A TWO-HOP ENERGY-EFFICIENT MESH PROTOCOL FOR WIRELESS SENSOR NETWORKS

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We develop a novel energy-efficient routing protocol called the THEEM (Two-Hop Energy-Efficient Mesh) protocol for wireless sensor networks. In the THEEM protocol, a comprehensive and integrated treatment is employed to achieve energy efficiency. In specific, a two-hop in-mesh transmission scheme and a centralized mesh (cluster) formulation method are employed, along with other design innovations, such as the concepts of mesh layer/column, the power-aware assignment of mesh heads and a low-energy media access protocol. Simulation results show that the THEEM protocol is able to reduce energy consumption quite significantly compared to currently existing protocols. Equal energy dissipation among all sensor nodes in a network is also achieved. In addition, the protocol maximizes network data throughput.

Keywords: Sensor networks; routing protocol; energy-efficiency.

1. Introduction

In recent years, the advance in embedded processors, integrated memory and wireless communication 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 ad hoc wireless sensor networks (WSNs) can be created and used in situations where traditional wired networks are unsuitable or infeasible. These WSNs are finding applications in more and more areas such as environment monitoring, border surveillance, observation of the deep ocean ecosystem, battlefield target detection etc. [Sass & Gorr, 1995; Mainwaring, 2002].

A WSN may consist of hundreds to thousands of sensor nodes. In most applications, these nodes will not be relocated after deployment, with the exception of a very small number of mobile sensor nodes. Usually, each node is supposed to sense some particular events in its environment and transmit sensed data to a distant base station, through which the end user can access the sensed information. Sensed data are often not transmitted directly to the base by individual nodes; instead, the data are aggregated, fused and compressed in some particular nodes before being sent to the base station since the transmission of raw data is very costly in terms of energy consumption. For instance, the energy cost of transmitting one K byte data to 100 meters away is approximately...
three Joules; while a general-purpose processor with 100 MIPS/W power is able to efficiently execute three million instructions using the same amount of energy [Pottie & Kaiser, 2000; Heinzelman, 2000]. For conventional wireless networks, mobility management and failure recovery are the most important in protocol development in order to achieve high system performance [Sohrabi et al., 2000]; however, the main challenge in WSN design is to have a long network lifetime since battery-powered nodes, which operate normally in inhospitable, hostile or inaccessible regions, are expected to perform sensing and communication without continual maintenance and battery replenishment. Therefore, the overall performance of a WSN becomes highly dependent on the energy efficiency of the network. In addition to the strict requirement on energy efficiency, a well designed WSN should have high QoS and short transmission delay, as well as the capability of handling the mobility of nodes. In the meantime, the network needs to be robust to node failure in order to maximize utilization. In other words, the loss or failure of a small number of nodes should not greatly affect the fundamental functionality of the WSN.

Many WSN routing protocols have been proposed and developed in these few years, among them the frequently cited ones are: The Power-Efficient Gathering in Sensor Information System (PEGASIS) protocol; the Minimum Transmission Energy (MTE) protocol; the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol; the Threshold sensitive Energy Efficient sensor Network (TEEN) protocol and the Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network (APTEEN) protocol. The main idea of PEGASIS [Lindsey & Raghavendra, 2002] is that sensor nodes form a chain so that each node communicates to its adjacent neighbors. In theory, PEGASIS could minimize energy dissipation in data transmission, but time delay is large. In the mean time, when the distance between two adjacent nodes along the chain is large, these nodes will drain out their energy and die faster than other nodes, which in turn causes neighboring nodes to die along the fixed chain and shortens whole 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. For the MTE protocol, intermediate nodes are chosen such that the sum of squared distances is minimized [Ettus, 1998; Heidemann & Estrin, 2002; Lindsey & Raghavendra, 2002; Shepard, 1996]. The MTE protocol aims to minimize transmitting energy along the route from nodes to the base station, but the data throughput is low. In the meantime, there is no guarantee for balanced energy dissipation among the nodes. LEACH [Heinzelman, 2000] is a clustering-based protocol which rotates the role of the cluster head among local nodes randomly in order to achieve even energy consumption; however, this objective is realized at the cost of large cluster set-up overhead. In addition, it is sometimes unable to ensure a complete coverage of the entire monitored area. The cluster formations in TEEN [Manjeshwar & Agrawal 2001] and APTEEN [Manjeshwar & Agrawal 2002] are based on the LEACH protocol and hence have the same drawbacks as LEACH.

