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A Hierarchy-Based Multi-Path Routing Protocol for Wireless Sensor Networks

Ying-Hong Wang
Tamkang University
R.O.C.

Chih-Hsiao Tsai
Takming University of Science and Technology
R.O.C.

Hui-Min Huang
Hsing Kuo University of Management
R.O.C.

Abstract

This work presents a Hierarchy-Based Multi-path Routing Protocol (HMRP) for wireless sensor networks. According to HMRP, the wireless sensor network is initially constructed as a layered network. Based on the layered network, sensor nodes have multipath routes to the sink node through candidate parent nodes. The simulation results indicate that the proposed HMRP can increase the lifetime of sensor networks better than other clustering or tree-based protocols.

Keywords: Wireless Sensor Network, Energy Efficiency, Hierarchy-Based Multi-Path Routing, Clustering Protocol, Data Aggregation.

1. Introduction

Advances in micro-electro-mechanical systems (MEMS) technology, wireless communications and digital electronics have allowed the development of low-cost, low-power, multi-functional small sensor nodes that are small in size and communicate without restriction at short distances [1, 11, 12]. These multi-functional sensor nodes can be utilized in a wide range of applications such as the military, battlefield, object detection, target tracking, environment monitoring and civil aviation by using *Wireless Sensor Networks* (*WSNs*) [14-16]. Each sensor performs a sensing task to detect specific events, and is responsible for gathering data to return the data to the Sink node or Base Station (BS).

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A significant difficulty in designing these networks is the battery energy, which limits the lifetime and quality of the networks. Good routing protocols have to be designed for the WSNs to extend the lifetime of sensor networks. In the approaches proposed in [2-3], the placement of the classical sensors and the network topology are predetermining. Communication in the sensor network is based on the wireless ad hoc networking technology [18]. If the sensor nodes cannot directly communicate with the sink, some intermediate sensors must forward the data.

Several multihop routing protocols have been proposed to forward the data packets back to the sink via other nodes. Hierarchical or cluster-based routing [4-10, 13, 17, 19] methods are well-known techniques with particular advantages relating to scalability and efficient communication.

This investigation develops an energy-efficient hierarchical mechanism, called Hierarchy-based Multipath Routing Protocol (HMRP). HMRP has many candidate paths to disseminate data packets to the sink. The data aggregation mechanism involves in every nodes apart from the leaf nods reducing the energy consumption in the networks. The proposed system was designed according to the following objectives:

■ *Scalability*

The sensing area may include hundreds or thousands, or even more, sensor nodes. The HMRP could be suitable for a small or large sensing scale, since the communication overhead among sensor nodes is very low.

■ *Simplicity*

The sensors have restricted computing capability and memory resources. Therefore, this approach attempts to minimize the numbers of operations performed, and of states maintained at each node. In particular, each sensor only has to maintain its candidate parents' information table to determine the routing path.

■ *System Lifetime*

These networks should operate for as long as possible, because recharging the battery of nodes may be inconvenient or impossible. Therefore, data aggregation and energy-balanced routing are adopted to decrease the number of messages in the network to extend its network lifetime.

2. Related Work

Routing in WSNs is generally divided in two ways: according to the network structure as *flat-based*, *hierarchy-based*, and *location-based* routing, and according to the protocol operation as *multipath-based*, *query-based*, and *negotiation-based*, *QoS-based*, or *coherent-based*. Heinzelman, et al. [10] introduced a hierarchical clustering algorithm for sensor networks, known as *Low-Energy Adaptive Clustering Hierarchy* (*LEACH*). LEACH is a cluster-based protocol that applies randomized rotation of the cluster heads to distribute the energy load evenly among the sensor nodes in the network. The operation of LEACH is organized in rounds, each consisting of a set-up phase and a steady-state phase. During the set-up phase, the network is separated into clusters, each with a randomly selected cluster head from nodes in a cluster. During the steady-state phase, the cluster heads gather data from nodes within their clusters respectively, and fuse the data before forwarding them directly to the sink. LEACH provides sensor networks with many good features, such as clustering-based, localized coordination and randomized rotation of cluster-heads, but expends much energy in cluster heads when directly forwarding data packets to the sink.

