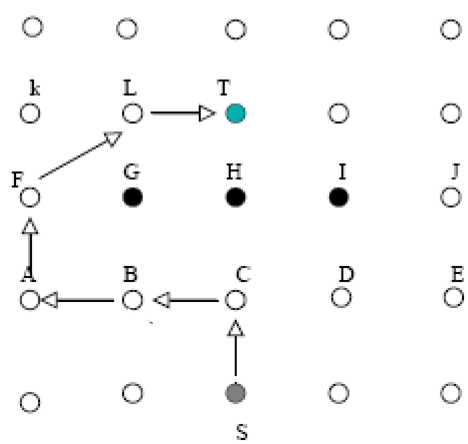

Figure 7. GEAR: Learning Route around Holes (From Ref [33])

Each node in GEAR keeps an estimated cost and a learning cost of reaching the destination through its neighbors. The estimated cost is a combination of residual energy and distance to destination. The learned cost is a refinement of the estimated cost that accounts for routing around holes in the network. A hole occurs when a node does not have any closer neighbor to the target region than itself. In Figure 7, nodes G,H and I are energy deleted nodes and therefore cannot relay packets. If node S wants to send a packet to node T, it would forward to its lowest cost neighbor, node C. At node C, it will have encounter a hole as all of node C's neighbors are further away from T that itself. Ties are broken by a pre-defined order (e.g. node ID). In this example in Figure 7, node B is chosen and the learned cost is updated. If there were no holes, the estimated cost would equal the learned cost. The learned cost is propagated one hop back every time a packet reaches the destination so that route set up for the next packet will be adjusted.

There are two phases in the algorithm. The first is forwarding packets towards the target region. Upon receiving a packet, a node checks its neighbors to see if there is one neighbor which is closer to the target than itself. If there is more than one, it selects the nearest neighbor to the target as the next hop. If they are all further than the node itself, implying a hole, one of the neighbors is picked to forward the packet based on the learning cost function. The choice can be updated according to the convergence of the learned cost during the delivery of the packet. The second is forwarding packets within the region. If the packet has reached the region, it can be diffused in that region by either recursive geographic forwarding or restricted flooding. Restricted flooding is only good when the nodes are not densely deployed. In high-density networks, recursive geographic forwarding is more energy-efficient than restricted flooding. As illustrated in Figure 8, the region is divided into four sub regions and four copies of the packet are created. This splitting and forwarding process is repeated until only one node is left. When no nodes are inside a sub region, the packet is dropped.

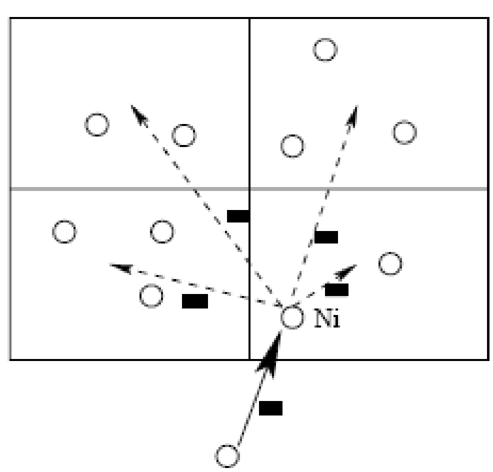

Figure 8. Recursive Geographic Forwarding in GEAR (From Ref [33])

2. Geographic Adaptive Fidelity (GAF)

GAF [34] is an energy-aware location based routing algorithm designed for mobile ad-hoc networks but has been applied to wireless sensor networks. GAF conserves energy by switching off redundant nodes. The network is divided into fixed zones and a virtual grid is formed for the covered area. Each node uses its GPS-indicated location to associate itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of packet routing costs. Nodes within a zone collaborate by electing one node to represent the zone for a time period while the rest of the nodes sleep. A sample situation is taken from [34] illustrated below. In the figure, node 1 can reach any of nodes, 2, 3 or 4. Nodes 2, 3 and 4 can reach node 5. Therefore, nodes 2, 3 and 4 are equivalent and two of them can sleep.

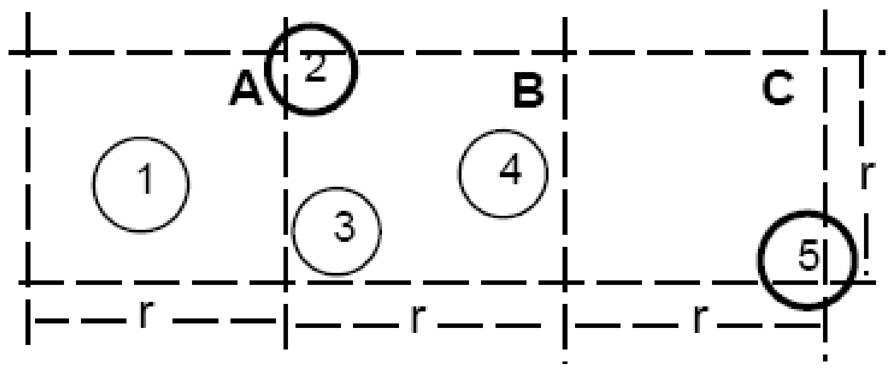

Figure 9. Example of Virtual Grid in GAF (From Ref [34])

Nodes rotate the active and sleep states so that the load to each node is balanced. It was noted that as the number of nodes increase, so would the lifetime of the network. There are three states in the defined in GAF. These states are: discovery – for determining the neighbors in the grid, active – reflecting the participation in the routing and sleep – when the radio is turned off. The state transitions taken from [34] are depicted below.

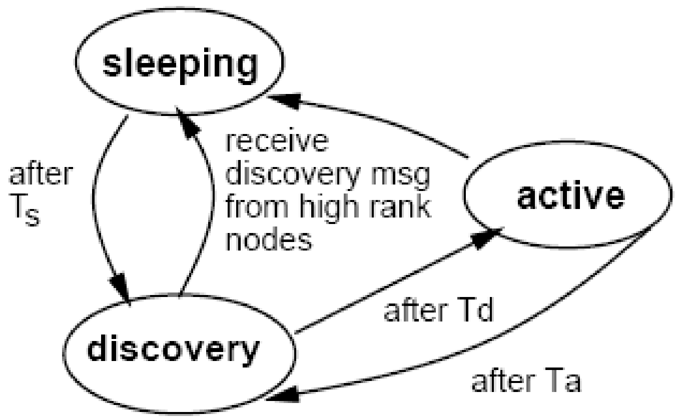

Figure 10. State Transitions in GAF (From Ref [34])

The duration of sleep is application dependent and the related parameters are tuned accordingly in the routing process. The mobility of nodes is handled by having the node in the grid estimate its time of leaving the grid and broadcasting it to all its neighbors. To maintain routing fidelity, the neighbor nodes adjust their sleep cycle to wake up and one of them becomes active.

GAF is a location based routing protocol but may also be considered a hierarchical based protocol where clusters are based on geographic location. In a particular grid, a representative node acts as a leader node to transmit data to other nodes. The leader node, however, does not do data aggregation or fusion as in hierarchical protocol discussed earlier.

F. SUMMARY

This chapter described the challenges in the design of routing protocol in wireless sensor networks and presented some of the routing protocols used in wireless sensor networks. The table below compares the three classifications: flat-based routing, hierarchical based routing and location based routing. The next chapter focuses on a specific flat-based routing protocol designed for wireless sensor networks called XMesh.

Protocol	Classification	Data Aggregation	Mobility	Position Awareness	Local-lisation	Scalability	Negotiation based	Multi-path	Query - based
SPIN	Flat	Yes	Possible	No	No	Limited	Yes	Yes	Yes
Directed Diffusion	Flat	Yes	Limited	No	Yes	Limited	Yes	Yes	Yes
EAR	Flat	No	Limited	No	No	Limited	No	No	Yes
DSDV	Flat	No	Yes	No	No	Limited	No	No	No
LEACH	Hierarchical	Yes	Fixed BS	No	Yes	Good	No	No	No
TEEN & APTEEN	Hierarchical	Yes	Fixed BS	No	Yes	Good	No	No	No
TTDD	Hierarchical	No	Yes	Yes	No	Low	No	Possible	Possible
GEAR	Location	No	Limited	No	No	Limited	No	No	No
GAF	Location	No	Limited	Yes	No	Good	No	No	No

Table 1. Classification and Comparison of Routing Protocols in Wireless Sensor Networks

IV. XMESH ROUTING PROTOCOL

A. CHAPTER OVERVIEW

XMesh is a multi-hop routing protocol developed by Crossbow to run on the MICA family of motes using the TinyOS environment [35]. It is an ad-hoc mesh networking protocol capable of network formation without the need for human intervention. It is also capable of adding and removing network nodes automatically without having to reset the network. It uses a routing beacon from the base station to establish route paths back. Given the general acceptance of Crossbow motes for research purposes, this chapter has been dedicated to a greater understanding of the XMesh multi-hop routing protocol which was evaluated.