In this paper, we introduce a Two-Hop Energy-Efficient Mesh (THEEM) routing protocol for WSNs. The THEEM protocol is able to achieve much high energy efficiency, low transmission latency, and equal energy dissipation. The development motivation and the idea of the THEEM protocol are discussed in Sec. 2. Section 3 presents simulation models and results. Section 4 concludes this article and outlines possible directions for future research.

2. The THEEM Protocol

The THEEM protocol is a hybrid mesh-based protocol which includes the concepts of a two-hop in-mesh routing scheme, a hierarchical network structure, the energy-aware assignment of mesh-heads, the multi-hop across-mesh transmission, and the TDMA/CDMA MAC layer implementation. The intensive computation such as mesh configuration, assignment of mesh heads and computation of routes is
completed by the base station (this is called centralized configuration).

2.1. The operation
As shown in Fig. 1, the covered area of a THEEM sensor network is partitioned into a certain number of meshes (clusters). Data collected by each individual node are transmitted to the mesh head as per a two-hop scheme which is discussed in Sec. 2.2. In each mesh, the node with the most residual energy is chosen as the mesh head by the base station at the beginning of each round. The role of mesh heads is rotated among nodes, which ensures the equal energy dissipation of nodes and thus all nodes in the same mesh use up their energy approximately at the same time. Since nodes inside a mesh are relatively close to each other, sensed data are usually correlated. Sensed data are fused and compressed locally by the mesh head in order to reduce the volume of transmitted data. A multi-hop scheme is then used for transmitting the data from the mesh head node to the base station. The reason is that WSNs are normally composed of hundreds or thousand of sensor nodes and the base stations are often far away from the network. The employment of the multi-hop scheme for communication between mesh heads and the station reduces energy consumption compared to the scheme to transmit data directly to the station. The base station assigns a different CDMA code to each mesh to eliminate interference between meshes. The mesh-head level communication is illustrated by Fig. 1 as follows:

- From the farthest mesh layer (layer 3) on, mesh-head nodes transmit data to mesh-head nodes in the adjacent layer (layer 2) simultaneously, i.e. the mesh-head nodes of meshes 7, 8, and 9 send out their data at the same time.
- Only the mesh head in the adjacent layer and the same mesh column receives the transmitted data from neighboring farther layers, e.g. only the mesh-head node of mesh 7 receives the data from the mesh-head node of mesh 9. Each mesh-head node will be assigned two CDMA codes: One for receiving and the other one for transmitting, e.g. mesh 6 uses one CDMA code to received data from mesh 9 and the other for transmitting data to mesh 3. Thus, each node in the network needs only two matched filter correlators, one for receiving and the other for transmitting.
- The data are transmitted along the multi-hop route from one mesh-head node to another in the same mesh column until reach the closest layer to the base station.
- Finally, sensed data are transmitted to the base station by mesh-head nodes in the mesh layers (meshes 1, 2, and 3) that are closest to the base station. The base station needs a bank of matched filter correlators to receive the data.

In the THEEM WSN, a communication session starts with a set-up phase whose function is to configure the WSN structure. Then, the operation proceeds round by round, as shown in Fig. 2. Each round consists of two phases: Assignment phase and data frame phase. An assignment phase is composed of a start beacon, an energy reporting frame and a control packet. The body part of each round is the data frame phase consisting of a certain numbers of frames that are transferred from node to mesh-head or from mesh-head to base station.

![Fig. 1. An example of the two-hop energy-efficient mesh protocol architecture.](image-url)
Figure 3 shows the details of the set-up phase. During the set-up phase, the node first sends out a short message (location and energy information) directly to the base station. Upon receiving this information from nodes, the base station broadcasts control packets to the whole network via a known radio channel to create working tables for each node. All sensor nodes listen to this common channel to receive the control packet from the base station, synchronize their internal clock and update their working tables. The information in the control packet includes timing signal, the ID of each node, selection of mesh-head, CDMA code assignment, distance to the mesh-head, hop number of the nodes and slots allocated.