Lindsey et al. [4] presented an enhanced LEACH protocol. The protocol, *Power Efficient Gathering in Sensor Information Systems* (*PEGASIS*), assumes that all nodes have location information about all other nodes, and that each can send data directly to the base station. Hence, the chain of PEGASIS is constructed easily using a greedy algorithm based on LEACH. Each node transmits to and receives from only one of its neighbors. In each round, nodes take turns to be the leader on the chain path to send the aggregated data to the sink. To locate the closest neighbor node in PEGASIS, each node adopts the signal strength to measure the distance of all neighbor nodes. However, the global information of the network known by each sensor node does not scale well and is not easy to obtain.

Since a sensor network generates too much data for the end-user to process, it has to aggregate the data. *Power Efficient Data Gathering and Aggregation in Wireless Sensor Networks* (*PEDAP*) [9] is based on a minimum spanning tree. PEDAP assumes that the sink knows the locations of all nodes, and that the routing information is calculated by *Prim's* algorithm with the sink as the root. PEDAP prolongs the lifetime of the last node in the system while providing a good lifetime for the first node. Conversely, whereas the power-aware version of PEDAP provides a near-optimal lifetime for the first node while slightly decreasing the lifetime of the last node. Additionally, sensor nodes transmit the sensed data to the sink via the previously constructed routing path to produce a minimum energy consuming system. Nevertheless, the intermediate nodes consume energy quickly. In the *Hierarchy-Based Anycast Routing* (*HAR*) *Protocol for Wireless Sensor Networks* [6], the sink constructs a hierarchical tree by sending packets (such as Child REQuest (CREQ), Child REPly (CREP), Child ACcePtance (CACP), Parent REQuest (PREQ)) to discover each node's own child nodes in turn. HAR avoids both flooding and periodic updating of routing information, but needs to reconstruct the tree when nodes fail or new nodes are added. The drawback of HAR is that it sends and receives too many packets in the network, expending much energy.

3. HMRP

3.1. Network environments and assumptions

Figure 1 shows an example of the system environment. The sensor nodes are distributed randomly in the sensing field. A network composed of a small number of sink nodes and many wireless sensor nodes in an interesting area is considered. The sensor nodes are assumed to be fixed for their lifetimes, and the identifier of sensor nodes is determined *a priori*. Additionally, these sensor nodes have limited processing power, storage and energy, while the sink nodes have powerful resources to perform any tasks or communicate with the sensor nodes. Once the nodes are deployed, they remain at their locations for sensing tasks. The sensor nodes can receive messages from other nodes. The sink node starts with hop value "0", while other sensor nodes are "∞". HMRP is a hierarchical routing protocol that can reduce the energy consumption and prolong the lifetime in sensor networks. It replies with a complete route from the source node to the sink quickly, and prepares many routes path to balance the energy of each node. HMRP enables intermediate nodes to aggregate all receive packets during a short period time and transmit only one aggregated packet to the following node.

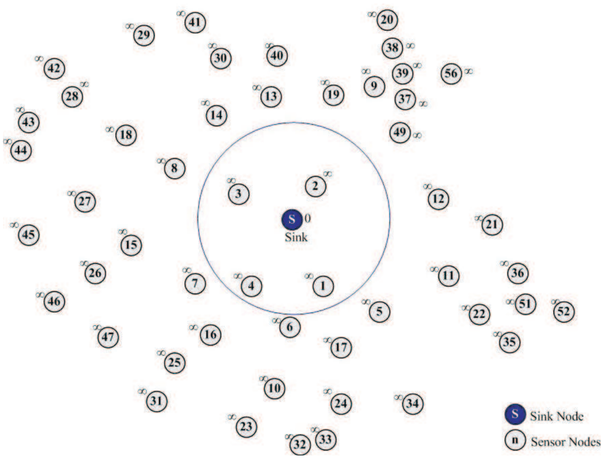

Figure 1. Example of sensor network environment.