B. PROTOCOL COMPONENTS

The high level interactions of all the components implementing the routing protocol are shown in the figure below. A routing beacon from the base station is used to establish paths back to it. Each node maintains estimates of the inbound link quality (i.e., reception) that is propagated back to its neighbors as the routing protocol is based on the outbound (i.e., transmission) link.

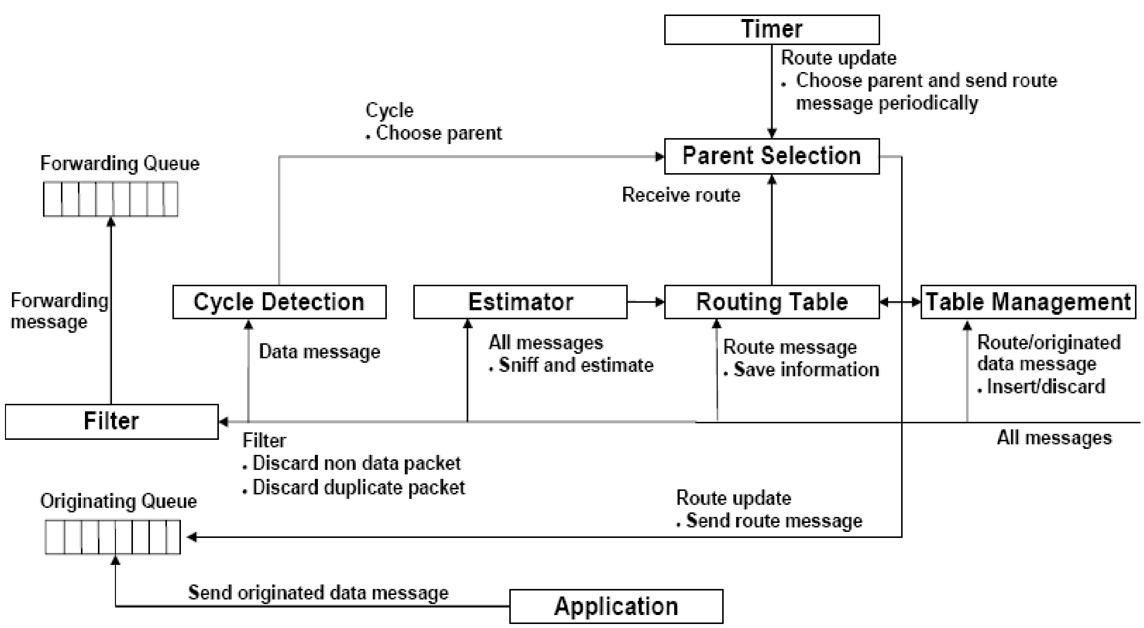

Figure 11. XMesh Routing Components. (From Ref [7])

1. Routing Table

The routing table contains the status and routing entries for neighbors. Its fields include the MAC address, an estimate routing cost to sink, parent address, a child flag, a list of reception (inbound) link quality, a send (outbound) link quality and link estimator data structures. The routing table can hold up to 16 entries.

2. Estimator

The estimator computes the link quality of its neighbor nodes. Link quality is the measure of the percent of packets that arrive undamaged on a link and is determined by the ratio of received to expected packets (i.e., the packet delivery success rate). Other measures include hop count and route stability.

The estimator snoops on packets in the channel and link quality is estimated by observing packet success and loss events. Higher level protocols use these estimations to build routing structures. The estimator is required to react quickly to large changes in link quality and yet be stable when the link is affected by short term fluctuations. It should not require significant storage and processing because of limited memory and computational ability. The ability to react quickly enables higher-level protocols to adapt to environmental changes and mobility. In XMesh, a window mean with an exponentially weighted moving average (WMEWMA) is used to estimate the link quality. It computes the success rate over a fixed time period and smoothes the average with an exponentially weighted moving average (EWMA).

3. Table Management

The eviction, insertion and reinforcement of nodes in the routing table are determined by the table management policy. A node performs neighbor discovery by recording information about nodes from which it receives packets either as a result of passive monitoring or active probing. Link estimation is used to determine which nodes should be considered neighbors. For each incoming packet upon which neighbor analysis is performed, the source is considered for insertion or reinforcement. Insertions are performed if the table is not full. If the source is represented in the table, a reinforcement operation may be performed to keep it there. If the source is not present and the table is full, the node must decide whether to discard the information associated with the source or to evict another node from the table.

4. **Parent Selection**

Parent selection is run periodically to identify one of the neighbors for routing. The cost of a node is an abstract measure of distance, based on various metrics such as hop count; number of transmissions or reconfiguration over time. A neighbor is selected as a potential parent only if its cost is less than a current cost of the node. It may also change to a new parent if the link quality of the current parent drops below a threshold, if the sink is unreachable through the current parent or if a cycle is detected. When connectivity to the current parent worsens, its link estimation will degrade over time, allowing the selection of a new parent. If the connectivity to the current parent is lost and no potential parents are available, the node declares it to have no parent and sets its cost to infinity. If the rate of parent change is high, fluctuations in routing will cause the network to be unstable, hence, routes are evaluated on a periodic basis rather than upon receiving a route update.

5. **Cycle Detection**

When a node originates a message and sees it returning, a loop has occurred (i.e., forwarding message to child instead of parent). By monitoring the forwarding traffic and snooping on the parents address in each neighbor's messages, neighboring child nodes can be identified and will not be considered as potential parents. Since each node is a router and a data source, cycles can be detected quickly. Once cycle is detected, it is broken by discarding the current parent by choosing a new one or by becoming disjoint from the tree.

6. **Filter**

The filter discards non-data packets and duplicate packets. Duplicate packets can be created upon retransmission when the ACK is lost. Without the filter, these will be forwarded and possibly causing more retransmissions and more contention, wasting energy. To avoid duplicate packets, the routing layer at the originating node appends the sender ID and originating sequence number to the routing header. To suppress forwarding duplicate messages, each parent retains the most recent originator ID and originating sequence number in child entries in the routing table.

7. **Timer**

The timer triggers the periodic update of routing tables, messaging etc.

C. ROUTING ALGORITHM

In the XMesh routing algorithm [36], the cost metric is one that minimizes the total number of transmissions in delivering a packet over multiple hops to a destination and is termed the Minimum Transmission (MT) cost metric. This differs from the traditional cost metric of distance vector routing which is hop count. In highly reliable links, retransmissions are infrequent and hop count would suffice in capturing the cost of packet delivery. However, with links of varying quality, a longer path with fewer retransmissions may be better than a shorter path with many retransmissions. That is, the energy required to transmit a packet over a distance with a single hop will be far greater that the energy required transmitting a packet over that distance with multiple hops.

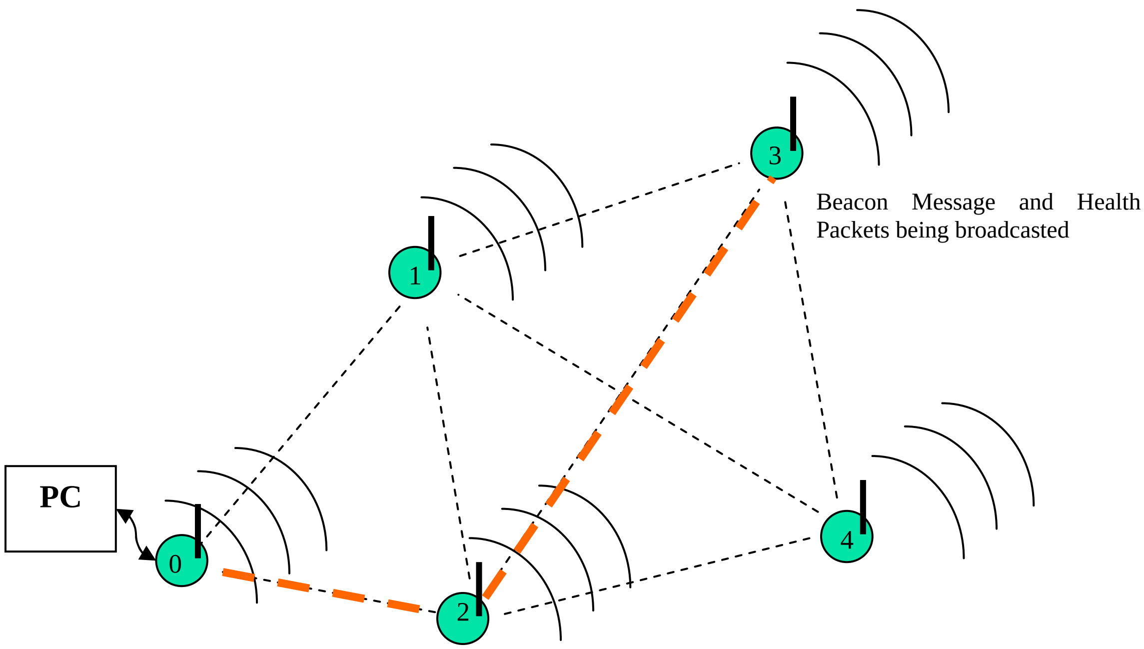

Figure 12. Broadcasting Beacon Messages and Health Packets (After Ref [36])

The multi-hop network is initially formed when motes broadcast periodic beacon messages to all other motes within radio range. In Figure 12, nodes one, two, three and four are within radio range of each other and only nodes one and two are inside the radio range of the base station mote, node zero. Health and/or data packets are also periodically transmitted to the base station. The health packets contain information about how well the mote is performing in the mesh network, specifically radio traffic. Other health packet information includes battery voltage and the parent's received signal strength indicator (RSSI) data. In Figure 12, node 3 is depicted sending health packets to the base station through node 2.

