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**A Two-Hop Energy-Efficient Mesh Protocol
for Wireless Sensor Networks**

by

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**A Thesis Submitted to the
Faculty of Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree of
Master of Applied Science**

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Abstract

Wireless sensor networks are important for a number of strategic applications such as coordinated target detection, surveillance and localization. The stringent constraint on energy resources is one of the most significant challenges. In this thesis, we develop a novel energy-efficient routing protocol called THEEM (Two-Hop Energy-Efficient Mesh) for wireless sensor networks. In the THEEM protocol, a two-hop scheme and a centralized mesh (cluster) formation method are employed along with other design innovations, such as the concepts of mesh layer/column, power-aware mesh-head assignment and a low-energy media access protocol, to achieve energy efficiency. This protocol reduces energy consumption quite significantly and thus prolongs the longevity of a sensor network. In the meantime, it increases network data throughput. Moreover, equal energy dissipation among all sensor nodes in a network is achieved. Simulation results show that the THEEM protocol performs much better in terms of all the above criteria when compared with other wireless sensor network routing protocols.

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Chapter 1

Introduction

In recent years, the advance in embedded processors, integrated memory and radio technology has led to the deployment of small and cheap sensor nodes which are able to perform relatively intensive computation and wireless communication. With these sensors, very powerful and versatile wireless sensor networks can be created and used in situations where traditional wired networks are not suitable or fail. These sensor networks can potentially revolutionize information gathering and processing in many areas. Some of those interesting and diverse applications are: tracking and surveillance of borders and battlefields [1]; monitoring forest fire, disaster sites, oceans and precision agriculture; and monitoring traffic density and road conditions. Among other applications are management of complex physical systems like airplane wings, monitoring remote ecosystems and endangered species, and management of security and medical systems [2] [3], etc.

The following are two examples that wireless sensor networks are currently used in the real world:

- US armed forces scattered hundreds of sensor devices in the latest war in Afghanistan [4], with their function being to track the movement of enemy's vehicles. (These sensor devices are called motes.)
- Wireless sensor devices have been used in NASA's interplanetary missions of exploring the Mars as well as in a number of scientific experiments. The information

gathered by these sensor networks will help provide planetary information such as climate history, atmospheric content variations, soil toxicity to humans, and the presence of water [5].

Many communication protocols have been proposed for wireless sensor networks [6-14], among them the frequently cited ones are: Power-Efficient Gathering in Sensor Information System (PEGASIS) [7], Minimum Transmission Energy (MTE) routing [12,101], Low-Energy Adaptive Clustering Hierarchy (LEACH) [6], Threshold sensitive Energy Efficient sensor Network protocol (TEEN) [11] and Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network protocol (APTEEN) [10]. The main idea of PEGASIS is that nodes form a chain so that each node communicates to its adjacent neighbors. In theory, PEGASIS [7] minimizes energy dissipation for data transmission, but time delay is large. When the distance between two successive nodes along the chain is large, these nodes will drain out their energy and die quickly, which in turn causes neighboring nodes to die along the fixed chain and shortens network lifetime. In addition, the chain-based binary (using CDMA capable sensor nodes) and the three-level (without CDMA capable sensor nodes) approaches in PEGASIS are difficult to implement in practice. In MTE routing, intermediate nodes are chosen such that the sum of squared distances is minimized [12]. MTE routing aims to minimize transmitting energy along the route from nodes to the base station, but the data throughput is low; and there is no guarantee for balanced energy dissipation among the nodes. LEACH [6] is a clustering-based protocol that utilizes randomized rotation of local cluster-heads to evenly distribute the energy load among the sensors in the network. It achieves energy efficiency with the penalty of large cluster set-up overhead, and it sometimes can not ensure the coverage of the entire monitored area (discussed in Chapter 4). The cluster

formations in TEEN [11] and APTEEN [10] are based on the LEACH protocol and hence have the same drawbacks as LEACH.

In this thesis, we develop a novel two-hop energy-efficient routing protocol (THEEM) for wireless sensor networks. This protocol overcomes the drawbacks mentioned above and, also, achieves a better performance than the above protocols.

In this chapter, we first introduce the basic components of wireless sensor nodes and the basic idea of wireless sensor networks. Then we present design challenges and potential solutions.

1.1 Wireless Sensor Networks

1.1.1 Wireless Sensor Nodes

Figure 1.1: Functional component of a typical wireless sensor node [15]

A sensor node is any device that maps a physical quantity from the environment to a quantitative measurement [6]. Figure 1.1 gives a schematic diagram of the functional components of a typical wireless sensor node. A transducer unit converts the sensed analog signals to digital signals; a control unit receives digital input from the sensing unit and performs protocol operations. The control unit contains memory units to save data, an Arithmetic and Logic Unit (ALU) to do calculation, comparison and other data manipulation, a timer unit to schedule data transmission, a protocol unit to implement the network protocol functions, and finally a CPU to control all the above units [15]. A radio unit transmits/receives the packets of sensed data over the wireless link. A battery unit is the power source of the entire sensor node.

Figure 1.2 lists some sensor nodes. The node could have one or more sensors. Examples of such sensors include seismic geophones, infrared dipoles and electrets microphones for acoustic sensing.

Figure 1.2: Modern sensor nodes [16]

1.1.2 Wireless Sensor Networks (WSN)

Before describing the characteristics of wireless sensor networks, we have a brief introduction to related conventional wireless network models: mobile ad hoc networks, cellular networks, and short range wireless local-area networks [13].

A mobile ad hoc network (MANET) is a peer-to-peer network which usually consists of tens to hundreds of communicating nodes that are able to cover ranges of up to hundreds of meters. Each node is envisioned as a personal information appliance such as a personal digital assistant (PDA) outfitted with a fairly sophisticated radio transceiver. A MANET usually aims to form and maintain a connected multi-hop network capable of transporting multimedia traffic between nodes and is designed to provide good throughput/delay characteristics in the face of high node mobility. Although the nodes are portable battery-powered devices, energy consumption in the system is of secondary importance, since each device is always attached to a person, and presumably the depleted battery will be replaced when needed [13].

A cellular network is a vast network consisting of both stationary and mobile nodes. The stationary nodes, or base stations, are connected to a sub-network with a wired backbone, forming a fixed infrastructure. Mobile nodes greatly outnumber stationary nodes, which are usually situated quite sparsely. The issue of organization is only encountered in terms of cell-to-cell handoffs as the mobile nodes navigate the region. Each mobile node is only one hop away from the closest base station. The primary goal here is to provide high QoS, along with high bandwidth efficiency [13].

Bluetooth [17] is a short-range wireless networking system intended to replace the cable between electronic consumer devices and provide RF connection between them. The

Bluetooth topology is a star network where a master node is able to have up to seven slave nodes attached to it to form a piconet¹. Each piconet uses a centrally assigned time-division multiple access (TDMA) schedule and frequency-hopping pattern. Another short-range commercial system under development is HomeRF [18]. The networking model is based on the IEEE 802.11 standard. The system is able to handle single-hop ad hoc networks. The radio is a frequency-hopping module. Channel access is possible under TDMA and carrier-sense multiple access (CSMA) modes [13].

In contrast to all the above networks, a wireless sensor network potentially comprises hundreds to thousands of nodes. These nodes are generally stationary after deployment, with the exception of a very small number of mobile sensor nodes. Each node senses the environment and sends a high-level description of events to a distant base station, through which an end-user can access the information. An example is shown in Figure 1.3.

Figure 1.3: A wireless sensor network for monitoring the movement of vehicles.

¹ Piconet –A collection of slave devices operates together with one common Master. All devices on a Piconet follow the frequency hopping sequence and timing of the Master

In general, a wireless sensor network is a network of densely distributed sensors over a physical area of interest, such as a battlefield, far away from the base station, rather than a big, centered multifunctional sensor system. The reasons are as follows. In free space, electromagnetic waves decay in intensity with the square of distance; in other media, they are subject to absorption and scattering effects that can induce even steeper declines in intensity with distance [19]. Many media are also dispersive (such as via multi-path or low-pass filtering effects), so a distant sensor requires such costly operations as de-convolution (channel estimation and inversion) to partially undo the dispersion [20]. Besides, many obstructions render electromagnetic sensor useless. Regardless of the size of the sensor array, objects behind walls or under dense foliage cannot be detected. Thus, if the system is to detect objects reliably, it has to be distributed [19]. In addition, to obtain a good estimate of any particular feature, we need either a long set of independent observations or high Signal-to-Noise Ratio (SNR). In a short detection range, the probability that the environment is essentially homogeneous is enhanced, reducing the number of environmental features. Also, higher SNR is obtained at short range. Thus, it is usually desired to have densely distributed sensors in order to achieve better performance.

In a wireless sensor network, sensed data are normally not transferred directly to the base station over the network; instead, the data are aggregated² in some nodes before being sent to the base station since transmission of raw data is very costly in terms of energy. For example, the energy cost of transmitting 1 Kb data to 100 meters away is approximately 3 Joules; while a general-purpose processor with 100 MIPS/W power could efficiently execute 3 million instructions for the same amount of energy [19]. In addition, aggregating the data of individual nodes allows users to accurately and reliably monitor an environment [6].

² Aggregation- An operation which summarizes current sensor values in some or all of a sensor network

Deploying hundreds or thousands of nodes in a wireless sensor network brings new benefits into sensing applications, such as extended range of sensing, fault-tolerance, improved accuracy and lower cost.

The traffic in wireless sensor networks will likely have statistical properties, which are unlike the multimedia data streams of conventional wireless networks. Although exact sensor data traffic properties are not known yet, it is clear that, due to the nature of the observed phenomena, the required bandwidth for sensor data will be low, in the order of 1–100 kb/s [19].

1.1.3 Design Analysis for WSN

For conventional wireless networks, mobility management and failure recovery are the most important in protocol development in order to achieve high system performance [13], however, the main challenge of wireless sensor networks design is to have a long network lifetime since battery-powered nodes that operate normally in inhospitable, hostile or inaccessible regions are expected to perform sensing and communication with no continual maintenance and battery replenishment. Therefore, the overall performance of a WSN becomes highly dependent on the energy efficiency of the network. As such, all the aspects of the design, from the sensor module to the hardware and protocols, should be energy-efficient.

Besides the strict requirement on energy efficiency, a well designed wireless sensor network should have high QoS and short data delay, as well as the ability to handle mobility of nodes. In addition, protocols need be robust to node failure in order to maximize network utilization. In other words, the protocols should be fault-tolerant such that the loss of a small

number of nodes does not greatly affect the overall network performance. It is also desired that the protocols should be scalable such that it does not require significant overhead to incorporate new nodes into an existing network.

Generally, a wireless sensor network has four protocol layers over the communication channel. The first layer is the physical layer, which provides mechanical, electrical, functional, and procedural characteristics to establish, maintain, and release physical connections (e.g., data circuits) between data link entities [21]. In the design of this layer, the major concerns are to manufacture low energy consumption components and to use good behavior power source. On the aspect of the power source, since a battery undergoing pulsed discharge has a greater capacity than an identical battery undergoing a constant discharge, the use of the charge recovery effect has been proposed as a method of extending the battery life of portable communication devices [22-26]. So, wireless sensor networks having the low duty cycle and bursty communication characteristics can benefit from the usage of the charge recovery effect battery. In practice, of course, taking advantage of the charge recovery effect means that the protocol should activate high-power dissipation components (e.g., the transceiver) in infrequent burst (result in a low duty cycle of operation) [21]. Data link layer protocol carries out this function.

The data link layer, or media access control (MAC) layer, is the second layer in wireless sensor networks. This layer deals with data transfer between network and physical layer. It also maintains the neighborhood information and controls the power and error. In a wireless sensor network, data transmission/receiving consumes most of the energy [19] and idle listening of nodes is the main source of wasting energy³ [14] [27]; therefore, the network

³ Many measurements have shown that idle listening consumes 50 ~100% of the energy required for receiving [14]. Stemm and Katz measure that the idle:receive:send ratios are 1:1.05:1.4 [30]

should be designed so that the radio is off as much of the time as possible and transmits only at the minimum required level. So, a node's MAC address in a network should include some variant of time division multiple access (TDMA). To lower the latency in the network, simultaneous data transfer is needed. As a result, CDMA protocol is usually applied in the design as well.

The third layer is the network layer. Energy-efficient routing protocol design is usually considered in this layer. Since energy dissipation in data transfer is inversely proportional to the distance between the nodes [28], short-range hop-by-hop communication to the base station is preferred to save more energy. Such multi-hop communication also provides a form of communication diversity in helping communicate around obstacles [8]. In addition, the use of multi-hop can also be exploited to improve detection performance since intermediate nodes along the route can perform data aggregation and make local decisions before relaying the data to the base station [29]. This prevents a bottleneck at the base station.

The highest layer of wireless sensor networks is the application layer, where data sensing and processing are executed. Energy saving can be acquired in the design of this layer by using data fusion, also called data aggregation, which combines data from different local sensors to eliminate redundant information.

In this thesis, our design focuses on the protocols in the second layer (MAC layer) and the third layer (network layer). We make use of the idea of data fusion in the application layer. The design of the application layer and physical layer is beyond the scope of this thesis.

1.1.4 Solution — The THEEM Protocol

We have designed and implemented a Two-Hop Energy-Efficient Mesh protocol (THEEM) for wireless sensor networks that achieves high energy-efficiency, high QoS, low latency, and excellent equilibrium of energy dissipation.

Usually, the end-user only requires a high-level description of events occurring in the environment the nodes are sensing. Correlation is strong among data signals from nodes that are close to each other [6]. Therefore, THEEM employs a hierarchical clustering architecture, where sensed data from nodes in the same cluster (we called it mesh) are fused before being sent out in order to reduce the size of data. As a benefit, energy needed for data transmission is saved. Another advantage of the hierarchical cluster topology is its good scalability and simplicity in routing data [21].

The fused data of a mesh is transmitted out via the mesh-head. One of sensor nodes in a mesh must take on the role as a mesh-head. If the mesh-head were fixed, the mesh-head node would use up its limited energy quickly and die, ending the life of the entire mesh. To avoid this situation, THEEM employs a scheme to rotate the mesh-head role among all the nodes in the network to evenly distribute the energy load. The rotation follows a power-aware rule, that is, the node having the most residual energy becomes the mesh-head in the next round.

Once meshes have been formed, the nodes should communicate their data to the mesh-head node in an energy-efficient manner. In THEEM, this is accomplished by using two approaches. First, a TDMA/CDMA hybrid protocol is applied in the MAC layer. The TDMA protocol allows nodes to shut down some internal components and to enter a sleep state when they are not transmitting data in order to save energy. Also, using TDMA avoids collisions of data within the same mesh and hence eliminates the intra-mesh interference. Nodes in each

mesh are assigned a unique CDMA code to prevent the inter-mesh interference. Secondly, a two-hop scheme is developed and used in the network layer. The two-hop scheme further shortens the distance over which data needs to be transmitted in the mesh and thus reduces the energy that mesh-head nodes would have consumed in receiving and fusing the data from the nodes.

THEEM uses a centralized method to form meshes. This ensures the monitoring coverage and eliminates the set-up overhead after the mesh formation is completed.

In summary, THEEM uses the following techniques to achieve its excellent performance:

- Two-hop scheme in the mesh
- Centralized mesh formation
- Low-energy media access protocol (C/TDMA)
- Local data processing, such as data fusion or compression
- Power-aware mesh-head assignment

The two-hop scheme saves energy by avoiding the single long-distance data transfer from the nodes to the mesh-head in a mesh. The centralized mesh formation assures the monitoring coverage and increases the network throughput by eliminating the set-up overhead. Using the C/TDMA schedule and implementing low-energy media access reduce the energy dissipation and latency. Local data processing achieves a large energy reduction by performing computation on the correlated data to greatly reduce the amount of data that must be transmitted over long distances. Finally, power-aware mesh-head assignment ensures equilibrium of energy dissipation among nodes.

We compare THEEM with two well-known protocols, i.e., MTE and PEGASIS. Our simulation results show that THEEM outperforms these two protocols in terms of energy-

efficiency, network throughput, and equilibrium of network energy dissipation.

1.2 Contribution of This Thesis

This thesis develops a new energy-efficient communication protocol for wireless sensor networks. Three novel design innovations – the centralized mesh formation and power aware mesh-head assignment, the two-hop scheme, and the multi-hop scheme – provide a better performance when compared with some other WSN protocols.

The centralized mesh formation and power aware mesh-head assignment minimize the communication overhead used in cluster formation at the beginning of each round; provide the uniform monitoring coverage over the entire surveillance area; and most importantly, ensure a more balanced energy dissipation among nodes.