HMRP is based on the hierarchical tree architecture, in which the sink nodes serve as root nodes. Each sensor node must be a member of the architecture, i.e., an internal or leaf node, to communicate with the sink node. HMRP has two phases, *Layer Construction Phase* (*LCP*) and *Data Dissemination Phase* (*DDP*).

3.2. Layer Construction Phase (LCP)

HMRP forms hierarchical relations with a *network construction packet* (*NCP*), which allows nodes to form autonomous relationships without any centralized control. The NCP format is ⟨*Seq_Number*, *Hop_Count*, *Source_ID*, *Sink_ID*, *Packet_Type*⟩. The *Seq_Number* field is a packet sequence. The *Hop_Count* field is the number of hops from the sink node, so the nodes that can receive the radio signal of sink are defined as one-hop nodes. The *Source_ID* denotes the ID of the node that layer packet came from. Owing to the HMRP support multiple sink, *Sink_ID* indicates which sink broadcasts the layer packet. The *Packet_Type* field specifies the packet type. Packet type catalogues are classified OR categorized into two types, which are the *Layer Construction Request* (*LCREQ*) packet (L) and *Candidate Parents Request* (*CPREQ*) packet (C).

The major activities in this phase are hierarchy setup, candidate information table creation and routing path formation for each node. The sink node (S) first increases the *Hop_Count* field by one, and broadcasts the *LCREQ* packet to discover the one hop nodes, i.e., the sink broadcasts the *LCREQ* packet $\langle 1, 1, S, S, L \rangle$ to its neighbor nodes, displayed in Figure 2. A node not yet attached to the layer determines its candidate parent(s) from the received *LCREQ* packet by waiting for a short period of time (T_{LCREQ}) to obtain one or more candidate parents, and records them in its *Candidates Information Table* (*CIT*). The initial value of *Event_Range* field is *NULL*.

In Figure 2, sensor node ① checks the *Packet_Type* of a received packet (which may come from different sink nodes or other nodes). If the value of *Packet_Type* field is L, then it is a *LCREQ* packet. The sensor node will compare the *Hop_Count* field with its hop value. If *Hop_Count* field is smaller than its hop value, then it keeps the packet during T_{LCREQ}, e.g., the value of *Hop_Count* field is 1, which is less than the hop value ∞ of node ①, and otherwise drops the packet. If the time of T_{LCREQ} is finished, node ① begins to select the packets with the lowest *Hop_Count* values as its candidate parents, and records the packet information into CIT. Node ① then raises the *Hop_Count* field of *LCREQ* packet by 1 and rebroadcasts. Node ⑥ additionally receives two layer packets from nodes ① and ④ with the same *Hop_Count* field value. Hence, the candidate parents

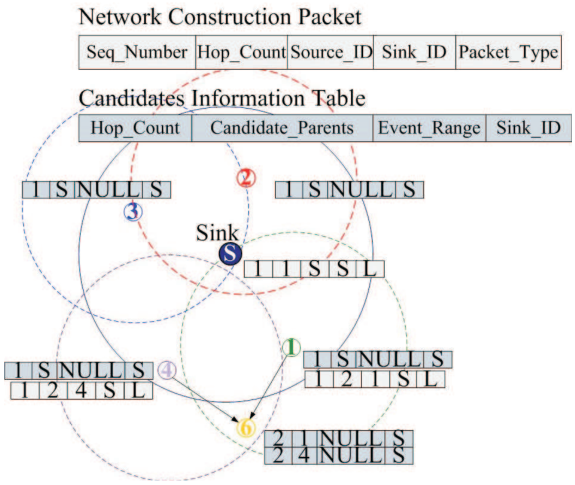

Figure 2. Layer construction flooding.

are both nodes ① and ④. Additionally, node ① receives an *LCREQ* packet from node ④, but the hop value of node ① equals to the *Hop_Count* field. Therefore, node ① ignores the *LCREQ* packet. Figure 3 shows the action flow when a node receives a packet. Every node continues flooding the *LCREQ* packet until the network level is constructed.