When the beacon messages are sent, they contain a cost value, which indicate to other motes the energy required to transmit a message to the base station. Higher cost indicates more energy required to make the transmission. The purpose of the cost metric is to minimize the total cost it takes to transmit to the base station mote (i.e. node zero). Each node in the mesh network will broadcast its cost value [36] which is derived later in this section. The beacon message includes the number of hops to send a message to the base station mote and a packet sequence number. The packet sequence number is a 16 bit integer and is incremented every time a message is transmitted from the base station mote or other motes. The beacon message also contains a neighborhood list (NL). The NL contains information about all other motes in the vicinity that the mote or base station mote can hear. The NL information has two parts:

- The ID of the neighborhood mote (NM).
- A received estimate on how well the mote can hear neighbor motes. The received estimate value is based on monitoring the sequence numbers of the received messages from the NM. The mote can then compute the percentage of lost packets which determines the link quality between nodes.

Since losing an acknowledgement would lead to a retransmission that wastes energy, the link qualities between motes in both directions are important. For each link, the MT cost is estimated by the inverse of the product of link qualities in the forward (SendQuality) and backward (RecieveQuality) directions. The link's cost to its parent or the Minimum Transmission cost is written as

$$MT_{ToParent} = \frac{1}{linkquality_{forward}} \times \frac{1}{linkquality_{backward}} = \frac{1}{SendQuality} \times \frac{1}{RecieveQuality} \quad (4.1)$$

For example, if the *SendQuality* between node one and node zero is 23% and the *RecieveQuality* is 29%, the link cost to node zero is 15.

The parent's cost would be the total cost of all hops to the base station.

$$\text{Parent's cost } = \sum(MT) \tag{4.2}$$

Hence, the node's cost value is calculated as:

$$\text{Node cost = Parent's cost + Link cost to Parent = } = \sum(MT) + MT_{ToParent} \tag{4.3}$$

Figure 13 shows the network status during initial configuration. The base station beacon message has a cost equal to zero and all other motes have an infinite cost as they do not know how to route messages back to the base station. There are no routing entries in the beacon message. Any data messages from the motes are sent with a broadcast address since no parents have been selected.

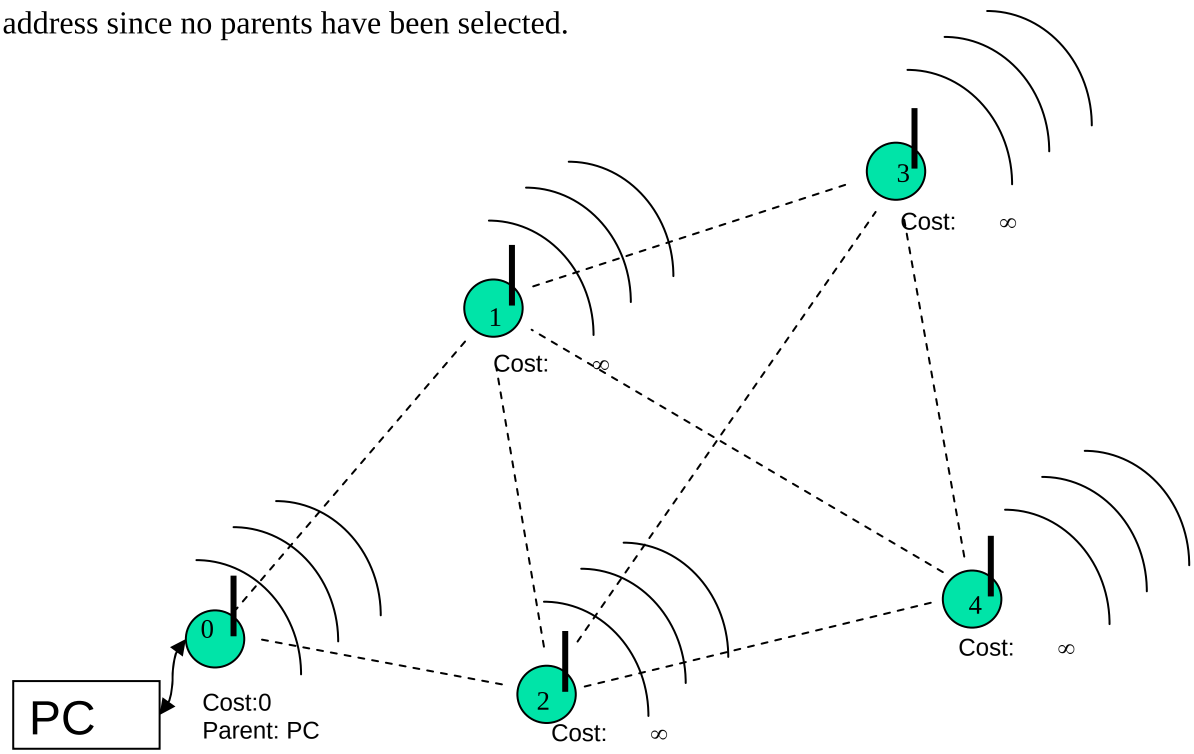

Figure 13. Network Status during Initial Configuration (After Ref [36])

After some time, all the motes within the network will be able to hear the beacon messages from the base station. The motes can then forward messages to the base station.

As the base station begins to receive messages from other motes, it will include them in its neighborhood list for broadcasting beacon message. In turn, the motes will include the base station and other neighbor motes for their beacon message broadcast. Once a parent is selected, the data message will change from a broadcast address to the parent address. The mesh network formation will then propagate to the motes that are further away and cannot hear the base station beacon messages. Figure 14 shows the network status with cost values established and illustrates the MT path from node three is the one taken through nodes four and one to node zero.

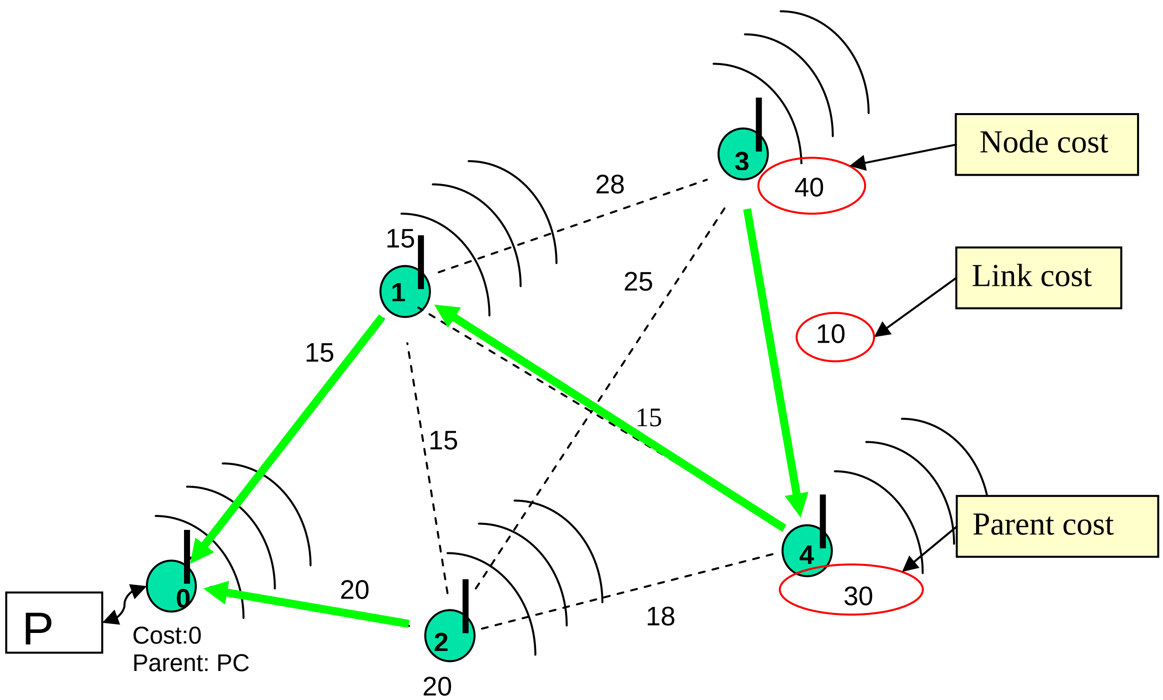

Figure 14. Network Status with Cost Values (After Ref [36])

D. XMESH PACKET FORMAT

The TinyOS message structure, shown below, consists of a five byte header, a 29 byte payload and a two byte CRC, which is used to determine successful packet reception.