The introduced two-hop scheme is a novel local data delivery protocol that can further reduce the energy dissipated in the nodes (especially for the mesh-head nodes) and hence prolong the network lifetime. Simulation results (in Appendix B) show that the two-hop scheme achieves much higher energy-efficient performance even when being used independently in a flat topology. This scheme can be extended to other types of wireless network protocols. For example, the two-hop scheme may be applied to Bluetooth and HomeRF applications to extend their scales in terms of the number of slave nodes and the connection range.

The multi-hop scheme employs the concepts of mesh layer and mesh column to organize a more efficient data transfer routing in order to achieve a higher network throughput and a lower data delay.

1.3 Thesis Structure

This thesis begins with a description of general telecommunication technologies related to wireless sensor networks in Chapter 2, including error control techniques and media access control (MAC). Chapter 2 also describes design challenges of wireless sensor networks and corresponding technical approaches (data fusion, power level control, GPS, and time synchronization). Chapter 3 introduces related work on wireless sensor networks protocols. The development motivation, the operation and analysis of THEEM are discussed in Chapter 4. Chapter 5 presents the simulation models and analytic and simulation results of our research. Chapter 6 concludes and outlines possible directions for future research.

Chapter 2

Background

2.1 Related Technologies

Wireless sensor networks are to detect signals in the environments and transfer the signals to the end user (the base station) via wireless communication channels. Some detection algorithms can be found in [31], [32], and [33]. The detail of these detection algorithms is beyond the scope of this thesis. Here we introduce some telecommunication technologies that have been used in wireless sensor networks for digital signal transfer.

2.1.1 Error Control Techniques

The wireless channel is error-prone due to factors such as interference, limited bandwidth, and radio propagation loss as well as data collisions. To improve the reliability of signal communication, error control techniques are employed. Generally, error control techniques involve inserting carefully controlled redundancy into the transmitted data, and exploiting this redundancy at the receiver to detect and/or correct transmission error [34]. Typical error control systems contain a source encoder, to encode the source data, followed by a channel encoder, to add controlled redundancy to the source data. The channel-coded data are sent over a channel, where noise is added to the stream. The channel decoder at the receiver side produces an estimate of the channel-coded stream and sends the decoded stream to the source decoder, which extracts the source data. The system is depicted in Figure 2-1.

Figure 2-1: Block diagram of an error control system

There are two common types of channel coders, block coders and convolutional coders. The block coders take a block of size k and produce a coded block of size n that depends only on the information in that block. This produces an (n, k) block code, where there are 2^k possible input blocks and 2^n possible output blocks. Standard array decoding and syndrome decoding are used to decode the block coded stream [34]. Some examples of the block codes are Hamming Codes, Cyclic Redundancy Check (CRC) codes, Bose-Chaudhuri-Hocqunghem (BCH) Codes, Reed-Solomon Codes, and Concatenated Codes. As opposed to the block codes, which operate on finite-length blocks of data bits, a convolutional encoder operates on a continuous sequence of data symbols. The convolutional coders also take blocks of size k as input and produce a coded block of size n . However, the output symbol is a function of the input block and a parameter m , where m refers to the memory requirement of the encoder and typically $m \leq 8$. Convolutional encoders are normally implemented using shift registers. Trellis Coded Modulation (TCM) involves the combination of convolutional coding with spectrally efficient M-ary modulation; it improves data communication performance without increasing the transmitted energy per bit (which is very suitable for energy constrained wireless sensor nodes) and without reducing the data transmission rate as

well as without increasing the bandwidth [34].

The Maximum Likelihood Sequence Estimation (MLSE) is used as the decoding method for the convolutional codes. The Viterbi algorithm (minimizes the probability of a data word error) and the Maximum a posteriori (MAP) algorithm (minimizes the probability of a data bit error) are the two main approaches to decoding the convolutional codes [34].

2.1.2 Media Access Control (MAC) Protocols

Figure 2-2: The concepts of TDMA and CDMA.

MAC protocols are used to create predefined ways for multiple users to share the channel [6]. There are two fundamentally different ways to share the wireless channel bandwidth among different nodes: fixed-assignment channel-access methods and random-access methods. Since random-access methods (e.g., IEEE 802.11 and carrier-sense multiple access (CSMA)) are a contention-based scheme, where nodes that have information to transmit must

try to obtain bandwidth, they suffer from possible data collisions, in which situation the nodes' energy will be wasted on retransmitting the incorrectly received data. This is not good for designing an energy-efficient wireless sensor network. So, to avoid data collision and to reduce the non-data overhead (causes longer radio electronics turn on time) in a wireless sensor network, we design fixed-assignment MAC protocols in this thesis.

Time-division multiple access (TDMA), code-division multiple access (CDMA), frequency-division multiple access (FDMA) and space-division multiple access (SDMA) belong to the fixed-assignment MAC protocols. We describe TDMA and CDMA since we only use these two protocols in our design.

2.1.2.1 Time-Division Multiple Access (TDMA)

In TDMA, time is broken into frames, and each node is given the entire bandwidth for a certain time-slot within the frame to transmit its data (see Figure 2-2a). During this time-slot, no other nodes should access the channel, so there are no collisions and the throughput is equal to the total data transmitted by each node. Assume there are N nodes that have data to transmit and the time for each frame is t_f and the channel bandwidth is B_w . Each node will get $t_s = \frac{t_f}{N}$ seconds to transmit data. Assuming a 1 bit/sec/Hz signaling scheme, each node can

transmit $B_w t_s = B_w \frac{t_f}{N}$ bits per frame or $R_b = \frac{B_w}{N}$ bps [6].

Transmission occurs in bursts in TDMA. This reduces energy dissipation compared to a protocol where the transmission is continuous because the transmitter hardware (e.g., the phase-locked loops for frequency generation, and the power amplifier) can be turned off when the node is not transmitting. In addition, this is a simple protocol to implement in the

radio hardware. However, this protocol requires that some nodes have knowledge of all the transmitting nodes to create a schedule, and if the number of nodes that need to transmit data is variable, the schedule must be update frequently, adding significant overhead to the protocol. In THEEM, we let the base station having knowledge of all the nodes carry out this particular duty to effectively eliminate the overhead that need to reschedule the transmission. Using TDMA also requires that all nodes be time-synchronized and requires guard slots (extra bits) to separate users [28]. We will discuss time-synchronization technique in section 2.2.

2.1.2.2 Code-Division Multiple Access (CDMA)

Wireless sensor networks usually use direct-sequence spread spectrum (DS-SS) to implement the CDMA⁴. Bandwidth spreading in the way of direct modulating a data-modulated carrier signal by a wideband spreading signal or code is called direct-sequence spread spectrum. In a CDMA system, different DS-SS codes are selected and assigned to the nodes, and multiple nodes share the same frequency and can transmit their data at the same time, as shown in Figure 2-2b.

In the DS-SS method, the data-modulated carrier signal is XORed with a pseudorandom sequence whose bandwidth is much greater than that of the carrier signal itself, thereby spreading its bandwidth [35][36]. The spread signal with wide bandwidth is less susceptible to the noise and interference. Figure 2-3 illustrates the spreading done on the data-modulated carrier signal $s(t)$ by the code signal $c(t)$ resulting in the spreading signal, $m(t)$, to be transmitted [37]. That is,

⁴ It is difficult to use frequency hopping system on a practical basis unless a super-fast synthesizer is employed.

$$m(t) = s(t) \otimes c(t) \quad (2.1)$$

The received spreading signal is despread by correlating it with a local pseudorandom sequence identical to and in synchronization with the sequence used to spread the carrier signal at the transmitting end.

Figure 2-3: Concept of direct sequence spread spectrum [37]

As more nodes transmit data using their unique spreading code, the signal-to-noise ratio (SNR) of each transmission is reduced. Therefore, the performance degrades as the number of nodes increased [28]. The SNR will depend on the amount of spreading and the number of the interfering signals. The number of simultaneous transmission in a CDMA system is [34]:

$$N = \eta_b c_d \times \frac{B_w}{R_b \left(\frac{E_b}{I_o} \right)} \quad (2.2)$$

where η_b is the bandwidth efficiency factor, c_d is the capacity degradation factor due to imperfect automatic gain control, B_w is the total bandwidth, R_b is the information rate, and $\frac{E_b}{I_o}$ is the bit energy to interference ratio required to achieve an acceptable probability of error. Assuming ideal conditions, in which $\eta_b=1$ and $c_d=1$, this equation simplifies to:

$$N = \frac{B_w}{R_b(\frac{E_b}{I_o})} \quad (2.3)$$

The minimum SNR required ($\frac{E_b}{I_o}=1=0$ dB) is achieved when the minimum spreading of the data is performed. In this case, $R_b=\frac{B_w}{N}$. Therefore, under ideal conditions with minimum spreading, each of the N users can transmit at the same bit-rate as in the TDMA [6].

2.2 WSN Design Challenges and Technical Approaches

In Chapter 1 we discussed design considerations on the communication layers. We will design the THEEM protocol at these layers. Here, we want to describe some other design challenges that have been pointed out and implemented by researchers in the past years.

Apart from the general design challenges of wireless network (limited channel bandwidth, electromagnetic wave propagation, error-prone channel, and mobile nodes [6]), the design of wireless sensor networks faces the presence of the limited node energy and the ad hoc nature of deployment. Researchers have implemented data fusion and power control algorithms to conserve node energy. And localization methods have been applied in wireless sensor networks to acquire the location of nodes. Finally, ensuring time synchronization in wireless sensor networks guarantees the performance.

2.2.1 Data Fusion

Data fusion, also called data aggregation, has been researched for years and has been discussed in different contexts such as large scale databases [38], active networks [39], and wireless sensor networks applications [8, 40-46].

Sensor data are different from the data associated with traditional wireless networks in that it is not the actual data itself that is important; rather, the analysis of the data, which allows an end-user to determine something about the environment that is being monitored, is the important result of a sensor network [6]. Therefore, automated methods of combining or aggregating the data into a small set of meaningful information are required [45] [31]. For example, sensors may collect temperature, pressure, and humidity signals from the field. We might be interested in finding the maximum or minimum values of such parameters. Data fusion can be used here to combine one or more packets to produce a same-size resultant packet.

In wireless sensor networks, data fusion performs in-network fusion of the data packets in an attempt to minimize the number and size of data transmissions and thus save node energy [8] [46] [41]. Such fusion can be performed when the data from different nodes are highly correlated. Using data fusion techniques can save more than half of the energy spent in communication [47] [48].

Data Funneling routing algorithm is one of the data fusion algorithms [47]. It allows the network to considerably reduce the amount of energy spent on communication setup and control. This is achieved by sending only one data stream from a group of sensors to the destination instead of having an individual data stream from each sensor to the destination. Data Funneling algorithm works as follows [47]:

Figure 2-4: Data Funneling algorithm. (a) Control node, target region, directional flood and border nodes in Data Funneling. (b) Funneling of data within the region and reporting back to the controller.

The interest packets [47] are sent from the controller to the region using directional flooding as shown in Figure 2-4a. By receiving the interest packet, nodes will know if they are in the target region. Nodes in the target region compute the routing to send their data to the border nodes. The function used to compute the routing is similar to the function used to compute the probabilities for selecting different paths in probabilistic routing [49]. As data flows within the region from the nodes to the border nodes, it can be aggregated along the way as shown in Figure 2-4b. In the end, all the data to be sent out by all the nodes within the region will be collated at one border node and sent back to the controller in a single packet.

Data fusion theory can be deduced as follows:

In a conventional sensor network, all the data X are transmitted to the base station, where they are processed (fused) to receive the data $f(X)$. The function f can sometimes be broken

up into several smaller functions $f_1, f_2, \dots, f_n$ that operate on subsets of the data $X_1, X_2, \dots, X_n$ such that:

$$f(X) \approx g(f_1(X_1), f_2(X_2), \dots, f_n(X_n)) \quad (2.4)$$

The ability to break the function in this manner leads to the possibility of the sensor nodes performing local computation on a subset of the data. This has the potential to greatly reduce the amount of information that needs to be transmitted to an end-user [6].

One method of fusing data is called beamforming [50]. Beamforming combines signal from multiple sensor as follows [6]:

$$y[n] = \sum_{i=1}^N \sum_{l=1}^L w_i[l] s_i[n-l] \quad (2.5)$$

where $s_i[n]$ is the signal from the i^{th} sensor, $w_i[n]$ is the weighting filter for the i^{th} signal, N is the total number of sensors whose signals are being beamformed, and L is the number of taps in the filter. This algorithm is depicted in Figure 2-5. The weighting filters are chosen to

Figure 2-5: Block diagram of the beamforming algorithm [6]

satisfy an optimization criterion, such as minimizing mean squared error (MSE) or maximizing signal-to-noise ratio (SNR) [6]. Various algorithms, such as least mean squared

(LMS) error approach and the maximum power beamforming algorithm [50], have been developed to determine good weighting filters.

2.2.2 Power Level Control

In a wireless, multi-hop sensor network, choosing transmission power levels has an important impact on energy efficiency and network lifetime. Besides, power control, where each node sets its transmit power to ensure the same amount of power at the receiving node, is especially important in CDMA system. Since if all nodes transmit at the same power, signal from nodes close to the receiving node will drown out signals from nodes further away from the receiving node (near-far problem).

There are many types of node's power control algorithms [51] [52] [53] [54] [55]. Here we introduce four algorithms out of them [51].

1. Threshold in number of neighbors:

The "local mean algorithm" (LMA) works in the following way: All nodes start with the same initial transmission power (TransPwr). Every node periodically broadcasts a life message (LifeMsg) including its unique identity. All the other nodes, which receive such a LifeMsg, reply with a life acknowledge message (LifeAckMsg) including the address of the LifeMsg sender. Before a node issues the next LifeMsg it counts the number of LifeAckMsgs received (NodeResp). If NodeResp is less than a minimum threshold (NodeMinThresh), the node increases its transmission power by a certain factor A_{inc} for every neighbor that is missing towards the NodeMinThresh; the transmission power is not increased by more than a factor of B_{max} in a single step. If NodeResp is larger than a maximum threshold (NodeMaxThresh), it decreases its transmission power by a certain factor A_{dec} for every

supernumerary neighbor; the transmission power is not decreased by less than B_{min} in a single step. If NodeResp is between NodeMinThresh and NodeMaxThresh the node does not change its transmission power anymore; it has converged. While this algorithm has a periodic nature, it is important to note that no close synchronization of nodes or global time base is required; the notion of periodicity is a purely local one.

2. Fixed transmission power

In case that the target configuration (i.e., the density and position of nodes) is known, the minimum transmission powers providing a fully connected network is known as well. These values are used as nodes' transmission powers.

3. Global solution with equal transmission power

The Equal Transmission Power (ETP) algorithm assigns a uniform power to all nodes. It chooses the minimal transmission power value that ensures a fully connected network for this particular scenario. To find the minimum transmission power, the following algorithm is used: 1) among the node pairs that are not yet connected, choose the one with the smallest distance, 2) set transmission power of all nodes to a value sufficient to connect these two nodes, 3) check connectivity of the resulting network and when the network is connected, the minimum power level is found; otherwise start from 1). This power value represents the smallest value for a fully connected sensor network with fixed transmission range and it also results in symmetric communication links. This algorithm uses global information and it is not evident how to implement a corresponding local algorithm that achieves the same results.

4. Global solution with diverse transmission power

The global solution with Diverse Transmission Power (DTP) algorithm creates a connected network but does not set all transmission ranges to the same value. Instead it tries

to find a minimum power level for every node individually. The algorithm works in the following way: 1) among the node pairs that are not yet connected, choose the one with the smallest distance, 2) set transmission power of these two nodes to a value sufficient to connect them, 3) check connectivity of the resulting network and when the network is not connected start from 1). This algorithm minimizes the overall transmission power consumption for the entire network, but it may result in asymmetric communication links, e.g., one node can receive data from a far neighbor which uses a higher transmission power, but can not answer directly due to its smaller transmission power. Even though it is possible to construct networks where this algorithm does not find minimum power levels for all nodes (it would be necessary to restrict the search for not connected neighbors to nodes in other connected components), DTP vastly outperforms any other global algorithm.

2.2.3 Localization

One of the localization methods used in wireless sensor networks is global positioning system (GPS).

The GPS signals are actually the signals that carry instantaneous readings of the position and clock of the satellites in view [56]. GPS is composed of 24 satellites. The receivers equipped in nodes receive the GPS signals from satellites and calculate their absolute locations by matching the incoming signals from four satellites with user-generated replica signals and measuring the received phase against the node's clock.