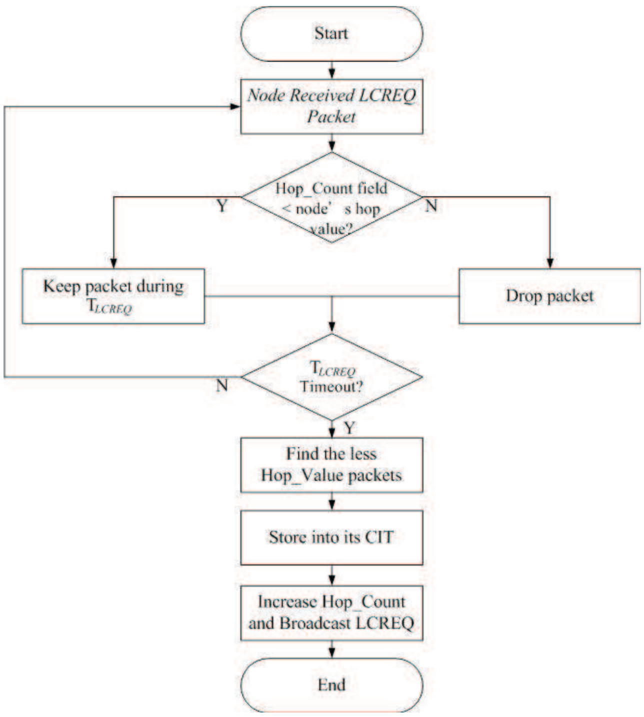

Figure 3. An action flow when node received *LCREQ* packet.

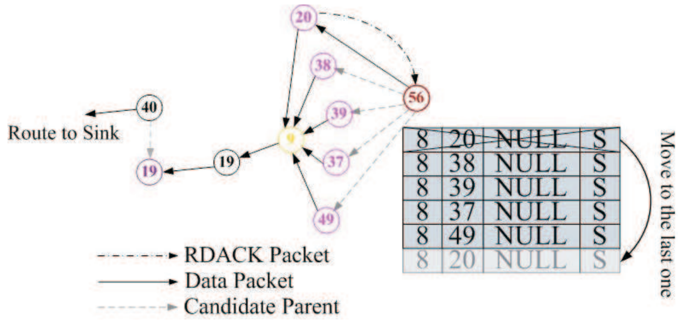

Figure 4. Data dissemination Phase.

3.3. Data Dissemination Phase (DDP)

Sensor nodes can start disseminating the sensed data to the sink via the parent node. The packet format is as follows: ⟨*Seq_Number*, *Source_ID*, *Dest_ID*, *Sink_ID*, *Data_Len*, *Payload*⟩. The *Seq_Number* field is a sequence number of the packet. The *Source_ID*, *Dest_ID*, and *Sink_ID* fields respectively are the source node of the packet, the destination node to which the packet forwards, and the sink node that requests the data packet. The *Data_Len* field denotes the packet length, and the *Payload* field is used to carrying the data. A *Received Data Acknowledge* (*RDACK*) packet is sent when the data packet is successfully transmitted to the parent node. The parent node then replies with this packet to notice the source node, and forwards the data packet to next hop.

For example, in Figure 4, node 56, with five candidate parents, 20, 38, 39, 37 and 49, sequentially selects a record from CIT. Node 56 first disseminates data packets to parent node 20. If node 20 replies with a *RDACK* packet, then node 56 moves the record at node 20 to the last position of CIT. Conversely, if node 20 does not reply with a *RDACK* packet, then it is removed from the CIT, since its energy may run out, or it is broken and data packet cannot transfer via this node later. Each node performs the same motion as node 56 until the data packet reaches the sink node. The data packet can be forwarded to the sink via many paths. The lifetime of the network system can be extended if the sensor node always uses a different path to send data packets.