Header (5)	Payload (29)	CRC (2)

Figure 15. TinyOS Message Structure (From Ref [37])

The fields in the TinyOS message header are:

- Address (2 bytes)
- Active Message type (1 byte). The field identifies the type of message being sent: Data, routing or broadcast.
- Group ID (1 byte)
- Payload length (1 byte). This field tells how much actual data is present as the payload size is variable.

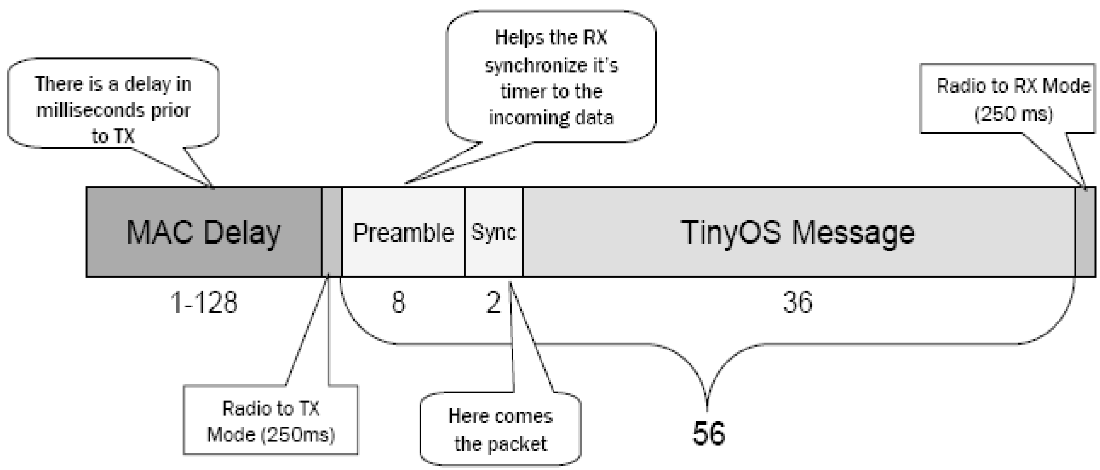

Figure 16. TinyOS Message Packet Transmission Sequence (From Ref [37])

The TinyOS message packet transmission sequence is depicted above. Prior to message transmission, a simple CSMA-based MAC is employed. A random delay is generated before listening for an idle channel. If the channel is busy, it backs off with a random delay over a predefined window. When the medium is clear the transmitter is turned on and the preamble and frame sync bytes are sent to synchronize the motes in the network. There are three types of preamble,

- Full Extended preamble – used in routing discovery and link monitoring. All route update messages are transmitted using the extended preamble message so that the nodes can discover new links and become synchronized into the network. In addition, all nodes also transmit their locally generated data messages using extended preamble packets.

- Short Extended Preamble – used for all routed traffic not originating from the local node. Therefore, all data being forwarded through a node is transmitted with the short extended messages. This applies to all forwarded messages except for those messages traveling to the base station.
- Standard Preamble – used for routed data traveling to the base station for the last hop. The base station has significantly higher network traffic than the rest of the network. Therefore, the use of the standard preamble packet lowers the power consumption of the nodes surrounding the base station.

After the message is sent over the SPI (SCSI Parallel Interface) port, the transmitter is turned off and the event that the transmission has been completed is signaled to the application.

At the receiving mote, the TOS packet is assembled. The CRC and group ID are checked. If the CRC is bad or the group ID does not match, the packet is rejected. Otherwise, it is accepted and the application signals that a packet has been received.

E. SUMMARY

This chapter described the routing components and algorithm of XMesh and presented the XMesh packet format. The next chapter presents the findings of the experimental study.

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V. EXPERIMENTAL STUDY

A. CHAPTER OVERVIEW

This chapter provides an overview of the hardware platform used in the experiments. It presents the empirical observations that characterize the network links. The energy requirements for motes and the network lifespan are discussed. With an understanding of the character of the network links, the XMesh routing protocol was observed and the experimental findings presented.

B. HARDWARE PLATFORM

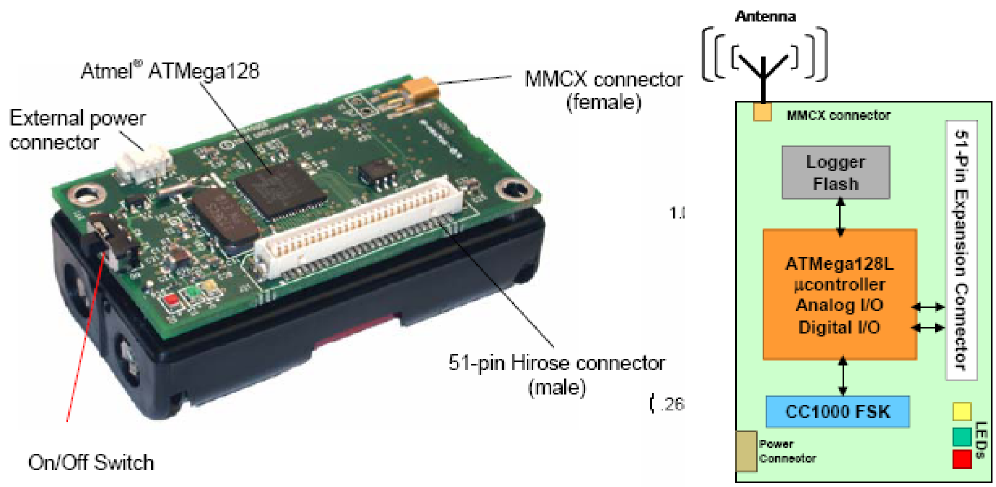


Figure 17. Photo and Block Diagram of MICA2 (from Ref [7])

The diagram above illustrates the hardware platform used in this study, the Crossbow Technology MICA2 motes running TinyOS. Each sensor node consists of a 7.37 MHz ATmega Microcontroller with 128 kB of Flash for program memory and 4 kB of SDRAM for data and variables. The network device is Chipcon's CC1000 radio at 916 MHz (MPR400[3]), frequency shift keying (FSK) RF transceiver with a max data rate of 38.4 kbps. The RF transmission power can be adjusted through software. The connectivity experiments used four power levels, -20 dBm (0.01 mW), -10 dBm (0.1 mW), 0 dBm (1 mW) and 5 dBm (3.16 mW). A node can be configured as a base station

[3] The MPR400 can operate in two frequency regions: 868 – 870 MHz (up to 4 channels) and 902 – 928 MHz (up to 54 channels). The actual number of possible channels is higher for all MICA2 motes but an adjacent channel spacing of 500 kHz is recommended to avoid adjacent channel interference.

to route over a standard serial port interface by attaching a hardware board (MIB 510). The base station serves as a traffic sink. The motes are designed for battery power with any battery combination (AA, AAA, C, or D, cells) with an output between 2.7 and 3.6 VDC. The typical batteries used are two AA cells. The antenna used is a monopole antenna.

C. CONNECTIVITY ANALYSIS

Previous studies have indicated that radio connectivity for MICA2 motes is imperfect and non-uniform even in ideal settings [38, 39]. Hence, an understanding of the loss behavior of the link in various circumstances is required before a practical topology formation and routing algorithm can be studied. The goal was to seek a simple characterization of the network connectivity to use in topology formation.

1. Node Connectivity

To characterize the link quality of the MICA2 motes, the loss rate between a pair of nodes at different distances were measured. This was achieved by varying the ranges between the nodes and observing the distances at which the link breaks and the distances when the link is re-established as illustrated in Figure 21. This experiment was conducted on the roof of Spanagel Hall as it almost free of physical obstructions. A total of four runs[4] were conducted for each of the four transmission power settings.