The structure of one round is shown in Fig. 4. At the beginning, 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 information to the base station via a two-hop scheme and a multi-hop scheme. Once receiving the energy and location information on nodes, the base station decides mesh-head nodes for each mesh in the current round. The node with the most residual energy is selected to be the mesh-head. Then, the base station assigns the hop number, TDMA structure and time slots to each node, and broadcasts a control packet to the network.

Figures 5(a) and 5(b) show the details of a data frame, where Fig. 5(a) shows the situation when a mesh has the most nodes (e.g. 30 nodes in this mesh) and Fig. 5(b) shows the situation when a mesh has average nodes (e.g. 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 Fig. 5(b)) 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.
Two-Hop Energy-Efficient Mesh Protocol

First Hop | Second Hop | Mesh-head to Base station
---|---|---
slot 1 | slot 2 | slot 14 | slot 16 | slot 17 | slot 29 | slot 30 | Layer 3 -> Layer 2 | Layer 2 -> Layer 1 | Layer 1 -> Base Station

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

Slot 1 | slot 10 | slot 11 | slot 20 | Sleep | Layer 3 -> Layer 2 | Layer 2 -> Layer 1 | Layer 1 -> Base Station

First Hop | Second Hop | Sleep State | Mesh-head to Base station
---|---|---|---

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

Fig. 5. The composition of one data frame.

(listen to the base station), while the non-mesh-head nodes in these meshes are put into sleep status, see Fig. 5(b). When the mesh that has the most nodes finishes its data transfer (after 30 slots data transfer, as shown in Fig. 5(a)), 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”. Non-mesh-head nodes can still sleep in the inter-mesh data transfer period to further conserve energy.

2.2. Two-hop scheme

Since the energy dissipation of nodes in data transmission/reception is proportional to the distance of data communication [Heinzelman, 2000; Rappaport, 2002], to reduce the energy dissipation in a mesh, it is always desired to find out a way to minimize the distance between transmission and receiving. The distance between nodes is often far less than the one from node to base station. By using two- or multiple-hop communication routing, each node transmits/receives data only to/from its 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 usually not at the center of the mesh. If we use a single-hop transmission scheme, such as the in-cluster communication scheme implemented in the LEACH protocol [Heinzelman, 2000], some nodes will have to send their data to the mesh-head node over a significantly longer distance. Therefore, to slow down energy dissipation, a two-hop routing protocol is used in a mesh. 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 remaining area of the square mesh. In the mesh, the nodes outside the circle are the source nodes and the nodes within the circle are the intermediate nodes.

It is reasonable to assume that nodes are randomly distributed in a mesh. Therefore, the mesh-head node (located at the centre of the circle) can be anywhere in the mesh since they take turns to be the mesh-head as explained before. The largest area covered by the circle in the mesh is \( \pi r^2 \), as shown in Fig. 6(a), and the smallest area is 0.25 \( \pi r^2 \), as shown in Fig. 6(b). The approximate covering average of the mesh by such a circle is thus 0.625 \( \pi r^2 \) (since the mesh-head node is uniformly distributed in the mesh). Let this area be half of the mesh area \( l^2/2 \), where \( l \) is the width of the square mesh, we have: \( r = \sqrt{4/(5\pi)} \times l = l/2 \).

An example to illustrate how the proposed two-hop scheme works in a mesh is shown in
are less than $r$. Data transmission within the mesh is divided into two hop-periods. In the first hop-period, all nodes outside the circle (nodes 7–11) transfer sensed data in sequence to their respective closest node within the circle, one of nodes 7–11 or the mesh head (e.g. node 5 transfers their data to node 11) — starting from the largest node number (node 1). In the second hop-period, all nodes within the circle (nodes 1–6) transmit their data (after fusing their sensed data with the one received from the node outside the circle) to the mesh head node in sequence — also starting from node with the largest node number (node 7).