In detail, assume that the node is stationary and that the node's clock is synchronized with the satellite clock. At the instant that the GPS signal is received, the node's local time is recorded. By comparing the local time and the satellite time and position carried by the GPS signal, we can calculate the measured delay caused by the finite speed of light and a range D

to the satellite. Therefore, the receiver's location is somewhere on a sphere of radius D centered at the satellite. Clearly if we were able to perform the same type of measurement with three satellites simultaneously, we could locate the node's position in three dimensions at the intersection of three spheres. However, most nodes' clocks are not perfectly synchronized with satellites, and therefore a fourth ranging measurement is necessary to account for the local clock bias [57].

A GPS receiver has been implemented in 0.5 μm CMOS technology. The estimated power consumption is under 30 mw [57].

Relative location methods without the assistance of GPS have also been implemented [58] [59] [60]. Since one needs to estimate its location with the help of 3 or more beacons with known positions, in wireless sensor networks a very high density of beacons nodes would be needed. To keep the required beacon density and energy low, a preferred method would be to jointly estimate positions of all the non-beacon nodes via a collaborative multilateration⁵ formulation based on criterion such as least-square error minimization [58]. To reduce the significant communication and associated energy cost, a locally distributed iterative multilateration can be used [61], where a node calculates its position and is promoted to be a beacon as soon as enough of its 1-hop neighbors are beacons. With a sufficient beacon density, a small number of successive multilateration steps lead to rapid convergence of location estimates. Another challenge in localization is the estimation of distance between a pair of nodes when the distances are too tiny and radio frequencies not very high. A readily available method would be to use the received signal strength indication (RSSI) provided by the radio [61].

⁵ Multilateration is the fixing of a position by reference to the time difference of arrival of a signal at a collection of sensors.

2.2.4 Time Synchronization

In wireless sensor networks protocol, time synchronization is important to ensure the reliable data collection and transfer. Synchronized time is extensively used in many contexts such as data fusion, TDMA schedules and synchronized sleep periods.

In [62] an approach called post-facto synchronization is described, which is based on unsynchronized node clocks. There, the oscillator frequency disciplines provided by NTP (Network Time Synchronization) with an instantaneous signal sent by a beacon are combined. A so-called “third party” node broadcasts a synchronization beacon to nodes in its transmission range. In [63] a different algorithm is proposed, which is based on calculation of time stamps and transferring these when passed between nodes. The transferred time stamps are compared in the nodes. This requires synchronized local clocks at nodes for the operation.

Recently, a light-weight synchronization algorithm is presented in [64]. The proposed algorithm is able to produce tight, deterministic synchronization to offset and clock drifts with only few message exchanges. It is especially useful in wireless sensor networks which are typically extremely constrained on the available computational power and bandwidth and have some of the most exotic needs for high precision synchronization. The algorithm, called tiny-sync, produces offsets and clock drifts at the micro-second level [64].

In addition, nodes could also be equipped with a global positioning system (GPS) [57] [65] to synchronize them or to be used for back-up and additional synchronization purposes.

Chapter 3

Related Work

In general, up-to-date routing protocols for wireless sensor networks can be classified into two categories: flat routing and clustering routing. All are based on multi-hop approaches.

3.1 Flat Routing in Wireless Sensor Networks

Wireless sensor networks are data centric, and thus do not require routing of data between specific nodes. This leads to the flat routing protocols, in which a route is set up when certain goals (e.g., least transmission energy dissipation or least latency) are achieved.

3.1.1 Power-Efficient Gathering in Sensor Information System (PEGASIS) [7]

In PEGASIS, nodes are organized to form a chain so that each node transmits/receives data to/from a nearby neighbor. This approach distributes the energy load evenly among the sensor nodes in the network and reduces the amount of energy spent for data transmission.

The operation detail is as follows. The chain can either be computed in a centralized manner by the base station and broadcast to all the nodes or be accomplished by the sensor nodes themselves using a greedy algorithm. Since this chain computation is done once, followed by many rounds of data communication, the energy cost is small compared to the energy spent in the data collection phase. The chain constructing process starts with the

furthest node from the base station (select a node randomly if there is a tie). The closest neighbor to this node is the next node on the chain. Successive neighbors are selected in this manner among unvisited nodes (with ties broken arbitrarily) to form the greedy chain. The neighbor distances increase gradually since nodes already on the chain cannot be revisited. Figure 3-1a shows node c_0 connecting to node c_1 , node c_1 connecting to node c_2 , and node c_2 connecting to node c_3 , in that order. When a node dies, the chain is reconstructed in the same manner to bypass the dead node.

Figure 3-1: PEGASIS. (a) Chain construction using the greedy algorithm. (b) Token passing approach.

For gathering data in each round, each node receives data from one neighbor, fuses the data with its own, and transmits to the other neighbor on the chain. Nodes take turns to transmit fused data to the base station (in round i , the node with node number of $i \oplus N$ (N represents the number of nodes) transmits to the base station). Thus, the leader in each round of communication is at a random position on the chain, which is important for nodes to die at random locations. The idea of nodes dying at random places is to make the sensor network robust to failures.

Each round of data collection can be initiated by the base station with a beacon signal which synchronizes all sensor nodes. Since all nodes know their positions on the chain, a time slot approach can be employed for transmitting data. A simply example showing the operation of PEGASIS is in Figure 3-1b. In the current round, node c2 is the leader and there are five time slots for this round. Node c0 passes its data to node c2 in time slot 1. After node c2 receives data from node c1 in time slot 2, node c4 passes its data towards node c2 via node c3. Finally, in the 5th time slot, c2 transmits fused data to the base station. PEGASIS performs data fusion at every node except the end nodes in the chain. Each node fuses its neighbor's data with its own to generate a single packet of the same length and then transmit that to its other neighbor (if it has two neighbors). In the above example, node c0 transmits its data to node c1. Node c1 fuses node c0's data with its own and then transmits to the leader. Then node c4 transmits its data to node c3. Node c3 fuses node c4's data with its own and transmits to the leader. Node c2 waits to receive data from both neighbors and then fuses its data with its neighbors' data, and transmits one message to the base station. Thus, in PEGASIS, each node, except the two end nodes and the leader node, will receive and transmit one data packet in each round and be the leader once every N rounds.

The time delay is quite large, since if there are N nodes in the network, the base station will need N data jumps to acquire all the data from the network. When implementing a PEGASIS scheme, we assume all the sensed data in the entire monitored field are correlated. While for our THEEM protocol, we only assume the sensed data in the mesh are correlated and the data between meshes are not correlated.

3.1.2 Minimum Transmission Energy (MTE) Routing

In this approach, intermediate nodes are chosen such that the sum of squared distances (and hence the transmit energy, assuming a d^2 power loss) is minimized [12]; thus for the configuration shown in Figure 3-2, node A would transmit to node C through node B if and only if [6]:

$$E_{transmit}(d = d_{AB}) + E_{transmit}(d = d_{BC}) < E_{transmit}(d = d_{AC}) \quad (3.1)$$

where $E_{transmit}(d = d_{AB})$, $E_{transmit}(d = d_{BC})$ and $E_{transmit}(d = d_{AC})$ are the transmission energies over the distances of d_{AB} , d_{BC} and d_{AC} , respectively, or, assuming a $\frac{1}{d^2}$ attenuation model,

$$d_{AB}^2 + d_{BC}^2 < d_{AC}^2 \quad (3.2)$$

Figure 3-2: Constructing principle for MTE routing

In MTE routing, each node runs a start-up routine to determine its next-hop neighbor as indicated above, as this minimizes the transmit energy required to get the data to the base station. As nodes run out of energy, the routes need to be recomputed to ensure connectivity with the base station. We also assume all the sensed data in the entire monitored field are correlated for MTE routing.

3.1.3 Direct Diffusion

Directed diffusion [8] is a data-centric dissemination paradigm in that all communication is for named data (data is named using attribute-values). Its application to query dissemination and processing is as follows. A sensing task (query) is disseminated through the sensor network as an interest for named data. The gradients are set up to draw data matching the interest towards the requesting node. Events (data) start flowing towards the requesting node along multiple paths. The sensor network reinforces one, or a small number of these paths to prevent further flooding.

As the authors indicated in [37], this type of information retrieval is well suited only for persistent queries, where requesting nodes are expecting data that satisfy a query for the duration of time. This makes it unsuitable for historical or one-time queries as it is not worth setting up gradients for queries that employ the path only once. But the features of data-centric dissemination, reinforcement-based adaptation to the empirically best path, and in-network (intermediate nodes) data aggregation and caching can enable highly energy-efficient and robust dissemination in dynamic sensor networks, while at the same time minimizing the per-node configuration.

There are two implementations based upon the directed diffusion paradigm [66] [67]. In [66], a Gradient-Based Routing (GBR) is adopted in which the “interested” message records the number of hops taken while being flooded. The difference between a node’s height⁶ and that of its neighbor is considered the gradient on that link. A packet is forwarded on the link with the largest gradient.

⁶ The minimum number of hops from a node to the user is called this node’s height [66].

3.1.4 Sensor Protocols for Information via Negotiation (SPIN)

The SPIN protocol makes use of the property which nearby nodes have similar data and distributes only the data that other nodes don't have, by using a negotiation method as follows.

Nodes running a SPIN communication protocol name their data using high-level data descriptors, called meta-data. SPIN does not specify a format for meta-data; this format is application-specific [9]. For example, sensors that cover disjoint geographic regions may simply use their own unique IDs as meta-data. The meta-data x would then stand for "all the data gathered by sensor x ". The principle formatting meta-data is: if x is the meta-data descriptor for sensor data X , then the size of x in bytes must be shorter than the size of X , for SPIN to be beneficial. If two pieces of actual data are distinguishable, then their corresponding meta-data should be distinguishable. Likewise, two pieces of indistinguishable data should share the same meta-data representation [9].

SPIN nodes use three types of messages to communicate:

- ADV – new data advertisement. When a SPIN node has data to share, it can advertise this fact by transmitting an ADV message containing meta-data.
- REQ – request for data. A SPIN node sends a REQ message when it wishes to receive some actual data.
- DATA – data message. DATA messages contain actual sensor data with a meta-data header.

Because ADV and REQ messages contain only meta-data, they are smaller, and cheaper to send and receive, than their corresponding DATA messages.

Here we describe a simple Handshake Protocol (SPIN-1) [9] for disseminating data

through a lossless network. It works in three stages (ADV-REQ-DATA), with each stage corresponding to one of the messages described above. The protocol starts when a node obtains new data that it is willing to disseminate. It does this by sending an ADV message to its neighbors, naming the new data (ADV stage). Upon receiving an ADV, the neighboring node checks to see whether it has already received or requested the advertised data. If not, it responds by sending an REQ message for the missing data back to the sender (REQ stage). The protocol completes when the initiator of the protocol responds to the REQ with a DATA message, containing the missing data (DATA stage).

This protocol's strength is its simplicity. Each node in the network performs little decision making when it receives new data, and therefore wastes little energy in computation. Furthermore, each node only needs to know about its single-hop network neighbors. The fact that no other topology information is required to run the algorithm has some important consequences. First, SPIN can be run in a completely un-configured network with a small, startup cost to determine nearest neighbors. Second, if the topology of the network changes frequently, these changes only have to travel one hop before the nodes can continue running the algorithm [9]. However, this protocol works proactively and distributes the information all over the network, even when a user does not request any data.

3.1.5 Other Flat Routing Protocols

Rumor Routing [68] is logical compromise between flooding queries and flooding event notifications. The idea is to create paths leading to each event; whereas event flooding creates a network-wide gradient field. In this way, when a query is generated, it can be sent on a random walk until it finds the event path; instead of flooding it throughout the network.

However, rumor routing can not certainly find the event path for its random walk.

Ant Algorithm [69] is based on simple biological “ant” that explores the network and rapidly learns good routings, using a novel variation of reinforcement learning. However, this algorithm can not be used in large-scale wireless sensor networks because the number of ant agents required to achieve good results tends to be very large.

[70], [71], and [72] are other three flat routing protocols for wireless sensor networks.

3.2 Clustering Routing in Wireless Sensor Networks

Similar to a cellular telephone network, sensor nodes in a clustering routing approach send their data to a central cluster-head and the cluster-head then forwards the data to the desired recipient. Clustering enables bandwidth reuse and can thus increase system capacity. It can also increase the throughput of the network.

3.2.1 Low-Energy Adaptive Clustering Hierarchy (LEACH)

LEACH is a clustering-based protocol that tries to evenly distribute the energy load among the network nodes by randomly rotating the cluster-head among the nodes. LEACH uses localized coordination to enable scalability and robustness for dynamic networks, as well as data aggregation to reduce the amount of data that must be transmitted to a base station [73].

In LEACH, clusters are formed by using a distributed algorithm, where nodes make autonomous decisions without any centralized control. The advantages of this approach are that no long-distance communication with the base station is required and distributed cluster formation can be done without knowing the exact location of any of the nodes in the network.

In addition, no global communication is needed to set up the clusters, and nothing is assumed about the current state of any other node during cluster formation.

In detail, the cluster formation algorithm is designed such that nodes are cluster-heads approximately the same amount of time, assuming all the nodes start with the same amount of energy. And the cluster-head nodes are spread throughout the network to get the minimum distance on which the non-cluster-head nodes need to send their data [73]. Once the nodes have elected themselves to be cluster-heads, the cluster-head nodes let all the other nodes in the network know that they have chosen this role for the current round. Each non-cluster-head node determines to which cluster it belongs by choosing the cluster-head that requires the minimum communication energy, based on the received signal strength of the advertisement from each cluster-head. The cluster-heads in LEACH act as local control centers to coordinate data transmissions in their cluster. LEACH makes use of TDMA/CDMA MAC to reduce intra-cluster and inter-cluster collisions. The cluster-head node sets up a TDMA schedule and transmits this schedule to the nodes in the cluster. After the TDMA schedule is known by all nodes in the cluster, data transmission (with DS-SS CDMA code) from each non-cluster-head node to the cluster-head node begins. To reduce energy dissipation, each non-cluster-head node uses power control to set the amount of transmit power based on the received strength of the cluster-head advertisement. Once the cluster-head receives all the data, it fuses the data and sends the resultant data to the base station.

The drawback of LEACH is that this protocol offers no guarantee about the placement and/or number of cluster-head nodes due to its distributed cluster formation algorithm [6]. Therefore, the coverage to the entire monitored area is not guaranteed.

To produce better clusters distribution, the LEACH-C (LEACH-Centralized) protocol is developed [6]. This protocol uses a centralized clustering algorithm and the same steady-state protocol as LEACH. During the set-up phase of LEACH-C, each node sends information about its current location and energy level to the base station. The base station runs an optimization algorithm to determine the clusters for that round. The cluster formed by the base station will in general be better than those formed using the distributed algorithm. In addition to determining good clusters, the base station also ensures that the energy load is evenly distributed among all the nodes. To do this, the base station computes the average node energy, and whichever nodes have energy below this average cannot be cluster-heads for the current round. Using the remaining nodes as possible cluster-heads, the base station runs a simulated annealing algorithm to determine the best nodes to be cluster-heads for the next round and the associated clusters. Once the optimal cluster-heads and associated clusters are found, the base station transmits this information back to all the nodes in the network. This is done by broadcasting a message that contains the cluster-head ID for each node. If a node's cluster-head ID matches its own ID, that node takes on the cluster-head role; otherwise, the node determines its TDMA slot for data transmission and goes to sleep until it is time to transmit data to its cluster-head [6].

LEACH-C still can not ensure the entire monitor coverage since the cluster formation is still based on the density of the distributed nodes.

A fixed cluster protocol, LEACH-F, is also developed to eliminate the set-up overhead at the beginning of each round. In LEACH-F, clusters are created using the centralized cluster formation algorithm developed for LEACH-C. The base station uses simulated annealing to determine optimal clusters and broadcasts the cluster information to the nodes. This

broadcast message includes the cluster ID for each node, from which the nodes determine the TDMA schedule and the order to rotate the cluster-head position. The first node listed in the cluster becomes cluster-head for the first round, the second node listed in the cluster becomes cluster-head for the second round, and so forth. LEACH-F protocol also has its drawback. Using fixed clusters and rotating cluster-head nodes within the cluster may require more transmit power from the nodes, increasing non-cluster-head node energy dissipation and increasing inter-cluster interference.

LEACH-B and LEACH-EM are other two derivatives of LEACH protocol, where the LEACH-B protocol [74] presents a new strategy of cluster heads election and cluster formation and the LEACH-EM protocol [75] modifies LEACH protocol to better suit for Event-Driven Data and Mobile Nodes.