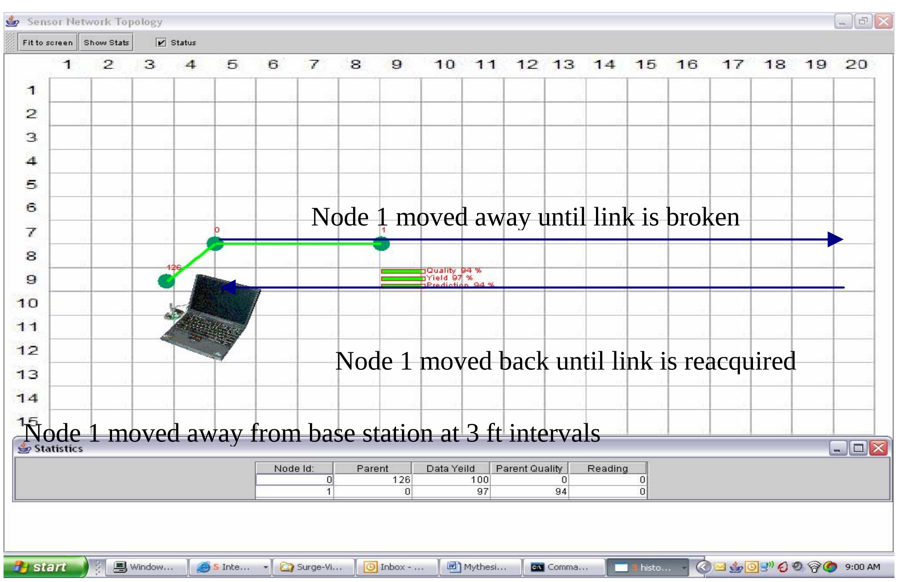


Figure 18. Node Connectivity Experiment Setup

[4] A run consist of moving the node away from the base station until the link was broken and then moved back towards the base station and noting when the link was reacquired.

Figure 22 shows data collected in a scatter plot. It shows how link quality varies over distance with the motes at the height of 2.5 feet (0.76 m) for a transmission power of -10 dBm (0.1 mW). It was also observed that the link quality can vary at a same distance. For example, the link quality at four feet varied between 100% and 98%.

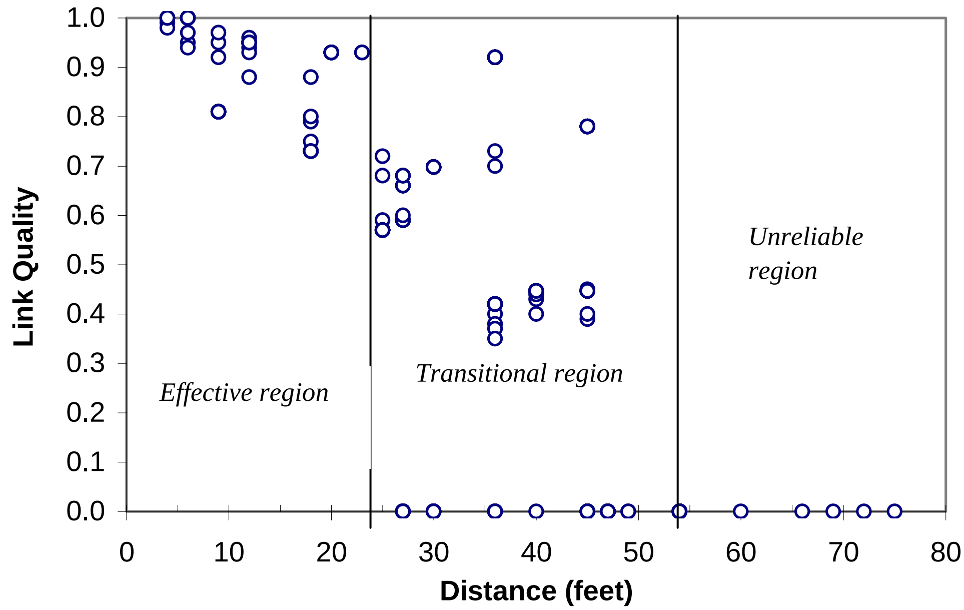


Figure 19. Reception Probability of Links in a Line Topology

For a given power setting, there is a distance within which the node pairs basically have good connectivity[5]. The size of this "effective region" increases with transmit power. There is also a point beyond which the nodes essentially have no connectivity, termed the "unreliable region". In the "transitional region" between these two points, the average link quality falls off fairly smoothly with some variation. The other transmission power settings show a similar structure. The results for the four transmission power levels were tabulated in Table 3 and plotted in Figure 23. It quantified that more transmission power was required to maintain good connectivity over larger distances. It was noted that the link between the base station and the node was

[5] Good connectivity is defined as link quality greater than 80%

established within a minute for each transmission power setting. This was attributed to the proximity of the mote to the base station (approximately one foot) at the start of each run.

Transmission Power (mW)		Effective Distance	Unreliable Distance
0.01	(-20 dBm)	4 feet (1.22 m)	7.5 feet (2.28 m)
0.1	(-10 dBm)	25 feet (7.62 m)	55 feet (16.76 m)
1	(0 dBm)	80 feet (24.38 m)	110 feet (33.53 m)
3.16	(5 dBm)	145 feet (44.20 m)	170 feet (51.82 m)

Table 2. Transmission Power versus Operating Distances

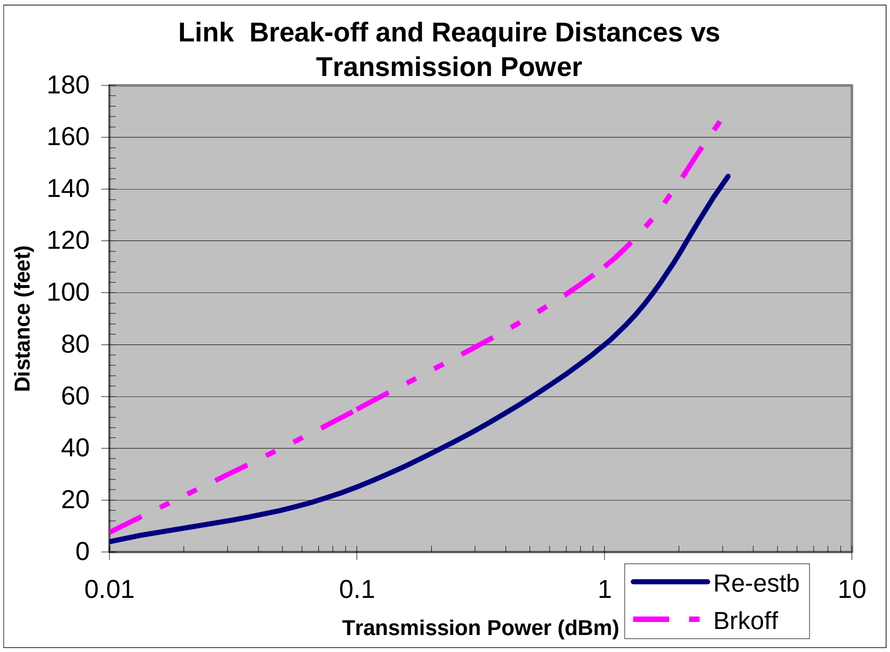


Figure 20. Transmission Power versus Transmission Distances

These readings differ from what was advertised in the Crossbow MICA2 datasheet [40]. Also, the Crossbow Technologies technical support (FAQ website) states "916 MHz band MICA2s have been tested to transmit up to ~500 feet (~165m) outdoors with a 1/2 wave dipole antenna, the RF power set to 5 dBm (maximum TX power), 1m+ off the ground, line of sight."

2. Network Connectivity

The number of nodes required to maintain network connectivity in a given area will be dependent on the transmission power of the motes. The following is an estimate of the number of nodes required for an open area with motes 2.5 feet above ground.

Transmission Power (mW)	Transmission Radius	Coverage required (m^2)	Number of Motes required
0.01 (-20 dBm)	7.5 ft (2.28m)	10000	613
		20000	1225
		50000	3062
		100000	6124
0.1 (-10 dBm)	55 ft (16.76m)	10000	12
		20000	23
		50000	57
		100000	114
1 (0 dBm)	110 ft (33.53m)	10000	3
		20000	6
		50000	15
		100000	29
3.16 (5 dBm)	170 ft (51.82m)	10000	2
		20000	3
		50000	6
		100000	12

Table 3. Mote Density Required for Connectivity

Hence, depending on the application of the sensor networks and the number of motes available, the transmission power can be adjusted to extend the lifetime of the sensor network.