In detail, node 1 is allocated to time slot 1 in a data frame, node 2 to time slot 2, ..., and node 11 to time slot 11. Table 1 shows the details of data transfer, where Tx stands for transmission and Rx stands for receiving. The vertical arrows indicate the data transmission direction in each individual time slot.

3. Analysis and Simulation

This section presents the performance analysis of the THEEM protocol through theoretical analysis and simulation. In simulation, the THEEM protocol is compared to the PEGASIS and MTE routing schemes in terms of network lifetime, energy dissipation, amount of data transfer, and latency. We choose these two protocols for comparison for these reasons: The PEGASIS scheme is a “near-optimal chain-based protocol that minimizes energy” and it outperforms most other competitive protocols (e.g. PEGASIS is better than LEACH by about 100 to 200 percent in terms of energy efficiency) [Lindsey & Raghavendra, 2002]; the 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.

3.1. Experimental set-up

We use the same radio energy and channel propagation models as those in [Heinzelman, 2000]. In the simulation, the network consists of 200 nodes which are randomly distributed in the
Table 1. Details of data transmission in a mesh.

<table>
<thead>
<tr>
<th></th>
<th>slot1</th>
<th>slot2</th>
<th>slot3</th>
<th>slot4</th>
<th>slot5</th>
<th>slot6</th>
<th>slot7</th>
<th>slot8</th>
<th>slot9</th>
<th>slot10</th>
<th>slot11</th>
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<td>Rx &amp; Fusion</td>
<td>Tx</td>
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<td></td>
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<td>Rx &amp; Fusion</td>
<td>Rx &amp; Fusion</td>
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<td>Mesh-head</td>
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<td></td>
<td></td>
<td>Rx &amp; Fusion</td>
<td>Rx &amp; Fusion</td>
</tr>
</tbody>
</table>

Fig. 8. Coverage area of the WSN.

The base station is placed at 60 meters from the closest node. For simplicity, the following assumptions are made in the simulation:

- The base station has unlimited energy supply.
- All sensor nodes have equal initial energy.
- Each node is able to adjust its transmission power and to transmit data to any other sensor nodes.
- Transmitter antennas are omni-directional.
- Clocks in sensor nodes are synchronized with each other and there is no clock drift.

3.2. Energy-efficiency

Figure 9 shows the total number of data packets received by the base station as a function of dissipated energy. From Fig. 9, the THEEM protocol transmits as much as three times and twice of the data to the base station than MTE
Fig. 9. The total number of data packets received by the base station versus energy dissipation.

Fig. 10. Energy \times delay versus simulation time.

Fig. 11. Number of nodes alive versus the amount of data sent to the base station.

routing and PEGASIS respectively under the same energy dissipation.

To analyze the performance of energy consumption more comprehensively, we use the “energy \times delay” metric as well. Note that the energy here is the total amount of energy dissipated in the network and the delay is defined as the average delay per packet. The reason to use “energy \times delay” as the energy performance criterion instead of energy dissipation only is as follows. 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 consumed per packet and the data delay. To maximize the quality of service, we need to lower both energy dissipation and packet delay. Hence, “energy \times delay” is an appropriate measure for optimization design [Lindsey & Raghavendra, 2002].

Figure 10 shows the comparison when this metric is used. We can see that as the simulation time passes, the energy \times delay of THEEM is only as half as that of PEGASIS and is the one-fourth of that of MTE. THEEM’s lower energy \times delay value is due to its two-hop scheme for in-mesh data transmission and that in-mesh data transmission proceeds simultaneously across the network. As shown in Fig. 11, THEEM can deliver much more data to the base station than the PEGASIS scheme and MTE routing for the same number of node deaths.

3.3. Throughput

One application-independent method of determining quality is to measure the amount of the data received at the base station [Heinzelman, 2000]. Figure 12 shows the total data received by the base station over time. From the simulation, we can see that the THEEM protocol could send the maximum as many as 8 times and 5 times of data to the base station than MTE routing and PEGASIS respectively.
3.4. **Network lifetime**

The simulation and comparison of lifetime is shown in Table 2. It is quite clear that the THEEM WSN has the longest lifetime compared to the PEGASIS and MTE protocols (15 times more data than PEGASIS and 30 times more data than MTE).