3.2.2 Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN)

Unlike LEACH protocol, which is a proactive network⁷ protocol, a reactive network⁸ protocol called TEEN has been developed. The timeline of TEEN is depicted in Figure 3-3 [11]. In this scheme, at every cluster change time, in addition to the attributes, the cluster-head broadcasts the following messages to its members:

- Hard Threshold (H_T): This is a threshold value for the sensed attribute. It is the absolute value of the attribute beyond which, the node sensing this value must switch on its transmitter and report to its cluster head.

⁷ Proactive Networks: The nodes periodically switch on their sensors and transmitters, sense the environment and transmit the data of interest. They are suited for applications requiring periodic data monitoring.

⁸ Reactive Networks: The nodes react immediately to sudden changes in the value of a sensed attribute beyond a pre-determined threshold value. They are well suited for time critical applications.

- Soft Threshold (S_T): This is a small change in the value of the sensed attribute which triggers the node to switch on its transmitter and transmit.

The nodes sense their environment continuously. The first time a parameter from the attribute set reaches its hard threshold value, the node switches on its transmitter and sends the sensed data. The sensed value is stored in an internal variable in the node, called the sensed value (SV). The nodes will next transmit data in the current cluster period, only when both the following conditions are true:

- The current value of the sensed attribute is greater than the hard threshold.
- The current value of the sensed attribute differs from SV by an amount equal to or greater than the soft threshold.

Whenever a node transmits data, SV is set equal to the current value of the sensed attribute. Thus, the hard threshold tries to reduce the number of transmissions by allowing the nodes to transmit only when the sensed attribute is in the range of interest. The soft threshold further reduces the number of transmissions by eliminating all the transmissions that might have otherwise occurred when there is little or no change in the sensed attribute once the hard threshold is reached. The main features of this scheme are as follows:

- Time critical data reaches the user almost instantaneously. So, this scheme is eminently suited for time critical data sensing applications.
- Message transmission consumes much more energy than data sensing. So, even though the nodes sense continuously, the energy consumption in this scheme can potentially be much less than in the proactive network, because data transmission is done less frequently.

- The soft threshold can be varied, depending on the criticality of the sensed attribute and the target application.
- A smaller value of the soft threshold gives a more accurate picture of the network, at the expense of increased energy consumption. Thus, the user can control the trade-off between energy efficiency and accuracy.
- At every cluster change time, the attributes are broadcast afresh and so, the user can change them as required.

The main drawback of this scheme is that, if the thresholds are not reached, the nodes will never communicate; the user will not get any data from the network at all and will not come to know even if all the nodes die. Thus, this scheme is not well suited for applications where the user needs to get data on a regular basis. Another possible problem with this scheme is that a practical implementation would have to ensure that there are no collisions in the cluster. TDMA scheduling of the nodes can be used to avoid this problem. This will however introduce a delay in the reporting of the time-critical data. CDMA is another possible solution to this problem. This protocol is best suited for time-critical applications such as intrusion and explosion detection.

Figure 3-3: Timeline for TEEN [11]

Figure 3-4: Timeline for APTEEN [10]

3.2.3 Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol (APTEEN)

APTEEN [10] [76] is able to combine the best features of proactive and reactive networks while minimizing their limitations to create a new type of network called a hybrid network. In this network, the nodes not only send data periodically, they also respond to sudden changes in attribute values. This uses the same model as TEEN protocols. In APTEEN once the cluster-heads are decided, in each cluster period, the cluster head first broadcasts the following parameters:

- **Attributes (A):** This is a set of physical parameters about which the user is interested in obtaining data.
- **Thresholds:** This parameter consists of a hard threshold (H_T) and a soft threshold (S_T). H_T is a value of an attribute beyond which a node can be triggered to transmit data. S_T is a small change in the value of an attribute which can trigger a node to transmit data again.

- **Schedule:** This is a TDMA schedule similar to the one used in [6], assigning a slot to each node.
- **Count Time (T_C):** It is the maximum time period between two successive reports sent by a node. It can be a multiple of the TDMA schedule length, and it introduces the proactive component in the protocol.

The nodes sense their environment continuously. However, only those nodes that sense a data value at or beyond the hard threshold transmit. Furthermore, once a node senses a value beyond H_T , it next transmits data only when the current sensed value differs from the previously transmitted value by an amount equal to or greater than the soft threshold S_T . The exception to this rule is that if a node does not send data for a time period equal to T_C , it is forced to sense and transmit the data, irrespective of the sensed value of the attribute [76]. Since nodes near to each other may fall in the same cluster and sense similar data, they may try sending their data simultaneously, leading to collisions between their messages. Hence, a TDMA schedule is used and each node in the cluster is assigned a transmission slot [37], as shown in Figure 3-4 [10]. The main features of this scheme are as follows:

- It combines both proactive and reactive policies. By sending periodic data, it gives the user a complete picture of the network, like a proactive scheme. It also responds immediately to drastic changes, thus making it responsive to time critical situations. It thus behaves as a reactive network.
- It offers a flexibility of allowing the user to set the time interval (T_C) and the threshold values for the attributes.
- Changing the count time as well as the threshold values can control energy consumption.

- The hybrid network can emulate a proactive network or a reactive network, by suitably setting the count time and the threshold values.

The main drawback of this scheme is the additional complexity required to implement the threshold functions and the count time. However, this is a reasonable trade-off.

3.2.4 Other Clustering Routing Protocols

Some other cluster formation algorithms are developed in [77], [78], [79], [80], [81]. Reference [13] addresses a multi-channel MAC protocol. Reference [82] introduces a power aware clustered TDMA protocol. Energy aware routing protocols are discussed in [83], [84] and [85].

Chapter 4

The THEEM Protocol

In previous chapters, we have known that hierarchical cluster based, multi-hop protocols are suitable for wireless sensor networks. Since sensor nodes in wireless sensor networks are usually energy-limited (battery powered) and it is inconvenient or even impossible to replace or recharge node batteries, the optimal design of wireless sensor networks is usually the ones that enhance QoS and energy-efficiency and prolong the network lifetime.

Wireless sensor networks are normally used for the surveillance of events in certain areas. In a monitored area, the critical signal may appear anywhere. Therefore, to fulfill the requirement of high monitoring quality, there should be no any area that is not covered by the network. But due to the variety of deployments, for example, sensors might be dropped by a plane or be placed on the ground manually without using any precise equipment; the distribution of sensors might not be uniform in the monitored area. Sensors also could be damaged by some factors such as bombing, fire or the corrosion of sea water since in many cases wireless sensor networks are used in monitoring rural areas where either the environments are very severe (e.g. seabed, forests or rough mountains) or even perilous (e.g. battlefields). So if the configuration of clusters is only based on the sensor density in the process of network organization, as discussed in section 3.2.1, there will be some “vacant areas” where no cluster is formed because of the sparse distribution of sensor nodes. In this case, the sparsely distributed nodes maybe join adjacent clusters with densely distributed

nodes or lose connectivity to the network, which causes serious QoS issues if the “vacant areas” happen to be critical ones.

However, if we use the centralized organization method to uniformly divide the monitored area into a certain number of clusters (we call them meshes); there will be no “vacant area” because the meshes will cover all the monitored area, no matter how the nodes are distributed. For the sparsely distributed areas of nodes, the mesh will still be forced to form. In the worst case scenario, if there is no live node in a “vacant area”, the base station will know exactly which area is “dead”. Thus, people are able to take appropriate actions such as to redeploy some nodes to the “vacant area” to complement the disconnection. In cases that nodes die out gradually or new nodes move in certain meshes, the base station can also acquire the change of network status from the energy and location information it receives and then re-organize the structure of the meshes accordingly and promptly.

In addition, once the meshes are formed by the centralized organization method, there will be no set-up phase of meshes in the afterwards communication. This eliminates the mesh (cluster) set-up overheads at the beginning of each round and hence improves the energy-efficiency.

To ensure the QoS and prolong the lifetime of the entire sensor network, it is desired that all the nodes in the network use up their energy and die in almost the same time so that the whole area could be replenished by a new set of sensor nodes. But the protocols introduced in section 3.1.1 and 3.1.2 fail to consider this.

Since data communication consumes the majority of energy in a wireless sensor network [13] [19], a more energy-efficient routing protocol results in a longer network lifetime.

Besides a long network lifetime, a good design for wireless sensor networks also requires a low-latency data transfer.

To meet these requirements, we developed a novel protocol called THEEM (Two-Hop Energy-Efficient Mesh) (see Figure 4-1). THEEM is a hybrid mesh-based protocol which contains the concepts of two-hop routing protocol, hierarchical structure, energy-aware assignment of mesh-heads, multi-hop transmission and receiving, and TDMA/CDMA MAC layer protocol. The mesh configuration, the assignment of mesh-head and the computation of the routing protocol are executed by the base station (this is called centralized configuration).

It has the following features:

- centralized formation of meshes, – ensure the monitor coverage and eliminate the overhead of the set-up phase between nodes and from nodes to the base station.
- energy-aware mesh-heads assignment, – further prolong the network lifetime.
- low-energy data transfers, – consume minimal energy dissipation in data transmission/receiving by using a two-hop scheme in the mesh and a multi-hop scheme between meshes.
- least collision of data transmission. – the base station assigns different CDMA codes for different meshes to avoid inter-mesh interference; intra-mesh interferences are resisted by allocating each node to its own TDMA slots in which to transmit and receive data.

4.1 The Operation of THEEM

Figure 4-1: Two-Hop Energy-Efficient Mesh Protocol Architecture. This is the situation where the monitored field is divided into 9 meshes and the base station is located far from the monitored field.

As illustrated in Figure 4-1, in the THEEM protocol, the covered area of the sensor network is divided into a certain number of fixed meshes. In each mesh, a node is chosen by the base station as the mesh-head based on its residual energy at the beginning of each round. The mesh-heads are rotated and the nodes take turn to be the mesh-head. The node that has

the most energy left in the individual mesh is assigned to be the mesh-head for the current round. This ensures uniform dissipation of energy for all the nodes in the network; hence the nodes use up their energy and die almost at the same time in a mesh. So the network will have the longest lifetime.

Inside a mesh, the nodes are relatively close together. So the sensed data are deemed to be correlated and can be processed locally by using data fusion in order to reduce the amount of data. The collected data are transferred as per a two-hop scheme (discussed in detail in 4.2). The novel two-hop scheme presents much better performance than PEGASIS and MTE in terms of energy-efficiency.

A multi-hop scheme is used when transmitting the data from the mesh-head node to the base station. This is because wireless sensor networks are normally composed of hundreds or thousand of sensor nodes and the base stations may be far away from the network. The usage of a multi-hop scheme for the communication among higher level nodes reduces the energy used to transmit data directly to the remote base station and hence prolongs the network longevity. The base station assigns a different CDMA code to each mesh to eliminate interferences between meshes. The working process at the mesh-head level communication is as follows:

- From the farthest mesh layer (layer 3 in Figure 4-1) on, the mesh-head nodes transmit their data to the mesh-head nodes in the adjacent layer (layer 2 in Figure 4-1) simultaneously (that is, the mesh-head nodes in mesh 7, 8, and 9 in Figure 4-1 send out their data at the same time).
- Only mesh-head node in the adjacent layer and in the same mesh column receives the data from its last layer (that is, only the mesh-head node in mesh 4 receives the data

sent out by the mesh-head node in mesh 9 in Figure 4-1). Each mesh-head node uses the last layer's CDMA code to receive the data from the last layer and uses its own CDMA code to transmit all of its data to the next layer. Thus, each node in the network needs only two matched filter correlators, one for receiving and the other for transmitting.

- The data are transferred along the multi-hop routing from one mesh-head node to another in the same mesh column until reach the closest layer. Finally, only the mesh-head nodes in the mesh layers that are closest to the base station (mesh 1, 2, and 3 in Figure 4-1, for example) transmit the data to the base station. The base station receiver needs a bank of matched filter correlators to obtain the data.

Note that the nodes between different meshes are located relatively far away, so the data between the meshes are not likely correlated. Thus we can not apply data fusion to the mesh-head level communication. Instead, each mesh-head node will transfer its own data and the data it received from the mesh-head node of last layer. For example, in Figure 4-1, assume one data packet is k bits, the mesh-head nodes in layer 3 transfer one data packet (k bits) to the mesh-head nodes in layer 2; the mesh-head nodes in layer 2 will transfer $2k$ bits data packets (their own k bits data packet plus k bits data packet they received from layer 3) to the mesh-head nodes in layer 1; and the mesh-head nodes in layer 1 will transfer $3k$ bits data packets (their own k bits data packet plus $2k$ bits data packets they received from layer 2) to the base station.

The operation of THEEM is divided into rounds.

There is a set-up phase to configure the network structure before the communication of the wireless sensor network. After that, each round begins with an assignment phase which is

composed of a start beacon, an energy reporting frame and a control packet. Then following is the long data frames where a certain numbers of data are transferred from the nodes to the mesh-heads and on to the base station, as shown in Figure 4-2.

Figure 4-2: Time-line showing THEEM operation. There is only one Set-up phase during the lifetime of the wireless sensor network.

Figure 4-3: The composition of the set-up phase.

Figure 4-4: The composition of one round.

(a) For the mesh that has the most nodes (assume 30 nodes in this mesh).

(b) For the mesh that has average nodes (assume 20 nodes in this mesh).

Figure 4-5: The composition of one Data Frame

Figure 4-3 shows the composition of the set-up phase. During the set-up phase, the nodes first send out short messages (their location and energy information) directly to the base station. Upon receiving the location and energy information from the nodes, the base station broadcasts control packets to the network via a known radio channel to create working tables for each of the node. All sensor nodes listen to this common channel to receive the control packets from the base station, synchronize their internal clock and update their working tables. The information in the control packet is as follows:

Timing signal — to synchronize all the nodes and to inform the network of the round start time, frame start time, frame numbers and the transmission start time for mesh-head nodes communication,

- ID of each node — to group nodes into different meshes, layers and columns. (Layer 1 is the closest layer to the base station), and to assign individual ID to each node,
- Selection of mesh-head — to assign the mesh-head for the current round,
- CDMA code assignment — to assign different CDMA codes for each mesh and let each node know the CDMA codes of its last layer mesh and its next layer mesh in the same column,
- Distance to the mesh-head — to inform each node the distance to the mesh-head for the current round,
- Hop number of the nodes — to assign the hop that each node should be in according to the computation of the distance from each node to its mesh-head node,
- Slots allocated — to assign TDMA structure for each mesh and allocate individual time slots for each node in which to transmit and receive data.

The structure of one round is composed of the assignment phase and the data frames, as shown in Figure 4-4. At the beginning of each round, in the assignment phase, the base station first broadcasts a start beacon informing the network the start of the current round. Then in the energy reporting frame, just like a normal data frame, nodes transmit their current energy and location values to the base station via a two-hop scheme and a multi-hop scheme. After all the nodes' energy and location values have been transferred to the base station, the base station decides the nodes of being mesh-heads for the current round according to their residual energy (the node with the most energy left is selected to be the mesh-head for the current round in a mesh), assigns the hop number and TDMA structure as well as time slots for each node, and broadcasts a control packet to the network. The items

and their sequences in this control packet are as the same as the control packet in set-up phase.

In one round period, the start beacon is very short (a couple of bits) and the energy reporting frame and the control packet are experienced only once; while the numbers of data frame could be very large. Therefore, the time of one round depends mainly on the total time of the data frames. For the simulation model (200 nodes, 9 meshes, and 180×180 meter monitored field) used in this thesis, we have 100 data frames per round (we will discuss why this frame number is reasonable for our simulation model in Chapter 5) and the average size of one data frame is about 5.2k bits (assume there are average 20 nodes in a mesh and the data packet size is 2k bits). Each data frame experiences the processes of data transmission, receiving and data fusion, in which the data are transferred from the individual node to the base station. These processes are being taken simultaneously in meshes. Since the number of nodes in each mesh may not be equal, the data frame time will depend on the time of the mesh that has the most nodes.

Figure 4-5a and 4-5b show the details of a data frame, where Figure 4-5a shows the situation when a mesh has the most nodes (assume 30 nodes in this mesh) and Figure 4-5b shows the situation when a mesh has average nodes (assume 20 nodes in this mesh). Since we use the TDMA protocol to perform data transfer in a mesh, nodes only need to turn on its power to transmit or receive data in their assigned slots. For the rest of the time the nodes can turn off their electronic circuits to conserve energy. In a data frame, the meshes not having most nodes will finish their two-hop transmission/receiving process earlier (after 20 slots' data transfer, as shown in Figure 4-5b) than the mesh that has the most nodes. Upon finishing the data transmission/receiving in a frame time, the mesh-head nodes are at idle status (listen

to the base station), while the non-mesh-head nodes in these meshes are put into sleep status, see Figure 4-5(b). When the mesh that has the most nodes finishes its data transfer (after 30 slots data transfer, as shown in Figure 4-5a), all the mesh-head nodes start to transfer data to the base station in their assigned time slots indicated as “Mesh-head to Base station” in Figure 4-5. Non-mesh-head nodes can still sleep in the inter-mesh data transfer period to further conserve energy.