D. ENERGY EFFICIENCY STUDY

Since the transmission powers levels can be programmed through software, the connectivity ranges of the motes will vary with the power settings. The higher the transmission power, the greater the connectivity range and the greater the power consumed. The typical power drawn by the MICA2 motes is 35 mA (1 mW transmission power) when awake and 10 μA when asleep [7]. The main power consumer in the MICA motes is the radio transceiver (approximately 20 mA). Consider that if there was no power saving scheme in place, continuous data acquisition would last less that 80 hours. This is illustrated in the following two graphs. The battery rating quoted by Energizer is 2850 mAh.

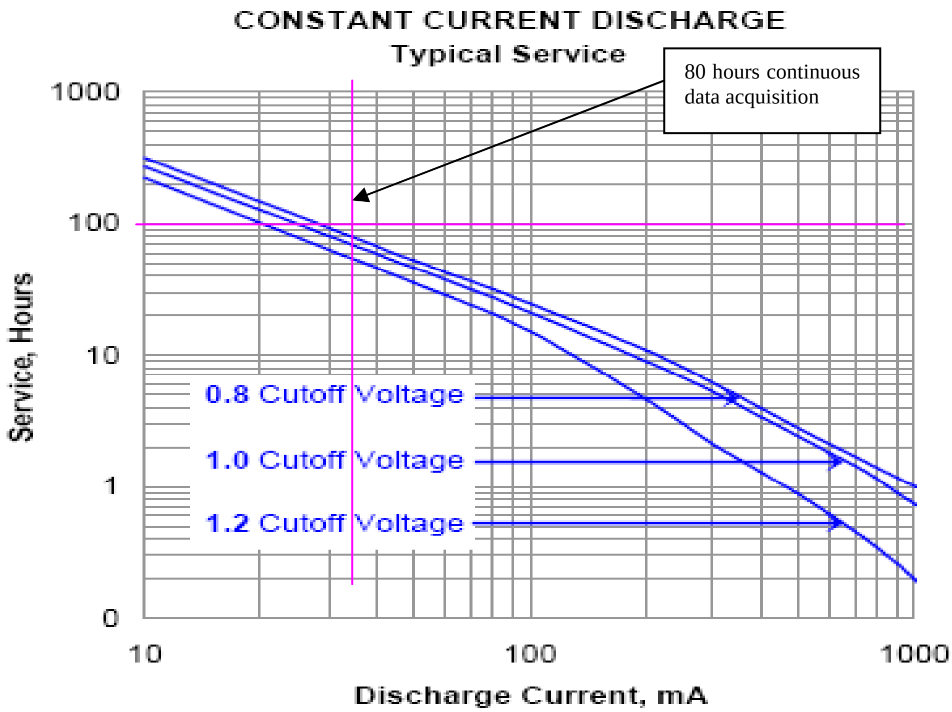


Figure 21. Battery Discharge Characteristic, Energizer e91 (www.energizer.com)

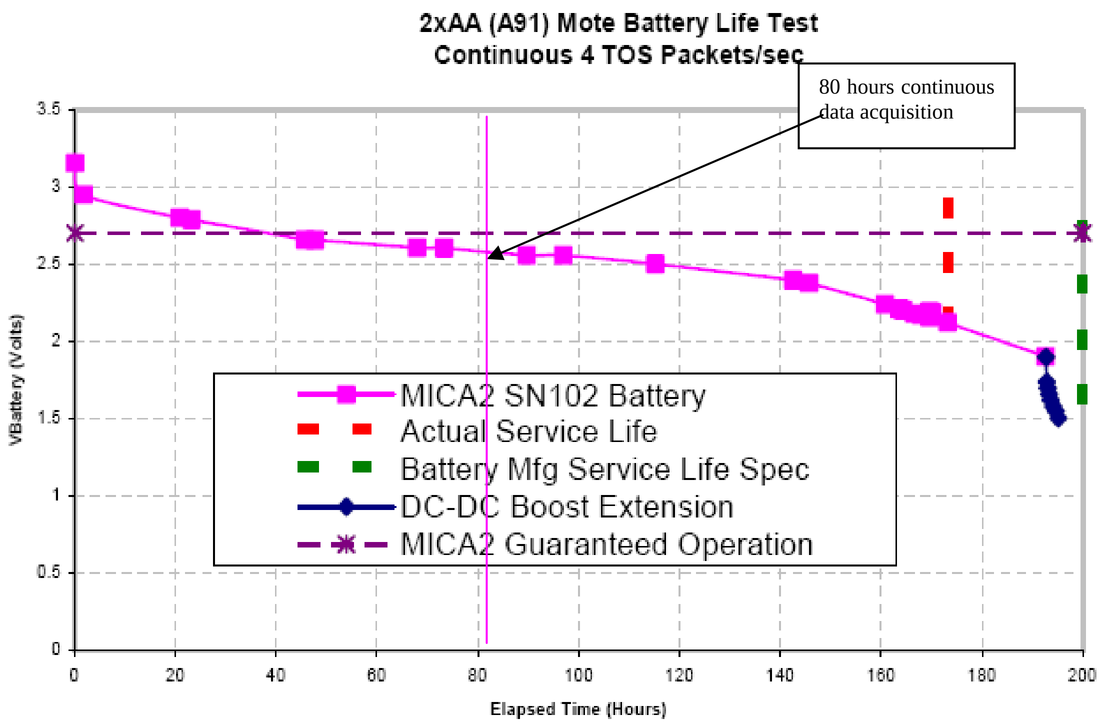


Figure 22. MICA2 Battery Pack Service Life Test Data (From Ref [7])

Power savings can be achieved via implementation of a duty cycle. For example, assuming that a mote must forward 10 packets and perform a sensor reading, consuming three seconds every time it wakes up, this will consume approximately 50 mA-sec/cycle = 0.014 mA-hours/cycle. A typical two-AA battery pack supplies 1700 mAh @ 15 mA drain. Therefore, $\frac{1700mAh}{0.014mAh/cycle} = 120,000\,cycles$. For 100% wake state or duty cycle, the mote will last $120,000\ cycles \cdot 3\sec/cycle = 100\ hours$. If a 1% wake state is implemented (297 seconds asleep per cycle), the lifetime of the mote is $120,000\ cycles \cdot 300\sec/cycle = 1.1\ years$. The recommended duty cycle for most applications is 0.5% to 2%. The wake state and the expected mote lifespan are tabulated below.

Duty Cycle (%)	Expected Lifetime (years)
100	0.01
35.5	0.03
11.5	0.10
7.53	0.15
5.61	0.20
2.22	0.51
1.00	1.14
0.50	2.28

Figure 23. Duty Cycle and their Corresponding Mote Lifetimes.