3.5. **Effect of the location of the base station on simulation**

Figure 13 shows the total data received at the base station when the first node dies as the base station location varies from the center of the network to 210 meters away from the network center. We can see from this figure that THEEM delivers much more data to the base station wherever the base station is.

![Network throughput](image1)

**Fig. 12.** Network throughput, where each node begins with 2 J of energy. The total amount of data received at the base station over time.

![Total data received](image2)

**Fig. 13.** Total data received by the base station when the first node dies as the base station location varies.

<table>
<thead>
<tr>
<th>Initial Energy (J/node)</th>
<th>Protocols</th>
<th>Simulation time when first node dies (seconds)</th>
<th>Number of packet received at BS (×10³)</th>
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<tr>
<td>0.25</td>
<td>MTE</td>
<td>9.4</td>
<td>4.7</td>
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<td></td>
<td>PEGASIS</td>
<td>18.6</td>
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<td></td>
<td>THEEM</td>
<td>47.6</td>
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<td>0.5</td>
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4. Conclusion and Future Work

The advance in wireless communication and microelectronics technologies makes it possible to integrate sensors, radio transmitters, microprocessors and memory into one single tiny chip or circuit. The application of WSNs consisting of these tiny sensor nodes has been attracting attention and growing dramatically in recent years since they are relatively easy to deploy and able to work at certain circumstances that traditional networks are not suitable. Nevertheless, the WSN is a newly emerging technology and many issues are still open to research.

The limited power supply and the ad hoc nature of node deployment are the two major differences between WSNs and other wireless networks, though all these networks are error-prone and time-varying. In fact, these two differences are the main challenge for the development of practical WSN applications. We take these constraints and factors into consideration when designing the THEEM protocols for WSNs.

4.1. Conclusions

In order to achieve maximum network lifetime, the THEEM protocol uses a two-hop in-mesh data transmission scheme and a low-energy MAC protocol to reduce and balance energy-dissipation among nodes in a WSN network. This objective is realized by shortening data transmission distance. The Low-energy MAC (TDMA) protocol was chosen to allow nodes to remain in the sleep state as long as possible, minimizing energy consumption. The reason is that nodes only need to be awake during their specific slots to transmit or receive data rather than waiting in an idle mode to see if they need to transmit/receive data, which still consumes energy. The two-hop scheme also balances the energy-dissipation among mesh-head nodes and non-mesh-head nodes by reducing the energy that the mesh-head nodes would have consumed in receiving and fusing the data from non-mesh-head nodes. Performing local fusion on the correlated data greatly reduces energy dissipation as well. Finally, the power-aware mesh-head assignment in THEEM ensures an excellent equilibrium of energy dissipation among nodes and hence prolongs the network lifetime.

In order to guarantee full monitoring coverage and quality over the entire surveillance area, THEEM uses centralized mesh formation methods based on the demands of the monitoring 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.

4.2. Future work

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

- Rather than using the amount of data received at the base station as the QoS standard, we need to consider situations where nodes alive are not detected and false alarms occur. The probability that nodes are undetected could be quite high when the distribution of sensor nodes is sparse, the residual energy in sensor nodes is low, or when the buffer of sensor nodes are not enough to handle the sensed data. 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. Improper setting (e.g. threshold value is set too low, or sensitivity is set too high) can cause false alarms. Therefore, it is needed to develop a probability curve indicating the un-detections, the error code rate, and the false alarms to define the QoS standard for WSNs.

- Apart from using a GPS receiver, other methods for the absolute localization of nodes ought to be developed. Since the 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.

- In the case of 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.

- In a complicated monitoring application, 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).
- A more general methodology in mesh configuration and in the routing design inside of a mesh for the circumstance of irregular monitored area will be studied.
- Further research needs to be done to determine how to trade off the ratio of local data processing (computation) and data transmission to achieve the minimum energy dissipation. In the mean time, it is also valuable to investigate how to trade off between the amount of bits allocated to data coding and the one to channel coding.

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