Each node in the network should follow its own work table to go through the sequence of transmission/receiving bursts and sleeping mode. In general, each node should know its time slot to function, ID information (mesh number, layer number and column number), and CDMA codes for itself and for the last layer in the same column. The node should also know the round in which it will execute its role as a mesh-head. Before each round, a node also need to know its hop number for the current round and its slots in which to transmit and receive data. These messages can be acquired and updated from the control packets broadcasted by the base station.

4.2 Two-Hop Scheme

The amount of sensor nodes in wireless sensor networks is large so the distances between the nodes are usually far less than the distances from nodes to the base station. By using multi-hop communication routing, each node transmits/receives data only to/from the close neighbors. This prevents transmitting/receiving over a long distance, ameliorates the high path losses incurred by radio transmission and thus reduces the amount of energy consumed.

In a mesh, the mesh-head node is normally not at the center of the mesh. If we use a single hop scheme, such as the in-cluster communication scheme implemented in LEACH

protocol [6], some nodes will have to send their data to the mesh-head node over a relatively long distance and hence will drain more energy. Therefore, to slash down energy dissipation, a multi-hop routing protocol should be used in a mesh.

[86] indicates the necessity of applying the multi-hop scheme when the distance between two transmission nodes is large.

A common model for the power consumed by multi-hop transmission is [86]:

$$P(h, d, c_{tx}) = c_{tx} [(h-1) P_{rxElec} + h (P_{txRad}(\frac{d}{h}) + P_{txElec})] \quad (4.1)$$

where h is the number of hops, d is the total transmission distance, c_{tx} is the transmit duty cycle, P_{rxElec} and P_{txElec} are the powers required by the receiving and transmission electronics, and $P_{txRad}(x)$ is the power required to overcome path loss attenuation over a distance x . Figure 4-6 illustrates this model for different values of d and h using $P_{rxElec} = P_{txElec} = 175$ mW and r^3 path loss.

From Figure 4-6, it is clear that when the distance (d) is less than 30 meters, direct-transmission is more energy-efficient than multi-hop transmission. But as the distance increases, it is better to increase the number of hops to maintain the energy efficiency. When the distance between two transmission nodes is within the range of (30, 50) meters, a two-hop routing scheme is the best; when the distance is in the range of (50, 70) meters, a three-hop routing scheme is the best.

Now the issue is how many hops we should select in a mesh for a routing protocol. If we select too many hops, the data will have to go through too many hops to reach the mesh-head node. This will increase the data transmission delay and the complexity of the routing protocol.

Taking the above factors into consideration, we introduce a two-hop scheme for the data routing in a mesh. Since meshes are formed and configured by a centralized formation method in the THEEM protocol, we can determine the size of the meshes (e.g. 60~100 square meter) in order to achieve the best performance for the two-hop scheme. In this thesis, we use the mesh size of 60×60 meters for the simulation model.

Figure 4-6: Evaluation of the ideal model. As the transmit distance increases, increasing the number of hops improves energy-efficiency. [86]

4.2.1 The Parameter for The Two-Hop Scheme

Since the energy dissipation of nodes in data transmission/reception is proportional to the distance of data communication [28] [6], to reduce the energy dissipation in a mesh, it is always desired to find out a way to reduce the distance between transmission and receiving. Therefore, as showed in previous sections, we introduce the two-hop routing scheme in a mesh and divide the mesh into two portions. Nodes in portion1 are farther from the mesh-

head node and we call them source nodes. Nodes in portion2 are closer to the mesh-head node and we call them intermediate nodes. Note that nodes take turn to be the mesh-head, so the source nodes and the intermediate nodes are different in different rounds of data transfer. The two-hop routing scheme works as follows: first, all the source nodes send their data to the intermediate nodes and this process is called the first hop; the first hop transmission direction is based on the MTE theory mentioned in Chapter 3; then the intermediate nodes fuse the received data with their own sensed data and send the fused one to the mesh-head node, which is called the second hop. By this way, the overall energy-dissipation for data transmission in a mesh is reduced.

One issue for the two-hop scheme is to partition the mesh into two equal portions. Suppose we have a circle with the radius of r and let the mesh-head node be the centre of the circle. We can find a value for r such that the area of this circle is approximately equal to the other area within the mesh. In the mesh, the nodes that are outside the circle are the source nodes and the nodes that are within the circle are the intermediate nodes.

Figure 4-7: Selection of radius r

Assume that nodes are uniformly distributed in a mesh. Since they take turns to be the mesh-head as explained before, the mesh-head node (located at the centre of the circle) can be anywhere in the mesh. The largest area covered by the circle in the mesh is $\pi \times r^2$, as shown in Figure 4-7a, and the smallest area occupied by the circle in the mesh is $\frac{1}{4}\pi \times r^2$, as shown in Figure 4-7b.

The approximate covering average of the mesh by such a circle is thus
$$\frac{(\pi \times r^2 + \frac{1}{4}\pi \times r^2)}{2} = \frac{5\pi \times r^2}{8}$$
 (since the mesh-head node is uniformly distributed in the mesh). Let this area to be half of the mesh area $\frac{l^2}{2}$, where l is the length of mesh, we have

$$\text{that } r = \sqrt{\frac{4}{5\pi}} \times l = \frac{l}{2}.$$

4.2.2 The Operation of The Two-Hop Scheme

An example to illustrate the operation of the two-hop scheme in a mesh is shown in Figure 4-8. This figure also shows the distribution of nodes in one round and the two-hop routes for this round.

There are total 12 nodes in the mesh – the black dot is the mesh-head node and the 11 white dots (numbered from 1 to 11) are the non-mesh-head nodes. The dash-dotted line implies the circle with radius of $r = l/2$, where l is the length of the mesh. The dashed lines with arrows represent the data transfer direction.

Figure 4-8: Two-hop scheme in a mesh

The distances from each node to the mesh-head node are decreasing with the nodes' number. The distances of nodes 1, 2, 3, 4, 5 and 6 to the mesh-head node are greater than $l/2$, so these nodes are called the source nodes in this round. They transmit their data in sequence to their respective intermediate nodes or directly to the mesh-head node in the period of the first hop –starting from the largest number of nodes (node1). The distances of node7, 8, 9, 10 and 11 to the mesh-head node are less than $l/2$, so these nodes are called the intermediate nodes in this round. In the second hop period these nodes transmit their data directly to the mesh-head node in sequence –also starting from the largest number of nodes (node7).

In detail, node1 is allocated to time slot1 in a data frame, node2 to time slot2, ..., and node11 to time slot11. Data transfer starts from node1 (in the time slot1) until to node11 (in time slot11). Table 4.1 shows the details of data transfer, where Tx stands for data transmission and Rx stands for data receiving. The vertical arrows indicate the data transmission direction in the individual time slot. Each node transmits one packet data and after each data fusion the data size is still one packet.

Table 4.1: Data transfer details in a mesh (for the example of having 12 nodes in the mesh)

[illegible]

Figure 4-9: Flow-graph of algorithm for finding source nodes and intermediate nodes

Figure 4-9 shows the algorithm of finding source and intermediate nodes, where $d_{SN to MH}$ is the distance of a source node to the mesh-head node, $d_{IN to MH}$ is the distance of an

intermediate node to the mesh-head node, d_{SNtoIN} is the distance of a source node to the intermediate node, and m is the number of non-mesh-head nodes in a mesh, n is the counter number.

4.3 Discussion

First, THEEM protocol requires that each node reports the information about its location to the base station after the deployment. As discussed in Chapter 2, the global positioning system technology can be employed and the GPS receiver in a sensor node can be activated at the beginning of the network formation period in order to obtain the location information of each node.

Secondly, THEEM protocol has the potential ability to deal with the dynamic network. In THEEM protocol, the base station continuously receives the energy and location information from the nodes that have already been in the network and the potential moving-in node at the beginning of each round. Once the base station receives the location information of newly deployed or moving-in nodes, it then broadcasts the location information of these nodes to the monitored field, adds these nodes to the meshes they belong to according to their locations, and updates the work tables of the respective nodes.

Thirdly, as mentioned in this chapter, the routing and TDMA/CDMA MAC protocols are designed to ensure low energy dissipation and also to ensure no data collision. To implement this, each mesh in THEEM uses its unique direct-sequence spread spectrum (DS-SS) CDMA code (described in Chapter 2) to communicate with other meshes. With enough spreading, radio signals from the neighboring meshes can be filtered out as noise during de-correlation. To be able to further lower the possibility of interference with nodes in the nearby meshes

and to reduce its own energy dissipation, each node needs to adjust transmission power when it transfers data to its mesh-head.

Fourthly, to support THEEM protocol, the assumption that data are correlated in a mesh is generally reasonable; and data fusion (aggregation) is needed to produce a meaningful description of events that are occurring in the environment. These assumptions are verified in reference [6].

Finally, we use the distance parameter (d^2 or d^4 accordingly) between the nodes or from the nodes to the base station to compute the dissipation energy of communication, but the communication energy may not scale exactly with the distance (e.g., in cases that a building or tree is impeding a good communication channel). However, gathering information about the communication channel between all nodes is impractical. The calculated energy dissipation is therefore an approximation of the real one by this approach [6].

The following facts indicate that THEEM protocol can further save energy: (these will be verified hereafter in this thesis)

- Using the two-hop scheme in a mesh,
- No set-up overhead needed when data are transmitted between mesh-head nodes; and no waiting period when data are transmitted from the closest layer mesh-head nodes to the base station,
- Only a very small portion of nodes (mesh-head nodes in the closest layer) transmit data directly to the base station.

Chapter 5

Analysis and Simulation

This chapter presents the design considerations and performance analysis of THEEM protocol through theoretical analysis and simulation. In simulation, THEEM protocol is compared with PEGASIS (Power-Efficient GATHERing in Sensor Information Systems) scheme and MTE (Minimum Transmission Energy) routing in terms of network lifetime, energy dissipation, amount of data transfer, and latency. The reasons that we compare THEEM protocol with PEGASIS scheme and MTE routing are that: PEGASIS scheme is “a near-optimal chain-based protocol that minimizes energy [7]” and it significantly outperforms other competitive protocols (e.g. PEGASIS performs better than LEACH by about 100 to 200 percent in terms of energy efficiency [7]); and MTE routing is a typical multi-hop “energy-aware” routing approach which minimizes the transmission energy required to get the data to the base station.

The simulation is performed using MATLAB [87][88][89].

5.1 Simulation Models

This section describes the models that were used for channel propagation, radio communication, and the computation of energy dissipation.

5.1.1 Channel Propagation Model

Typically, there are two types of wireless channel models for electromagnetic wave propagation, direct line-of-sight and multipath fading. No matter which model is used, the received power decreases as the distance between the transmitter and receiver increases [28]. For the experiments described in this thesis, both the line-of-sight model (free space model) and the multipath fading model are used, depending on the distance between the transmitter and receiver. If the distance between the transmitter and receiver is less than a certain cross-over distance ($d_{crossover}$), the Friss free space model is used (d^2 attenuation), and if the distance is greater than $d_{crossover}$, the two-ray ground propagation model is used (d^4 attenuation). The cross-over point is defined as follows [6]:

$$d_{crossover} = \frac{4\pi\sqrt{L}h_r h_t}{\lambda} \quad (5.1)$$

where

$L \geq 1$ is the system loss factor not related to propagation,

h_r is the height of the receiving antenna above ground,

h_t is the height of the transmitting antenna above ground, and

λ is the wavelength of the carrier signal.

If the distance is less than $d_{crossover}$, the transmit power is attenuated according to the Friss free space equation as follows [6]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L} \quad (5.2)$$

where

$P_r(d)$ is the receive power given a transmitter-receiver separation of d ,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

λ is the wavelength of the carrier signal,

d is the distance between the transmitter and the receiver, and

$L \geq 1$ is the system loss factor not related to propagation.

This equation models the attenuation when the transmitter and receiver have direct, line-of-sight communication, which will only occur if the transmitter and receiver are close to each other. If the distance is greater than $d_{crossover}$, the transmit power is attenuated according to the two-ray ground propagation equation as follows [6]:

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4} \quad (5.3)$$

where

$P_r(d)$ is the receive power given a transmitter-receiver separation of d ,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

h_r is the height of the receiving antenna above ground,

h_t is the height of the transmitting antenna above ground, and

d is the distance between the transmitter and the receiver.

In this case, the received signal comes from both the direct path and a ground-reflection path [28].

In the experiments described in this thesis, an omni-directional antenna is used with the following parameters: $G_t = G_r = 1$, $h_t = h_r = 1.5$ m, no system loss ($L=1$), 914 MHz radios,

and $\lambda = \frac{3 \times 10^8}{914 \times 10^6} = 0.328$ m. Using these values, we get $d_{crossover} = 86.2$ m.

5.1.2 Radio Energy Model

We select the same radio energy model as in [6]. In this work, we assume a simple model where the transmitter dissipates energy to run the radio electronics and the power amplifier and the receiver dissipates energy to run the radio electronics [90]. As discussed in the previous section, the power attenuation is dependent on the distance between the transmitter and receiver. For relatively short distances, the propagation loss can be modeled as inversely proportional to d^2 , whereas for longer distances, the propagation loss can be modeled as inversely proportional to d^4 . Power control can be used to invert this loss by setting the power amplifier to ensure a certain power at the receiver. Thus, to transmit a k -bit message at a distance d , the radio expends [6]:

$$E_{Tx}(k, d) = E_{Tx-elec}(k) + E_{Tx-amp}(k, d) \quad (5.4)$$

$$E_{Tx}(k, d) = \begin{cases} kE_{elec} + k\epsilon_{friss-amp} d^2 & : d < d_{crossover} \\ kE_{elec} + k\epsilon_{two-ray-amp} d^4 & : d \geq d_{crossover} \end{cases} \quad (5.5)$$

and to receive this message, the radio expends [6]:

$$E_{Rx}(k) = E_{Rx-elec}(k) = kE_{elec} \quad (5.6)$$

The radio energy dissipation model is shown in Figure 5-1. The electronics energy, E_{elec} depends on factors such as the digital coding (or decoding), modulation (or demodulation), and filtering of the signal before it is sent to the transmit amplifier (or filtering of the signal after it is received by the receiver amplifier). In addition, when using DS-SS, the electronics energy accounts for the spreading of the data when transmitting and the correlation of the

data with the spreading code when receiving. For the experiments described in this thesis, we set the energy dissipated per bit in the transceiver electronics to be the same as in [6]

$$E_{elec} = 50 \text{ nJ/bit} \quad (5.7)$$

for a 1 Mbps transceiver. This means the radio electronics dissipates 50 mW when in operation (either transmission or receiving). This value is reasonable since researchers have designed transceiver baseband chips that support multi-user spread-spectrum communication and operate at 165 mW in transmitting mode and 46.5 mW in receiving mode [91].

The parameters $\epsilon_{friss-amp}$ and $\epsilon_{two-ray-amp}$ will depend on the required receiver sensitivity and the receiver noise figure. We take the deduced results from [6] and will use these radio energy parameters for the simulations described in this chapter:

$$\epsilon_{friss-amp} = 10 \text{ pJ/bit/m}^2 \quad (5.8)$$

$$\epsilon_{two-ray-amp} = 0.0013 \text{ pJ/bit/m}^4 \quad (5.9)$$

The computation energy for data fusion (aggregation) E_{FU} is set to 5nJ/bit/signal according to [6], [92] and [93].

Figure 5-1: Radio energy dissipation model [6]

5.1.3 MATLAB Implementation

We use MATLAB to implement THEEM, PEGASIS and MTE protocols. The last two protocols are for general-purpose comparison with THEEM. Program paradigms for these implementations can be found in Appendix A.

5.2 Experimental Set-up

Figure 5-2: 200-nodes random test network.

For most of the experiments in this thesis, the random distributed 200-nodes network shown in Figure 5-2 was used. The network size was 180×180 meter and the base station was placed at 60 meters from the closest node, at location $(x=90 \text{ m}, y=240 \text{ m})$. We also used

some other network sizes and placed the base station at other locations to study the performances of THEEM such as the optimum number of the meshes and the favorable locations of the base station.

The network parameters are summarized in Table 5.1.