E. EVALUATION OF XMESH

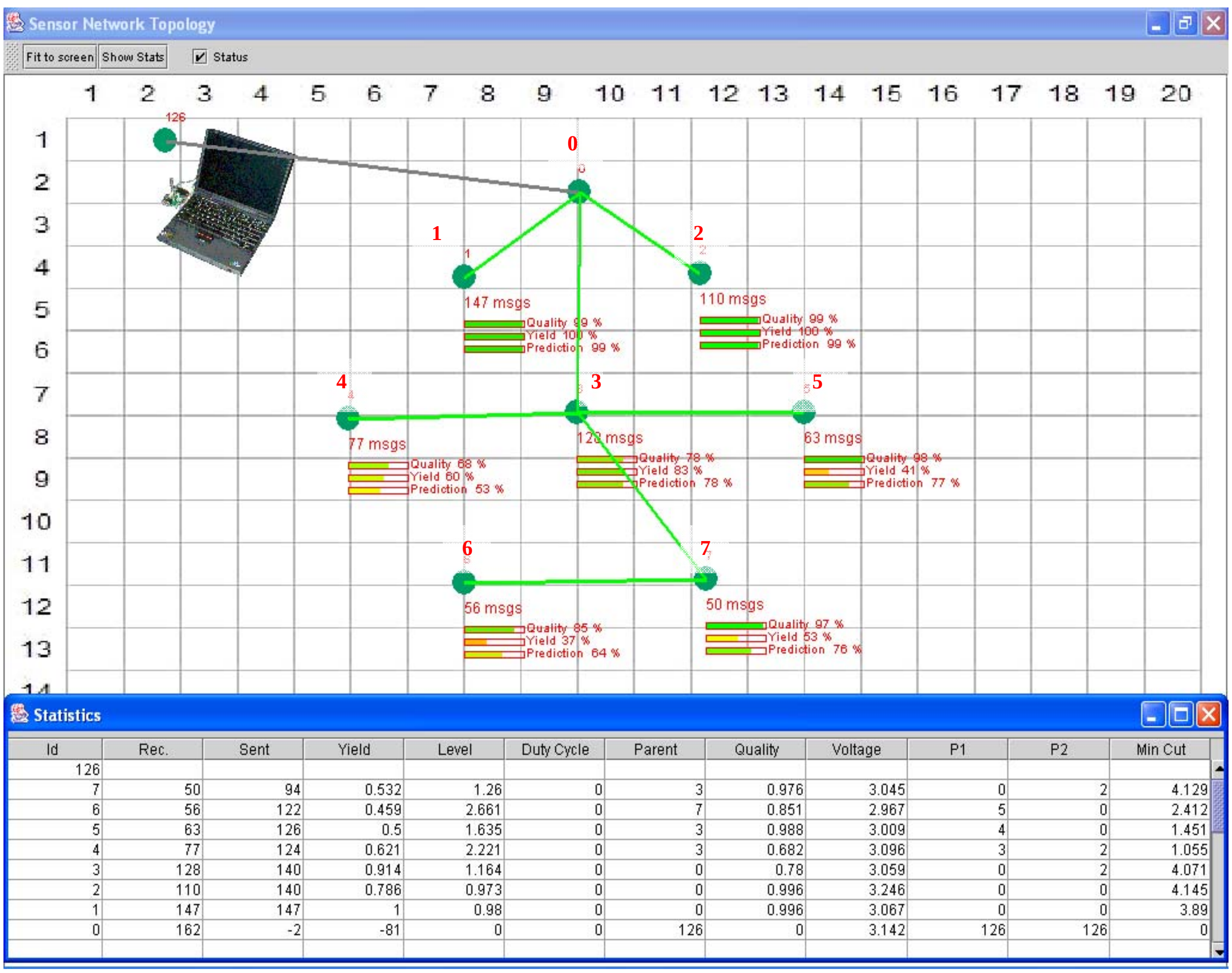
1. Experiment Setup

The photo below presents the environment (Bullard Hall study space) where the experiment was conducted with eight MICA2 motes. The motes were to cover a 4.5 meters by 4.5 meters portion (approximately 20 m^2) of the study space.

Figure 24. Motes Deployed in Bullard Hall Study Space

It was observed that if the motes were switched on near the base station prior to deployment, the time taken for the network to be established was shorter that if they were to be switched on after being deployed. The average time taken for the motes to establish connectivity when placed close to the base station was approximately five to seven minutes while the average time taken of establish connectivity if the motes were deployed then switched on was between twelve and eighteen minutes. Also, observed was that the link quality between pairs of nodes differed considerably. For example, Node 3 may report a link quality of 92% with Node 5, but node 5 reports a link quality of 56% with Node 3. Hence, it was concluded that link asymmetry existed between nodes.

To expedite the experiment, the motes were placed at a distance of one foot to the base station prior to being deployed. The *Surge* program was used to record the performance of the network. The motes were subsequently placed on the tops of the cubicle partitions which were 2.2 meters (seven feet) from the ground with their transmit powers set to 0.01 mW. The *Surge* graphical user interface (GUI) was used to monitor the network status in real time. The figure below was a snap-shot of the network was connectivity was established amongst the motes.



Id	Rec.	Sent	Yield	Level	Duty Cycle	Parent	Quality	Voltage	P1	P2	Min Cut
126											
7	50	94	0.532	1.26	0	3	0.976	3.045	0	2	4.129
6	56	122	0.459	2.661	0	7	0.851	2.967	5	0	2.412
5	63	126	0.5	1.635	0	3	0.988	3.009	4	0	1.451
4	77	124	0.621	2.221	0	3	0.682	3.096	3	2	1.055
3	128	140	0.914	1.164	0	0	0.78	3.059	0	2	4.071
2	110	140	0.786	0.973	0	0	0.996	3.246	0	0	4.145
1	147	147	1	0.98	0	0	0.996	3.067	0	0	3.89
0	162	-2	-81	0	0	126	0	3.142	126	126	0

Figure 25. Snapshot from *Surge* GUI of the sensor network after links were established

After the motes established good connectivity, node three was switched off to simulate node failure. The motes were able to reorganize despite the loss of node three as illustrated in Figure 29 below.

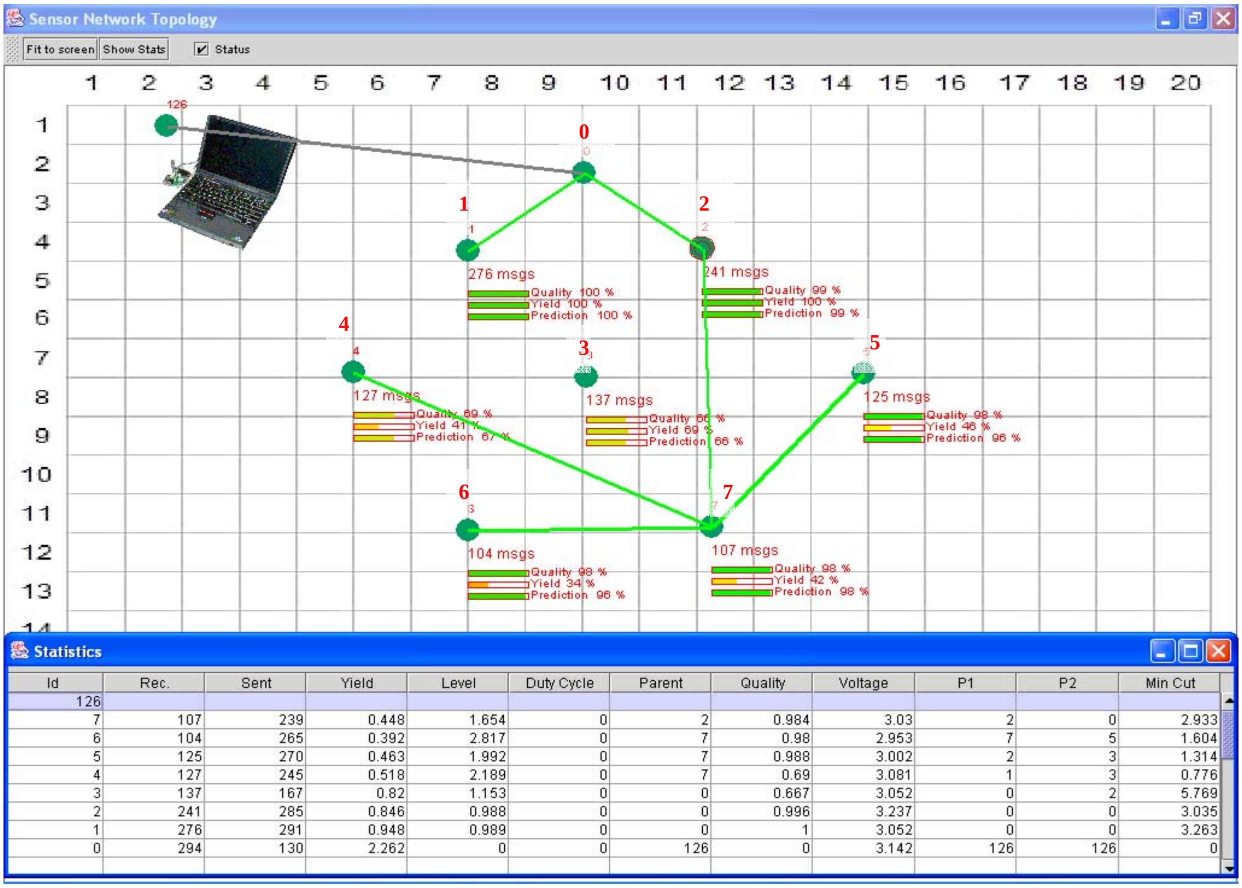


Figure 26. Network with Simulated Node Failure and Rerouting via Node 7.

The definition of each column in the *Surge* GUI is given below:

Column	Definition
ID	The node ID
Rec	Messages Received
Sent	Messages Sent
Yield	# packets received/ # packets sent
Duty Cycle	% time off/ % time on
Parent	Node parent
Quality	# packets sent or received at parent/ # packets sent or received

Voltage	battery voltage of mote
P1	Primary parent
P2	Secondary parent
Min Cut	Minimum number of nodes that need to be removed in order for a mote do disappear from the network.

Table 4. Definition of *Surge-View* Statistics

2. Evaluation Metrics

The metrics used to evaluate the performance of the XMesh routing protocol are packet delivery ratio or yield (as termed in *Surge-View* GUI) and stability.

a. Packet Delivery Ratio

The packet delivery ratio, or yield, is the number of packets received at the sink for a node divided by the number originated. Losing packets reaching the sink wastes energy and resources. The packet delivery ratio describes the loss rate at the routing layer that will affect the maximum throughput the network can support. This metric will characterize completeness and correctness of the routing protocol.

b. Stability

Stability measures the total number of route or parent changes in the network over a period of time, which indicates the stability of the routing topology. A stable routing topology should make higher level operations such as scheduling and aggregation easier.