Table 5.1: Network parameters used in the simulation

Simulation Parameters	Value
Channel bandwidth (R_b)	1 Mbps
Data packet size (P)	2K bits
Number of nodes (N)	200, 100, 400
Network size ($X \times Y$) ($m \times m$)	180, 90, 270 square
Position of the Base station (X, Y)	(90, 240), others
Maximum buffer size (B)	1000 packets
Initial energy (J)	2 J
Radio electronics energy (E_{elec})	50 nJ/bit
Computing energy for data fusion (E_{FU})	5 nJ/bit
Cross-over distance for Friss and two-ray ground attenuation models	87 m
Radio amplifier energy ($\epsilon_{friss-amp}$)	10 pJ/bit/m ²
Radio amplifier energy ($\epsilon_{two-ray-amp}$)	0.0013 pJ/bit/m ⁴
Antenna gain factor (G_t, G_r)	1
Antenna height above the ground (h_b, h_r)	1.5 m
Signal wavelength (λ)	0.325 m
Radio propagation speed	3×10^8 m/s

The following assumptions were made in our simulation model:

- The sensor nodes are randomly distributed within a square area. Every node has its own location information and the base station knows all the locations and energy information about the nodes.
- The base station has unlimited energy supply.
- Our model sensor network contains homogeneous and energy constrained sensor nodes with initial uniform energy. Each sensor node has the ability to adjust its transmission power and to transmit data to any other sensor node or directly to the base station [94] [95].
- There is no processing delay on transmitting, receiving and data fusion.
- There is no packet loss in the network and in the sensing processing (each node has enough buffer to store the packets).
- Transmitter antennas are omni-directional.
- Clocks in sensor nodes are synchronized with each other and there is no clock drift.

We use different performance metrics that capture different performance requirements.

Some non-intuitive metrics are defined as follows:

- Average delay per data packet: Defined as the network operation time divided by the total data packets number received at the base station. The less this metric is, the better the network performance will be (less latency).
- Data received at the base station per unit energy: Defined as the division of total data packets number received at the base station and the total energy dissipated in the network. The network performs better with more data received at the base station for the same energy dissipation.

- Average energy consumed per packet: Defined as the division of total energy consumed in the network and the total data packets number received at the base station. This metric represents the average energy consumed in transmitting and receiving a data packet. A routing algorithm that minimizes the energy consumed per packet will, in general, yield better energy savings and increase network lifetime [84].

5.3 Optimum Number of Meshes

The optimum number of meshes depends on many application-specific factors such as the network topology, the attributes (mission attributes and mission priorities) of the wireless sensor networks, and the relative costs of computation versus communication, etc. Here we just want to analyze the general rules under which the optimum number of meshes should be for the purpose of enhancing the energy-efficiency.

5.3.1 Theoretical Analysis

In THEEM protocol, the distributed nodes area is divided into a certain number of fixed meshes. What is the optimum number of meshes such that the energy dissipation in the network is minimal? We can analytically determine the optimal number of meshes in a THEEM network using the computation and communication energy models developed in the previous section. Assume there are N nodes distributed uniformly in an $M \times M$ region. If there are X meshes, there are on average $\frac{N}{X}$ nodes per mesh.

In each mesh, data from the source nodes (with the distances to mesh-head node being greater than half of the mesh size) will be first transmitted to the intermediate nodes (or to the

mesh-head node), be fused with the data of intermediate nodes. This is called the first hop. Mesh-head node then receives the fused data from the intermediate nodes in the second hop. Assume there are on average $\frac{N}{2X}$ source nodes which distances to mesh-head node are greater than half of the mesh size. Presumably the distance between these source nodes and their intermediate nodes are less than the cross-over distance, so the energy dissipations follow the Friss free-space model (e.g. d^2 power loss). The total energy used in these nodes during a single frame is:

$$E_{>l/2} = \frac{N}{2X} \times (kE_{elec} + k\epsilon_{friss-amp} d_{SNtoIN}^2) \quad (5.10)$$

where k is the number of bits per signal packet, l is the mesh size, and d_{SNtoIN} is the distance from the source nodes to the intermediate nodes.

The total energy dissipated in the intermediate nodes when doing data receiving, fusion and transmitting (to the mesh-head node) during a single frame is thus:

$$E_{<l/2} = \left(\frac{N}{2X} - 1\right) \times (2kE_{elec} + kE_{fusion} + k\epsilon_{friss-amp} d_{INtoMH}^2) \quad (5.11)$$

where d_{INtoMH} is the distance from the intermediate nodes to the mesh-head node.

Since the base station is usually located away from the mesh-head nodes, presumably the distances from the mesh-head nodes to the base station are greater than the cross-over distance and the energy dissipation follows the two-ray-ground model (e.g. d^4 power loss). And since in THEEM, only mesh-head nodes in the closest layer (to the base station) transfer the summation of the data to the remote base station (as described in section 4.1), we only consider the mesh-head nodes in this layer when compute the energy dissipation for data transfer from the network to the base station. Therefore, the energy dissipated in the mesh-head nodes during a single frame is:

$$E_{MH} = \left(\frac{N}{2X} - 1\right) \times (kE_{elec} + kE_{fusion}) + \sqrt{X} \times k\varepsilon_{two-ray-amp} d_{toBS}^4 \quad (5.12)$$

where d_{toBS} is the distance from the mesh-head node to the base station.

Next we deduce the approximate values of d_{INtoMH} and d_{SNtoIN} . Assume that the mesh-head node (at the centre of the circle of having radius of $r = \frac{l}{2}$) is uniformly distributed within the area of the mesh. We consider two extreme situations where mesh-head node locates at the center of the mesh and at the corner of the mesh, corresponding to the situations of the biggest area occupied by the circle and the smallest area occupied by the circle respectively, as shown in Figure 5-3 (a) and (b). We compute the approximate d_{INtoMH} and d_{SNtoIN} respectively in these two situations and average these two values. This way, we get the approximate d_{INtoMH} and d_{SNtoIN} .

Figure 5-3: The approximate deduction of d_{INtoMH} and d_{SNtoIN} .

In Figure 5-3a, the average distance points from the intermediate nodes to the mesh-head node is located along the circumference of the circle that has the radius of d_{ba} , so $d_{INtoMH} 1 = d_{ba}$. The average distance from the source nodes to the intermediate nodes is d_{db} , where point

d is the geometrical center of the right-angled triangle with the height of d_{ce} , so $d_{S_{NtoIN} 1} = d_{db}$.

In Figure 5-3b, the average distance points from the intermediate nodes to the mesh-head

node is located along the circumference of the circle that has radius of d_{gf} , so $d_{INtoMH 2} = d_{gf}$.

The average distance from the source nodes to the intermediate nodes is the average length of

d_{jg} and d_{hg} , where point j is the geometrical center of the right-angled triangle with the height

of d_{ki} and point h is the geometrical center of the hexagon in the middle of the mesh (point h

is also the geometrical center of the mesh), so $d_{S_{NtoIN} 2} = \frac{d_{hg} + d_{jg}}{2}$.

First, we compute $d_{INtoMH 1}$ and $d_{S_{NtoIN} 1}$ in Figure 5-3 (a).

Let the area of S_1 = the area of S_2 ,

we have that $\pi \times d_{INtoMH 1}^2 = \pi \times (\frac{l}{2})^2 - \pi \times d_{INtoMH 1}^2$,

so, $d_{INtoMH 1} \approx 0.35 l$,

$$d_{ce} = d_{ae} - \frac{l}{2} = \sqrt{(\frac{l}{2})^2 + (\frac{l}{2})^2} - \frac{l}{2} \approx 0.207 l.$$

Let the area of S_4 equal the area of S_3 , where S_4 is the right-angled triangle with the height of

d_{de} and S_3 is the trapezoid with the height of d_{cd} ,

we have that $\frac{1}{2} \times d_{de} \times 2d_{de} = \frac{1}{2} \times d_{ce} \times 2d_{ce} - \frac{1}{2} \times d_{de} \times 2d_{de}$,

so, $d_{de} = 0.15 l$,

$$d_{S_{NtoIN} 1} = d_{db} = d_{cd} + d_{cb} = (d_{ce} - d_{de}) + (\frac{l}{2} - d_{INtoMH 1}) = 0.207 l.$$

Now we compute $d_{INtoMH 2}$ and $d_{S_{NtoIN} 2}$ in Figure 5-3 (b).

Let the area of S_5 = the area of S_6 ,

we have that $\frac{\pi}{4} \times d_{INtoMH 2}^2 = \frac{\pi}{4} \times (\frac{l}{2})^2 - \frac{\pi}{4} \times d_{INtoMH 2}^2$,

so, $d_{INtoMH} \approx 0.35 l$,

Let the area of S_8 = the area of S_7 , where S_8 is the right-angled triangle with the height of d_{jk} and S_7 is the trapezoid with the height of d_{ij} ,

we have that $\frac{1}{2} \times d_{jk} \times 2d_{jk} = \frac{1}{2} \times d_{ik} \times 2d_{ik} - \frac{1}{2} \times d_{jk} \times 2d_{jk}$,

since $d_{ik}^2 + d_{jk}^2 = (\frac{l}{2})^2$,

we get $d_{ik} \approx 0.35 l$,

so, $d_{jk} \approx 0.25 l$,

$$\begin{aligned} \text{hence, } d_{SNtoIN} &= \frac{d_{hg} + d_{jg}}{2} = \frac{(d_{hf} - d_{INtoMH}) + (d_{fk} - d_{INtoMH} - d_{jk})}{2} \\ &= \frac{(0.707l - 0.35l) + (1.414l - 0.35l - 0.25l)}{2} = 0.58 l. \end{aligned}$$

Finally, the approximate average values of d_{INtoMH} and d_{SNtoIN} are as follows:

$$d_{INtoMH} \approx \frac{d_{INtoMH} + d_{INtoMH}}{2} = 0.35 l \quad (5.13)$$

$$d_{SNtoIN} \approx \frac{d_{SNtoIN} + d_{SNtoIN}}{2} = 0.40 l \quad (5.14)$$

$$\text{where } l = \sqrt{\frac{M}{X}} \quad (5.15)$$

The energy dissipated in a mesh during a frame is:

$$E_{mesh} = E_{MH} + E_{<l/2} + E_{>l/2} \quad (5.16)$$

and the total system energy for the frame is:

$$E_{total} = X \times E_{mesh} \quad (5.17)$$

substitute 5.16, 5.10, 5.11, 5.12, 5.13, 5.14 and 5.15 into 5.17, we have

$$\begin{aligned}
E_{total} &\approx \frac{Nk}{2} \times [4E_{elec} + 2E_{fusion} + \varepsilon_{friss-amp} \times (d_{SNtoIN}^2 + d_{INtoMH}^2)] + \sqrt{X^3} \times k \varepsilon_{two-ray-amp} \times d_{toBS}^4 \\
&= 2NkE_{elec} + Nk E_{fusion} + \frac{0.14Nk\varepsilon_{friss-amp} M^2}{X} + \sqrt{X^3} \times k \varepsilon_{two-ray-amp} \times d_{toBS}^4
\end{aligned}$$

We can find the optimum number of meshes by setting the derivative of E_{total} with respect to X to zero (to get highest energy efficiency):

$$\begin{aligned}
\frac{dE_{total}}{dX} &= 0 \\
\sqrt{X} \times \varepsilon_{two-ray-amp} \times d_{toBS}^4 &= 0.14 N \varepsilon_{friss-amp} \left(\frac{M}{X}\right)^2 \\
X &= \left(\frac{0.14N\varepsilon_{friss-amp} M^2}{\varepsilon_{two-ray-amp}}\right)^{\frac{2}{5}} \times \left(\frac{1}{d_{toBS}^4}\right)^{\frac{2}{5}} \quad (5.18)
\end{aligned}$$

For our experiments, $N = 200$ nodes, $M = 180$ m, $\varepsilon_{friss-amp} = 10$ pJ, $\varepsilon_{two-ray-amp} = 0.0013$ pJ, and $60 < d_{toBS} < 150$ (the minimum and maximum distances from the base station to the nodes in the first layer), so we expect the optimum number of meshes to be:

$$3 < X < 12 \quad (5.19)$$

These analytical results were verified using simulations where we varied the number of meshes between 1 and 25 and ran THEEM for 1 million data packets.

5.3.2 Experimental Results

Figure 5-4 shows the average energy dissipated per data packet as a function of the number of meshes with the nodes number varying from 100 to 1000. The size of the monitored field is $180\text{m} \times 180\text{m}$ and the location of the base station is (90, 240). This graph shows that the optimum number of meshes changes with the change of the node number. In the same condition as our experiment, 200 nodes and 180 square meter monitored field as

well as the base station location of (90, 240), as predicted by the analysis, the optimum number of meshes is 9 or 4 ($3 < X < 12$). Consequently, the number of meshes is set to 9 for the same experimental models in this thesis.

Other intuitive conclusions are also showed in Figure 5-4. When there are 100 nodes in the field, the optimum number of the meshes is 4. When there are 400 nodes in the field, the optimum number of the meshes is 9 or 16. When there are 1000 nodes in the field, the optimum number of the meshes is 16 or 25. So we can say that as the number of nodes increase, the optimum number of the meshes should increase accordingly in order to achieve the best energy-efficiency. When there is only 1 mesh, the non-mesh-head nodes often have to transmit data very far to reach the mesh-head node, draining their energy, hence the average energy dissipation per data packet are very high; whereas, when there are more than the optimum number of the meshes in the monitored field, there is not as much local data aggregation being performed and the mesh-head nodes have to transfer more uncorrelated data packets to the base station, also causing more energy dissipation.

Figure 5-5 shows the average energy dissipated per data packet as a function of the number of the meshes with the field size varying at $90\text{m} \times 90\text{m}$, $180\text{m} \times 180\text{m}$, and $270\text{m} \times 270\text{m}$. This graph shows that the optimum number of the meshes also changes with the change of the field size. When the field size is $90\text{m} \times 90\text{m}$, the optimum number of the meshes is 1, indicating the needlessness of dividing a small monitored field into individual meshes. When the field size gets larger, the optimum number of the meshes should also be larger. As shown in Figure 5-5, the optimum number of the meshes is 9 for the field size of $180\text{m} \times 180\text{m}$ and is 16 for the field size of $270\text{m} \times 270\text{m}$.

Figure 5-4 Average energy dissipated per data packet in THEEM as the number of the meshes is varied between 1 and 25 with different numbers of nodes. The size of the monitored field is 180m × 180m and the location of the base station is (90, 240).

Figure 5-5 Average energy dissipated per data packet in THEEM as the number of the meshes is varied between 1 and 25 with different sizes of field. The number of the nodes is 200 and the location of the base station is (90, 240).

5.4 The Round Time

As indicated in section 4.1, the operation of THEEM is divided into rounds. Each round starts off with an assignment phase then follows with the long data frames where data transfer occurs from the nodes to the base station in many consecutive frames. It is very important to set up a proper round time, that is, to set up a proper number of frames through which the data are being transferred. In the assignment phase, each node should send out its energy value signal to the base station through its mesh-head node, and the base station assigns a new mesh-head and a new two-hop routing to each mesh according to the residual energy and the location of each node. Therefore, the data frames should be long enough compared with the assignment phase in order to lessen the energy dissipated used in transmitting nodes' energy value to the greatest extent. Whereas, running the data frames for too long will drain the energy of the mesh-head nodes and curtail the communication between the non-mesh-head nodes that still have energy and the base station. Hence, there is a trade-off in selecting the round time. Equation 5.10 and 5.11 describe the energy dissipation of non-mesh-head nodes and equation 5.12 describes the energy consumption of a mesh-head node during a single frame of data transfer. So the total energy drained from each node per round depends on the average number of frames per round, $N_{frame/round}$, as follows:

$$E_{MH/round} = N_{frame/round} \times E_{MH} \quad (5.20)$$

$$E_{non-MH/round} \approx N_{frame/round} \times \left(\frac{E_{>1/2}}{\frac{N}{2X}} + \frac{E_{<1/2}}{\frac{N}{2X} - 1} \right) / 2 \quad (5.21)$$

where $E_{MH/round}$ is the energy dissipation for the mesh-head node to receive all the data from the non-mesh-head nodes, to fuse the data, and to send the fused data to the base station, while $E_{non-MH/round}$ is the average energy dissipation for the non-mesh-head nodes to

send the data to the mesh-head node.

One method of determining the round time is to ensure that each node's energy lasts long enough to allow the node to be a mesh-head node for several times (instead of only once) during its lifetime to make full use of the energy-aware mesh-head assignment algorithm. It is subtle to decide the average time that each node should be a mesh-head node before dies. For a node, the times of being a mesh-head can neither be only once nor be many times. Being a mesh-head for one time means the energy in each node can support this node to be a mesh-head only once before draining off, this is not good for the equilibrium of energy dissipation among the nodes in case that few nodes locate a little far away from the majority nodes in a mesh and drain their energy quickly in a single round. On the other hand, if we let each node be the mesh-head many times before die, that is, there are too many rounds before the network partition, the network will have to go through the assignment phase many times and will reduce the energy-efficiency. Therefore, we set the number of being a mesh-head to be 3, that is, each node's energy lasts long enough to allow the node to be a mesh-head three times during its lifetime and to be a non-mesh-head node during the other rounds. Assume each node begins with E_{start} Joules of energy, we have:

$$3 \times E_{MH/round} + 3\left(\frac{N}{X} - 1\right) \times E_{non-MH/round} = E_{start}$$

Combine equations 5.10, 5.11, and 5.12 with equations 5.20 and 5.21:

$$\begin{aligned} N_{frame/round} \times \left[\left(\frac{N}{2X} - 1\right) \times (kE_{elec} + kE_{fusion}) + \sqrt{X} \times k\epsilon_{two-ray-amp} d_{toBS}^4 \right] + N_{frame/round} \times \left(\frac{N}{X} - 1\right) \\ \times \frac{kE_{elec} + k\epsilon_{friss-amp} d_{SNtoIN}^2 + 2kE_{elec} + kE_{fusion} + k\epsilon_{friss-amp} d_{INtoMH}^2}{2} = \frac{E_{start}}{3} \end{aligned} \quad (5.22)$$

We can solve for $N_{frame/round}$ as a function of the system parameters:

$$N_{frame/round} = \frac{E_{start}}{3k} \times \left[\left(\frac{N}{2X} - 1 \right) \times (E_{elec} + E_{fusion}) + \sqrt{X} \times \varepsilon_{two-ray-amp} d_{toBS}^4 \right. \\ \left. + \left(\frac{N}{X} - 1 \right) \times \frac{3E_{elec} + \varepsilon_{friss-amp} d_{SNtoIN}^2 + E_{fusion} + \varepsilon_{friss-amp} d_{INtoMH}^2}{2} \right] \quad (5.23)$$

Assuming there are $\frac{N}{X}$ nodes per mesh and each k -bit data packet takes $t_{msg} = \frac{k}{R_b}$ seconds,

the total frame time is $t_{frame} = \frac{N}{X} \times \frac{k}{R_b}$ seconds.

The time for each round is thus:

$$t_{round} = N_{frame/round} \times t_{frame} \quad (5.24)$$

Substitute 5.13, 5.14, 5.15 and plugging in the values $E_{elec} = 50$ nJ/bit, $E_{fusion} = 5$ nJ/bit, $\varepsilon_{friss-amp} = 10$ pJ/bit/m², $\varepsilon_{two-ray-amp} = 0.0013$ pJ/bit/m⁴, $N=200$, $M=180$ m, $X=9$, $k=2000$ bits, and $R_b = 1$ Mbps bits gives:

$$N_{frame/round} = \frac{E_{start}}{0.02}$$

$$t_{frame} = 44 \text{ ms}$$

$$t_{round} = \frac{E_{start}}{0.455} \text{ (seconds)}$$

So the frame number in a round and the round time depend on the initial energy of the nodes, E_{start} . If we set E_{start} to be 2 Joules, the frames number in a round will be 100, and the round time will be 4.4 seconds.

We use 100 frames in a round for the THEEM simulations in this thesis.

5.5 Simulation Results

For the experiments described in this section, we implemented THEEM, PEGASIS and MTE routing. We will briefly summarize each of these protocols.

In THEEM, monitored field is divided into a certain number of meshes and the mesh-heads are assigned by the base station according to the current energy of the nodes at the beginning of each round. This ensures a perfect equilibrium of energy dissipation for all the nodes in the network. Data transfer in a mesh follows a low-energy two-hop scheme in order to acquire the best energy-efficiency. A multi-hop routing protocol guides the data transportation between the meshes and makes sure that the direct transmission of the data to the base station occurring only from the closest mesh-head nodes, conserving further energy. This protocol can also cope with the network scalability and the nodes mobility.

In PEGASIS, sensors form chain by using the greedy algorithm so that each node transmits to and receives from a nearby neighbor. Gathered data move from node to node, get aggregated and are eventually transmitted to the base station by a node header. Each node takes turns to be that node header.

For MTE routing, nodes set up routes to minimize the amount of transmission energy required to get their data to the base station by using several short hops. The routes are computed at the beginning of the simulation and are reorganized each time when nodes die.

5.5.1 The Comparisons of the Energy-Efficiency

Since the nodes have limited energy, they use up this energy during the course of the networks simulation. Certain energy values are deducted whenever a node transmits or receives data and whenever it performs data fusion. Once a node runs out of its energy, it is

considered to be dead and can no longer transmit or receive data. The simulations end when all the nodes in the network run out of their energy.

Energy-efficiency is very important performance for wireless sensor networks. Higher energy-efficiency means not only the lower energy dissipation and the higher data throughput in networks, but also, in many applications, the lower time delay for the sensed data to reach the base station.

Figure 5-6 shows the total number of the data signals received at the base station as a function of the amount of total network dissipated energy. For the three protocols (THEEM, PEGASIS and MTE), the total number of data means the effective data, that is, the original sensed data by all the nodes before the data have been aggregated. Figure 5-6 shows that, at the same network energy dissipating level, THEEM delivers more than 3 times of the data to the base station than MTE routing and it delivers more than 2 times of the data to the base station than PEGASIS. From Figure 5-6 we know that THEEM delivers the most data per unit energy, therefore, THEEM is more energy-efficient than the other two protocols. To explain energy-efficiency more comprehensively, we introduce the energy $\times$ delay metric as the parameter to evaluate the energy-efficiency of a wireless sensor network. The energy here is the total amount of energy dissipated in the network and the delay is defined as the average delay per packet, that is, the total simulation time divided by the total data packet number.

Why we use energy $\times$ delay to evaluate the energy-efficiency performance of wireless sensor networks instead of using only energy dissipation? For battery operated wireless sensor networks, energy saving is a very important factor among the network performances, but increased energy saving often comes with a penalty of increased delay. Therefore, there is a tradeoff between the energy spent per packet and the data delay. To maximize the quality

of service, we need lower both the energy dissipation in the networks and the packet delay at the base station. Hence, “energy $\times$ delay is an appropriate measure to optimize for in wireless sensor networks” [7].

Figure 5-7 shows the energy dissipated multiplied by the signal delay in the network as a function of simulation time. From this Figure, we see that as the simulation time goes by, the energy $\times$ delay of THEEM is the half as that of PEGASIS and is the one-fourth as that of MTE. The lower energy $\times$ delay value of THEEM protocol comes from the two-hop scheme in the in-mesh data deliver and the simultaneous data transfer over the networks.

Figure 5-8 shows that the energy $\times$ delay with different number of nodes in the networks when first node dies in the network. The graph shows that, with different number of nodes, THEEM always has the least energy $\times$ delay value among the three protocols. In addition, we see from Figure 5-8 that when the number of nodes in the network is less (e.g., 100 nodes), the energy $\times$ delay values for MTE routing and PEGASIS scheme are close. But when the number of nodes increases (e.g., 400 nodes), the energy $\times$ delay value of MTE routing is much higher than that of PEGASIS scheme, this is because more hops are needed before one data packet can be transmitted to the base station in MTE routing due to the dense node distribution, this leads to more energy dissipation. While in PEGASIS, as the number of nodes increase the data packets are transmitted and received to/from the closer neighbor nodes, the energy dissipation is not increase dramatically.

Figure 5-9 shows that with the different initial energies of the node, the number of data received at the base station. THEEM always reaches the highest data collection at the base station whenever first node dies (Figure 5-9a) or all the nodes die (Figure 5-9b). At the

situation of first node dies, the base station gets 50 times and 10 times more data from THEEM protocol than from MTE routing and PEGASIS scheme, respectively.

Also clearly shown in Figure 5-10, THEEM can deliver much more amount of data to the base station than PEGASIS scheme and MTE routing for the same number of node deaths. That means nodes in THEEM are able to better use the available energy to transfer much more data to the base station, hence have better energy-efficiency.

Figure 5-6: The total amount of data received at the base station as a function of total network dissipated energy.

Figure 5-7: Energy $\times$ delay over simulation time. The graph shows that THEEM has the least Energy $\times$ delay value among the three protocols.

Figure 5-8: Energy $\times$ delay with different number of nodes in the networks. Each node begins with 2J of energy. The graph shows that, with different number of nodes, THEEM always has the least Energy $\times$ delay value among the three protocols.

(a)

(b)

Figure 5-9: Energy-efficiency of the network with different initial energy. (a) Number of data received at the base station when first node dies. (b) Number of data received at the base station when all the nodes die.

Figure 5-10: Number of nodes alive per amount of data sent to the base station, where each node begins with 2J of energy.

5.5.2 The Comparisons of the Quality of Service (QoS)

One application-independent method of determining quality is to measure the amount of the data received at the base station [6]. The more data the base station receives, the more accurate monitoring result a wireless sensor network will reach. Therefore, we can define the quality of service (QoS) as the network throughput, that is, data packets number received at the base station per time unit.

Figure 5-11 shows the total data received at the base station over time. It shows that THEEM sends more than 8 times of the data to the base station than MTE routing and it sends more than 5 times of the data to the base station than PEGASIS in most simulation

time. Therefore, THEEM achieves lower latency and higher throughput. The reason that THEEM performs much better than PEGASIS and MTE routing in terms of QoS is that THEEM uses the hierarchical communication architecture, and the data transfers occur simultaneously in all the meshes.

Figure 5-11: Network throughput, where each node begins with 2J of energy. The total amount of data received at the base station over time.

5.5.3 The Comparisons of the Network Lifetime

Does THEEM always operate at the longest simulation time meanwhile with the most number of data packets received at the base station? We ran simulations and summarized in Table 5.2 the simulation times and the data packet number received at the base station for the three protocols –THEEM, PEGASIS and MTE. The nodes are assigned with different initial

energies in these simulations. Table 5.2 shows that THEEM always has the longest simulation time (the time when first node dies) and always gets the most data at the base station (15 times more data than PEGASIS and 30 times more data than MTE).

Table 5.2 Lifetime and throughput with different amounts of
initial energy for the sensor nodes

Initial Energy (J/node)	Protocols	Simulation time when first node dies (seconds)	Number of packet received at BS ($\times 10^3$)
0.25	MTE	9.4	4.7
	PEGASIS	18.6	9
	THEEM	47.6	135
0.5	MTE	18.7	9.35
	PEGASIS	36.7	18.3
	THEEM	93.7	280.7
1	MTE	37.6	18.8
	PEGASIS	89.4	44.7
	THEEM	186.2	548.2
2	MTE	78.8	39.4
	PEGASIS	170.2	85.1
	THEEM	368.3	1062.8
4	MTE	148.6	74.3
	PEGASIS	417.7	208.9
	THEEM	854.8	2346.2

An interesting phenomenon appears in Figure 5-12 when we draw the graphs of number of nodes alive over the simulation time. In THEEM, the time when first node dies and the time when all the nodes die are very close. That means the nodes in THEEM almost die at

the same time. Providing the highest network data output among the three protocols in Figure 5-6, 5-9, and 5-11, this phenomenon actually reveals another advantage that THEEM owns, which is, an excellent equilibrium among the nodes' energy dissipation.

Figure 5-12: Number of nodes alive over simulation time. In THEEM, the time when first node dies and the time when all the nodes die are very close. That means energy dissipation in THEEM is quite uniform.

5.5.4 The Location of the Base Station

The results presented in the previous sections show that THEEM is more energy-efficient and latency-efficient than PEGASIS scheme and MTE routing when we simulate the network with the base station locating at 150 meter away from the center of the network. Will the location of the base station affect the performance of THEEM protocol? How? Does THEEM still outperform PEGASIS and MTE with the variation of the location of the base station?

To answer these questions, we ran simulations where we varied the location of the base station with respect to the network shown in Figure 5-2. Figure 5-13 shows the time to first node die as the base station location varies between $(x=90, y=90)$ and $(x=90, y=300)$. We see from this Figure that when the base station is not in the center area of the network, the simulation time of THEEM is longer than of PEGASIS and MTE. Only when the location of the base station is within the center area of the network, the time to first node die of MTE routing is longer than that of THEEM protocol. This is because when the base station is located within the center area of the network, for MTE routing, there is no long-distance hop across which nodes need to send data and more nodes in the network can send their data directly to the close base station. This saves a large amount of energy for MTE routing and implies that MTE routing performs better when the base station is located within the network, especially in the area of network center, in terms of the network lifetime. However, in terms of total packets received at the base station during the simulation time, THEEM outperforms much better than MTE routing and PEGASIS scheme, even in the case when the base station is at the center of the network, as shown in Figure 5-14.

The performance comparisons are summarized in Table 5.3. For the parameters in Table 5.3, data per unit energy is defined as the total data packets received at the base station divided by the total energy dissipated in the network. For all the base station locations we simulated, THEEM protocol performs better than PEGASIS scheme by about a factor of 5, performs better than MTE routing by at least a factor of 2 and as much as a factor of 39.

Figure 5-13: Time to first node die as the base station location varies between $(x=90, y=90)$ and $(x=90, y=300)$ for the different protocols.

Figure 5-14: Total data received at the base station when first node dies as the base station location varies between $(x=90, y=90)$ and $(x=90, y=300)$ for the different protocols.

Table 5.3 Performance of the different protocols as the base station location is varied

Base Station Location/ Distance From Network Center	Protocols	Data Per Unit Energy ($\times 10^3$)	Performance Improvement Over MTE Routing	Performance Improvement Over PEGASIS
(x=90, y=90) / 0 m (at the center of The network)	THEEM	7.78	1.81	5.60
	PEGASIS	1.39	0.33	1
	MTE	4.31	1	3.1
(x=90, y=150) / 60 m	THEEM	8.09	3.80	6.63
	PEGASIS	1.22	0.57	1
	MTE	2.13	1	1.75
(x=90, y=180) / 90 m (at the edge of The network)	THEEM	8.03	6.42	6.53
	PEGASIS	1.23	0.98	1
	MTE	1.25	1	1.02
(x=90, y=210) / 120 m	THEEM	7.87	10.78	5.54
	PEGASIS	1.42	1.95	1
	MTE	0.73	1	0.51
(x=90, y=240) / 150 m	THEEM	7.39	21.11	5.96
	PEGASIS	1.24	3.54	1
	MTE	0.35	1	0.28
(x=90, y=270) / 180 m	THEEM	6.56	28.52	4.86
	PEGASIS	1.35	5.87	1
	MTE	0.23	1	0.17
(x=90, y=300) / 210 m (far away from The network)	THEEM	5.17	39.77	4.35
	PEGASIS	1.19	9.15	1
	MTE	0.13	1	0.11

5.5.5 Nodes Begin with Unequal Energy

As presented in Chapter 4, THEEM has the optimal energy-efficient performance since the base station assigns mesh-heads based on the residual energy of the nodes. This protocol makes full use of the high-energy nodes that are in the network and ensures the balanced energy dissipation. Figure 5-12 has already shown this feature. To further verify the above statement, we ran the same simulations as previous sections for the three protocols (THEEM, PEGASIS, and MTE). Instead of use 2J of initial energy for each node, we assign 100J of initial energy to 9 nodes and distribute these 9 nodes into each mesh (for THEEM protocol). The remaining 191 nodes still begin with 2J of initial energy.

Figure 5-15 shows the total data received at the base station per given amount of energy, the total data received at the base station over time, and the total energy dissipated over time for the three protocols. At the beginning of the simulation, each network has $(9 \times 100 + 191 \times 2)$ J = 1282 J of total energy.

From Figure 5-15a and 5-15c, we see that the networks of PEGASIS scheme and MTE routing partition when 400J to 500J energy has been consumed, while the network of THEEM protocol partitions when 1280J energy has been consumed. This indicates the better energy-efficiency of THEEM protocol. Therefore, THEEM can achieve more than 5 times of total data throughput than PEGASIS and more than 10 times of total data throughput than MTE, as shown in Figure 5-15a and 5-15b.

Figure 5-16 shows the number of nodes that are alive per data received at the base station for the three protocols. This graph shows that nodes in MTE routing and PEGASIS scheme start to die after delivering only a small amount of data to the base station, but nodes in THEEM remain alive to deliver much more data for the same number of node deaths. Our

simulation shows that by using THEEM protocol, each of the 9 nodes that begins the simulations with 100 J of initial energy becomes a mesh-head at an average of 2500 times during the simulation, while each of the 191 nodes that begins the simulations with 2 J of initial energy becomes a mesh-head at an average of 3 times during the simulation. This verifies that THEEM protocol does take advantage of the high-energy nodes.