3. Results

The *Stats* software in *Surge-View* summarized the output of the completed experiment in the table below. These results were collected over a period of 55 minutes.

Node Number	Packets Received	Packets Sent	Success Rate	Parent Changes	Level Changes	Average Level	Battery Voltage
1	284	299	0.950	0	1	0.989	3.052
2	248	292	0.849	0	1	0.988	3.237
3	137	167	0.820	2	3	1.153	3.052
4	127	245	0.518	5	4	2.189	3.081
5	126	276	0.457	6	4	2.000	3.002
6	105	273	0.385	4	4	2.752	2.960
7	114	246	0.463	5	2	1.675	3.030

Table 5. Output from *Stats* Program in *Surge-View*

a. Observations on Packet Delivery Ratio

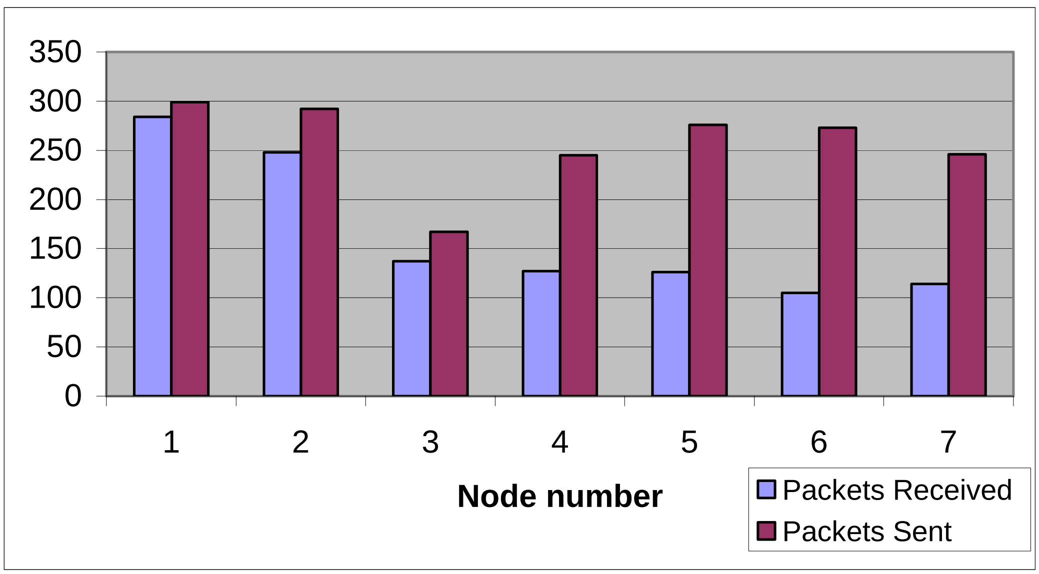


Figure 27. Packet Delivery Ratio

The initial packet delivery ratio was approximately 89% for all nodes. The chart above depicts the packet delivery ratio with node failure on node number three. It was observed that the packet delivery ratio of the motes four, five and seven, which were further away form the base station, had a low packet delivery ratio (approximately 40%), whereas, motes one, two and three, which were closer to the base station, had a high packet delivery ratio (over 80%). This low packet delivery ratio for motes situated farther away can be attributed to a significant amount of packets lost for nodes four five, six and seven when node three was switched off to simulate node failure.

b. Observation on Stability

The stability of the network was determined through the number of parent changes over the experiment. In the chart below, the number of parent changes in motes one and two were zero, whereas motes four, five, six and seven had several parent changes. This can be attributed to the communications link being affected by pedestrian traffic and the asymmetric nature of link quality between nodes. However, it can be concluded that the network was able to react quickly to large changes in link quality and yet be stable when the link is affected by short term fluctuations.

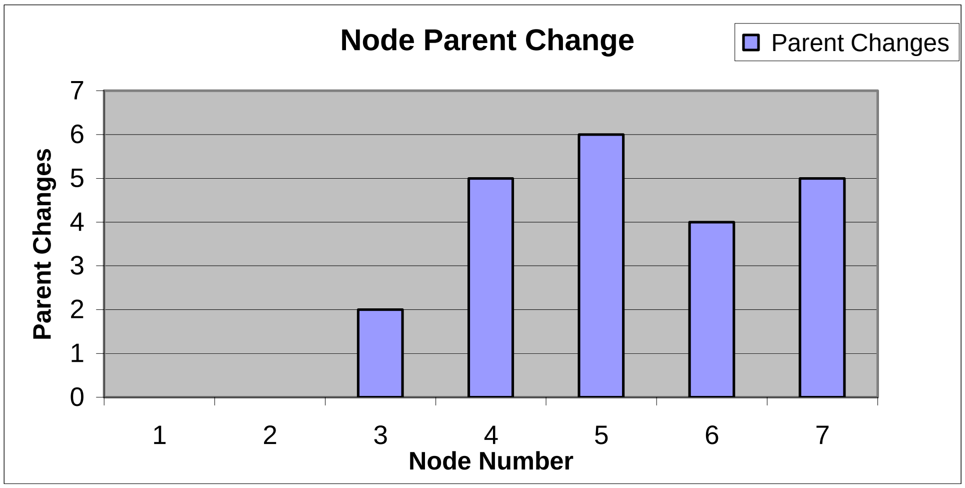


Figure 28. Stability of the Network

F. SUMMARY

This chapter presented the results from the experiments and tests on a network of MICA2 motes. Experiments were conducted to determine the node and network connectivity with varying transmission powers. The relationship between transmission power and node/network lifetime was studied. Network performance was evaluated in terms of packet delivery ratio and stability. Further experimentation on the network performance was omitted due to time constraints. Conclusions based on the experimental results follow in the next chapter, along with recommendations for future work.

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VI. CONCLUSION AND FUTURE WORK

A. CONCLUSION

Wireless sensor networks can be used to monitor dispersed areas, such as environmental and agricultural monitoring; physical things such as structure monitoring and medical diagnostics of human physiology; and the interaction of things with each other and the encompassing space such as warehouse inventory control and HVACS. The evolution of integrated circuit technology, wireless communications and networking will continue to decrease the size of sensors and increase their utility. As such, applications using wireless sensor networks will continue to grow.

In this thesis, the communications characteristics of the MICA2 radio were studied. The key points of the study are as follows:

- The antenna radiation pattern was that of a dipole antenna.
- For any given power setting, there were three regions of communications, the effective, transitional and unreliable regions.
- The size of this "effective region" increases with transmit power. There is also a point beyond which the nodes essentially have no connectivity, termed the "unreliable region". In the "transitional region" between these two points, the average link quality falls off fairly smoothly with some variation.
- The number of motes required for connectivity in a given area is proportional to the amount of transmitted power of the motes.
- It was analyzed that to prolong the network lifetime, a duty cycle must be implemented so that the motes can conserve power by staying asleep. For a 1% duty cycle, the lifetime of a network is approximately 1.1 year.

This thesis also observed the routing protocol of XMesh, using several MICA2 motes deployed in a cluttered indoor environment. The observations are as follows:

- The average time taken for the motes to establish connectivity when placed close to the base station was approximately five to seven minutes while the average time taken to establish connectivity if the motes were deployed before being switched on was between twelve and eighteen minutes.
- When all nodes were working, the network packet delivery ratio was approximately 89% with few parent changes. It was concluded that the network performance was reliable and stable.

- When node three was switched off to simulate node failure, it was observed that there was significant packet loss from the nodes situated farther away from the base station. Node parent changes also increased during this period. However, when the routes were reestablished, the packet delivery ratio increased and parent changes decreased.

It can be concluded that the effects of node failure did not adversely affect the routing protocol in XMesh as the network was able to reconfigure itself and adapt to the change.

B. FUTURE WORK

This thesis surveyed several routing protocols. To evaluate the performance of XMesh further, other routing protocols can be implemented on the Crossbow MICA2 motes and their performance compared with XMesh in a variety of environmental conditions.

As there were only eight MICA2 motes with which to experiment, this thesis was not able to evaluate the scalability of the routing protocol. It is recommended that similar experiments be conducted with thirty or forty nodes, beginning with several motes and slowly introducing more motes to see the effects on the network.

It is also recommended also to study of the maximum stable throughput of the network [41, 42]. This is the maximum amount of traffic per unit time (measured in bit per second) that can be injected into the network from all sources while the size of the queue at any network node is bounded. Coupled with the available battery energy and the efficiency with which the packets are converted to RF power for transmission, it will determine the number of motes required in an area based on the amount of information that is required to be routed.

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