Figure 5-15: Unequal energy simulation, where 9 nodes begin with 100 J of energy and the remaining 191 nodes begin the simulation with 2 J of energy. (a) The total amount of data received at the base station per given amount of energy. (b) The total amount of data received at the base station over time. (Figure continued on the next page)

(c)

Figure 5-15: Unequal energy simulation. (c) The total amount of energy dissipated in the network over time.

Figure 5-16: Unequal energy simulation, where 9 nodes begin with 100 J of energy and the remaining 191 nodes begin the simulation with 2 J of energy. Number of nodes alive per amount of data sent to the base station.

5.6 Discussions

In THEEM, all the nodes send their location information directly to the base station only once at the beginning of the network formation period; while in the protocol such as LEACH-C, nodes need to send their current location information directly to the base station at the beginning of each round, cause more traffic overhead and more energy consuming.

Generally, THEEM protocol fits for any shapes of monitored areas, for example, a monitored area may form a belt shape along the river side or road, or maybe is more uneven, in which cases we only need to design asymmetric mesh layers and mesh columns accordingly.

To prolong the longevity and enhance the QoS of the network, we may use threshold (hard and soft threshold) algorithms [10] [11] and data naming approaches [8] [9] [96] to further reduce the transmission overhead between the nodes and to get ride of the influence caused by the environmental factors. For example, nodes should be able to decide whether to send the data to the mesh-head based upon the data attributes and the data delta⁹. In these cases, if we select the thresholds and define the naming of data properly, only those unnecessary data will lose. To achieve this, we have to balance the extent of signal processing and decision making to produce an energy-efficient operation at the nodes' side. This issue is beyond the scope of this thesis.

In actual applications, an event-driven data collection and delivering model should be considered, where nodes decide whether to send the detected data based on the events occurred locally instead of based on the time intervals. In addition, node failure rate not only

⁹ If the difference of the sensed consecutive data at a node is less than a delta, the node just sends out a "one bit" signal (0 or 1) to present the increment or decline trend instead of sending off a data packet.

depends on the energy dissipation, but also depends on the failure of the hardware itself as well as the properties of the medium.

Chapter 6

Conclusions and Future Work

Wireless sensor networks have been growingly used in recent years since they are low cost, easy to deploy, and are able to work at any environments. The maturity of the techniques such as tinier processors, larger memory and more advanced radio technology makes it possible for wireless sensor networks to become a new wireless communication application. Nevertheless, the wireless sensor network is a newly emerging technology, so its communication protocols need to go through the phases of development and maturity.

The limited node power supply and the ad hoc nature of the node deployment are the differences between the wireless sensor networks and the other wireless networks, though all these networks are error-prone and time-varying. We take these constraints into consideration when designing the wireless sensor networks.

6.1 Conclusions

The THEEM protocol developed in this thesis shows advantages in coping with these design constraints, as summarized as follows:

1. The limited node power supply.

There are two aspects when dealing with this issue.

- 1). We need to reduce and balance the node energy dissipation to extend network lifetime.

THEEM uses a two-hop scheme and a low-energy MAC protocol to reduce and

balance energy-dissipation. The two-hop scheme reduces the energy dissipation used in data transfer by shortening the data transmitting distance. The Low-energy MAC (TDMA) protocol was chosen to allow the nodes to remain in the sleep state for a large amount of operation time. The nodes only need to be awake during their specific slots to transmit or receive data, and they never need to go into the idle mode, where they are waiting to see if any nodes have data to transmit. The two-hop scheme also balances the energy-dissipation among the mesh-head nodes and the non-mesh-head nodes by reducing the energy that the mesh-head nodes would have consumed in receiving and fusing the data from the non-mesh-head nodes. In addition, THEEM minimizes energy dissipation by exploiting the data-gathering aspect. Performing local data fusion on the correlated data greatly reduces energy dissipation. Finally, power-aware mesh-head assignment in THEEM ensures an excellent equilibrium of energy dissipation among nodes and hence prolongs the network lifetime.

2). We need to enhance the energy-efficiency of the network to offer higher data output.

The centralized mesh formation minimizes the communication overhead used in cluster formation at the beginning of each round and enhances the energy-efficiency of the network. The two-hop scheme reduces almost half of the energy for the non-mesh-head nodes to transmit their data to the mesh-head nodes. The multi-hop scheme in THEEM introduces the concepts of mesh layer and mesh column in the higher hierarchical architecture and organizes a more efficient data transfer route, results in a higher network throughput.

2. The ad hoc nature of node deployment.

In order to guarantee the monitoring coverage and quality over the entire surveillance

area, THEEM uses centralized mesh formation methods based on the demands of the monitor and the conditions of the terrain to configure the networks. In addition, THEEM makes use of the GPS technology to get the position of the nodes, which ensures that nodes do not need to be placed in specific, known locations.

3. Error-prone attribute.

The mixture of DS-SS CDMA and TDMA protocol used in THEEM decreases the errors caused by the data communication to the greatest extent. In THEEM, the use of rotating mesh-heads in the mesh assures that node failure due to the draining out of the energy affects other nodes for a maximum of one round.

4. Time-varying attribute.

A start beacon sent by the base station at the beginning of each round ensures the time synchronization of THEEM network.

As presented in Chapter 5, THEEM outperforms some WSN protocols (PEGASIS and MTE) in terms of energy-efficiency, QoS (throughput), and network lifetime. Therefore, the design of the THEEM protocol is proven to be successful and marks a great step towards the optimal communication protocols for wireless sensor networks.

The contributions of this thesis can be summarized as follows:

1. Developed a novel communication protocol (THEEM) for wireless sensor networks.

This protocol solves most of the design constraints of WSN and overcomes the drawbacks of the previous WSN protocols.

2. Demonstrated a two-hop scheme for in-mesh data communication.

3. Introduced a method of centralized mesh configuration.

6.2 Future Work

Several considerations should be taken into account in the future works.

1. Rather than using the amount of data received at the base station as the QoS standard, we need to consider the situations where miss detections and false alarms occur. The probability of the miss detection is high when the distribution of the sensor nodes is sparse, the residual energy in the sensor nodes is less, or when the buffers in the sensor nodes are not enough to handle the sensed data. Hardware failure of sensor nodes can also cause the miss detection. Besides, error code rate and false alarms should also be considered when defining the QoS. Gaussian noise, multi-path fading, and data/channel decoding failure could cause error code. And un-proper setting (e.g., threshold value is set too low, or sensitivity is set too high) can cause false alarms. Therefore, we should come up with a probability curve indicating the miss detections, the error code rate, and the false alarms to define the QoS standard for wireless sensor networks.
2. Apart from using GPS receiver, other methods for the absolute localization of the nodes ought to be developed. Since GPS technology is sometimes unpractical due to the attributes of the sensor's antenna and the cost of adding a second receiver to a small node.
3. In the case of the proactive networks, there is a need for simpler and faster data transmission algorithms to further save the energy dissipated in local data transmission. For example, if the difference of consecutive sensed data at a node is

less than a predefined delta, the node can just send out a “one bit” signal, 0 or 1, to indicate the data decline or increase, instead of sending out a full size data packet.

4. In a combined monitor network, there is a need for better and more accurate data fusion algorithms to handle multi-attribute signals from different sensors (e.g., cameras, microphones, and seismic sensors).
5. We have to develop more general methodology in mesh configuration and in the routing design inside a mesh for the circumstance of very irregular monitored area.
6. Further research needs to be done to determine how to tradeoff the ratio of local data processing (computation) and data transmission to achieve the minimum energy dissipation. Also has to be determined is the tradeoff between how much the amount of bits should be allocated to data coding and how much to channel coding.

As the rapid development of the wireless sensor networks, there exists a universal future work that needs to be done for all the researchers who engage in this industry, that is, to standardize the different WSN protocols. This will rescue the wireless sensor network industry from its present state of very successful but incompatible proprietary protocols existing in a number of niche markets, with their combined volume too low to reach economies of scale necessary for significant growth.

Appendix A

MATLAB Implementation

In this thesis, we use MATLAB [87] [88] [89] to implement the three protocols (THEEM, PEGASIS, and MTE) for comparison purposes.

For the three protocols, *rand* sentences are used to generate the random locations of the nodes in the monitored area. The initial energy level is set to each node at the beginning of the simulation, and certain energy is removed when the node performs data transmission, data reception or data fusion. The amount of the energy removed for data communication or computation is defined in Chapter 5.

One node that is located away from the rest of the nodes is designated as the base station. This node has no energy constraints and is the node to which all data are eventually sent. The base station node must keep track of the amount of data it receives, the simulation time and the energy dissipating status of the network. Using these values, we can calculate the amount of data that is received during a given time so that to determine the quality of different protocols. We can also calculate the latency of different protocols by using these values.

In the simulations, if a node runs out of its energy, it is deemed to be dead. In such situation, in THEEM simulation, base station removes (ignores) those dead nodes from the mesh and assigns new time frame slot to each live node at the beginning of each round. In PEGASIS simulation, the base station removes (ignores) those dead nodes. The upstream nodes will jump over those dead nodes and transmit the data packet to next nodes on the

chain. In MTE simulation, the source nodes will ignore the dead nodes when building next hop to the base station.

A.1 THEEM Implementation

THEEM is implemented exactly as described in Chapter 4. The operation procedure of THEEM simulation is as follows:

1. Assign random distributed nodes to the monitored area and assign initial energy to each node.
2. For each round, configure the first hop routing and second hop routing for the live nodes in each mesh. Assign time frame slot for each node and compute the simulation time for this round. The simulation time is based on the operation time of the mesh that has the most live nodes.
3. For each frame in a round, compute the energy dissipation of data communication and fusion for each live node in the individual mesh and the data packet number in the first hop and second hop. Then compute the energy dissipation and data packet number for mesh-head nodes' communication.
4. Compute the total energy dissipation, total data packets the base station receives and count the simulation time thus far.
5. Assign new mesh-head to the meshes for the next round and repeat the above procedure.

The paradigm for configuring the first hop in a mesh (e.g., for mesh 1) is as follow:

for dd1=1:a,

d_nodetoMH_MH1(dd1)=sqrt((MH1(mhformh1,1)-MH1(dd1,1))^2+(MH1(mhformh1,2)-

```

        MH1(dd1,2))^2);    %compute the distances between nodes and MH
end;
%MH finds the node from the farthest to the closest, this is to ensure the correct hop, data
%fusion, and transmission.
for w=1:a,
    distance=max(d_nodetoMH_MH1); %set the distance to be the max distance
    for dd1=1:a,
        if (d_nodetoMH_MH1(dd1)==distance),
            %if the distance between MH and a node is greater than L/2, MH will then find an
            %intermediate node for this node for the first hopping
            if (d_nodetoMH_MH1(dd1)>=0.5*SizeofField/sqrt(MH)),
                packet_MH1=packet_MH1+1; %count the data packet number
                d_nodetoMH_MH1(dd1)=0; %Move the node that has been computed for the first
                %hopping so this node will not be considered in the
                %second hopping computation

                for ddd1=1:a,
                    if (ddd1~=dd1 & ddd1~=mhformh1),
                        %compute the distance to MH for each node (with the exception of MH and the source
                        %node) via the intermediate node
                        routing_forMH1_first_hopping(ddd1)=sqrt((MH1(dd1,1)-MH1(ddd1,1))^2+
                            (MH1(dd1,2)-MH1(ddd1,2))^2)+sqrt((MH1(ddd1,1)-MH1(mhformh1,1))^2+
                            (MH1(ddd1,2)-MH1(mhformh1,2))^2);
                        else routing_forMH1_first_hopping(ddd1)=SizeofField; %make this value not to be
                        %considerable

                    end;
                end;
            end;
        end;
    for ddd1=1:a,
        if (routing_forMH1_first_hopping(ddd1)==min(routing_forMH1_first_hopping)),
            %find the shortest routing
            ndformh1firsthopping=ddd1; %MH1(ddd1,:) is the first hop destination node
        else
            end;
        end;
    else

```

```

    end; %end--if (d1_nodetoMH_MH1(dd1)>=0.5*SizeofField/sqrt(MH)),
    else
    end; %end--if (d1_nodetoMH_MH1(dd1)==distance),
    end; %end--for dd1=1:a,
end; %end--for w=1:a,

```

The paradigm of removing the dead nodes and reconfiguring the network is as follow:

```

%remove dead nodes from the mesh and compute the distances between live nodes and
%MH, reorganize the structure in this mesh
for nn=1:aa,
if (min(Node_die_MH1)==0),
    if (a>1),
        for dd1=1:a,
            if (Node_die_MH1(dd1)==0),
                a=a-1;
                for nd1=dd1:a,
                    MH1(nd1,1)=MH1(nd1+1,1);
                    MH1(nd1,2)=MH1(nd1+1,2);
                    Node_die_MH1(nd1)=Node_die_MH1(nd1+1);
                end;
                Node_die_MH1(nd1+1)=1;
            else
            end;
        end;
    else
        Node_die_MH1=zeros(1,aa);
    end;
else
end;
end;

```

A.2 PEGASIS Implementation

PEGASIS is implemented as described in Chapter 3 (3.1.1). The paradigm for building the chain is as follow:

```
%build the chain from the farthest node on
for i=1:NumofNode,
    if (d_nodetobase(i)==max(d_nodetobase)),
        m=n(1,:);
        n(1,:)=n(i,:);
        n(i,:)=m;
        q=energy(1);
        energy(1)=energy(i);
        energy(i)=q;
    else
        end;
end;

%build the chain using greedy algorithm and make the numbers of nodes along the chain
%follow the sequence
for j=1:NumofNode-1,
    for i=j:NumofNode-1,
        d_nodetonode(i)=sqrt((n(j,1)-n(i+1,1))^2+(n(j,2)-n(i+1,2))^2);
    end;
    for i=j:NumofNode-1,
        if (d_nodetonode(i)~=0 & d_nodetonode(i)==min(d_nodetonode)),
            p=n(j+1,:);
            n(j+1,:)=n(i,:);
            n(i,:)=p;
            s=energy(j+1);
            energy(j+1)=energy(i);
            energy(i)=s;
        else
            end;
    end;
end;
```



```
d_nodetonode=0;
end;
```

A.3 MTE Implementation

For MTE routing, routes from each node to the base station were chosen such that the energy dissipation is minimum when data are transferred from each node to its next-hop neighbor in the direction of the base station.

The algorithm that configures the hop routing for MTE follows these rules:

1. The sum of distance1 and distance4 should be minimal to ensure the next-hop node is the closest node that is in the direction of the base station.
2. The sum of the distance1² and the distance2² is less than the distance3². Otherwise, the source node transmits the data directly to the BS.

where, Distance1 is the distance from the source node to the next-hop node (intermediate node). Distance2 is the distance from the next-hop node to the base station. Distance3 is the distance between the source node and the base station. Distance4 is the sum of distance1 and distance2.

Appendix B

Energy-Efficiency of the Two-Hop Scheme

Unlike some two-hop protocols that have been developed in wireless channel access, in which cases there exist nodes that cannot communicate directly with an Access Point (AP) because of the distant location or the shadowing due to obstacles [97] [98] [99] [100], the two-hop scheme we introduce in this thesis is by all means a new thought that can further save the energy for those nodes that locate farther from the mesh-head node.

Figure B-1 shows that our two-hop scheme outperforms PEGASIS and MTE in terms of the energy-efficiency even when we directly apply the two-hop scheme to the entire monitored field without dividing it into meshes (the number of mesh is 1). In Figure B-1, we use the same set-ups as in Chapter 5 (200 nodes in a monitored field of 180×180 m and the base station at the location of (90, 240)).

Figure B-2 shows the total amount of data received at the base stations as a function of total network dissipated energy with the field sizes of 60×60 m and the node number of 20. Note that the size of each mesh for the THEEM simulations in Chapter 5 is 60×60 m and the node number in each mesh is about 20. So Figure B-2 shows that when we apply the two-hop scheme to a monitored area with the same size as a mesh in the simulations in Chapter 5, its energy-efficiency is still much better than those of PEGASIS and MTE.

Figure B-1: The total amount of data received at the base station as a function of network dissipated energy with node initial energy of 5J and the base station at (90, 240). For THEEM, the number of mesh is 1.

Figure B-2: The total amount of data received at the base station as a function of network dissipated energy with node initial energy of 1J and base station at (30, 240)

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