3.4. Network Layer Maintenance

In addition, a new sensor node attaches to the network or a node had appended to the network but cannot find any candidate parent from their CIT that can use *rediscovery mechanism* to find their candidate parents. In Figure 5, the sensor node broadcasts

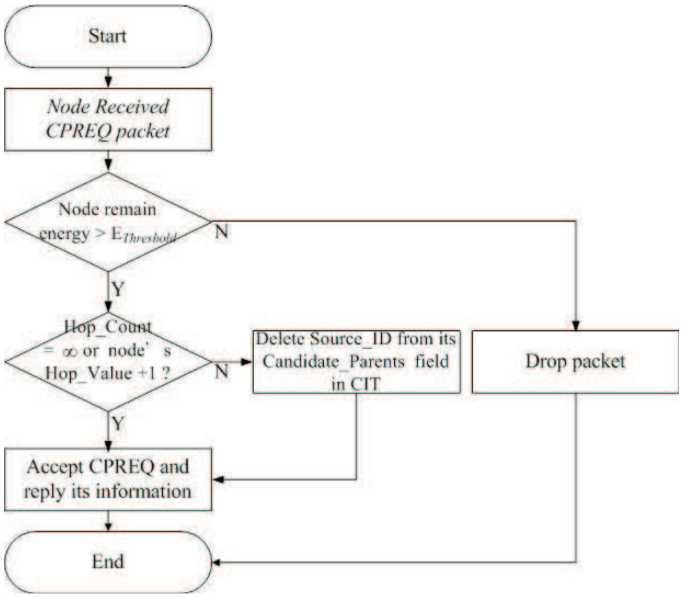

Figure 5. An action flow when node received *CPREQ* packet.

an NCP with its hop value and *Packet_Type* value *C* (meaning *Candidate Parent Request*, *CPREQ*) to its neighbor nodes to aware of its existence. Any neighbor nodes receiving this packet check that the remaining energy is greater than $E_{Threshold}$ (50% of the initial energy). This threshold depends on the different application of sensor networks. If a neighboring node has sufficient energy, then it inspects the *Hop_Count* field to identify the request packet. If the request comes from a newly deployed sensor node (*Hop_Count* field is "∞"), then the neighboring node accepts the request, and replies with a *LCREQ* packet to the joining node by unicasting. Otherwise, the neighboring node checks whether the *Hop_Count* of the requesting node equals to its own *Hop_Value* + 1. If "yes", then the neighboring node accepts the request and replies with a *LCREQ* packet to the joining node by unicasting. If "no", then it deletes the *Source_ID* of this request from its *Candidate_Parents* field in CIT; and replies with a *LCREQ* packet to the joining node by unicasting. Significantly, this *LCREQ* packet is same as that described in Section 3.1, except that unicasting is adopted instead of broadcasting. If the request node does not receive any *LCREQ* packet after broadcasting the CPREQ packet, then either no node exist within its radio coverage, or none of its neighboring nodes have yet attached themselves to the network layer. In this case, the request node rebroadcasts the *CPREQ* packet periodical for waiting an incoming *LCREQ* packet after one of its neighbors has attached to the layer.

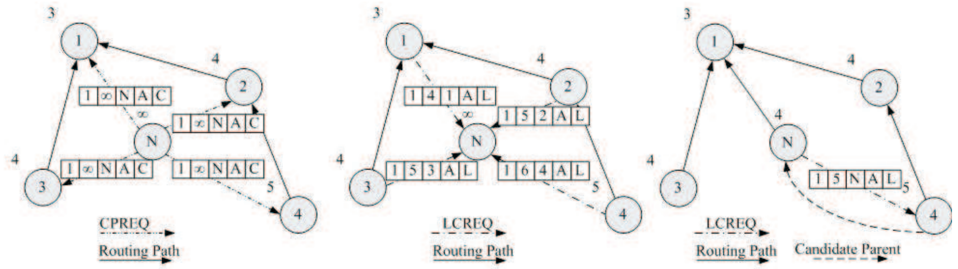

Figure 6. (a) New node broadcast CPREQ (b) Neighbor nodes reply LCREQ (c) New node transmit LCREQ to lower level node

When the request node received a *LCREQ* packet from its neighbor nodes, it chooses the packet(s) with the lowest *Hop_Count* field as its candidate parent(s). If *Hop_Count* equals to *Hop_Value* + 1, then the candidate parent(s) is (are) its sibling node(s). Otherwise, the candidate parent(s) must be certain of its child node(s). In Figure 6, after a new deployed node has set its candidate parent(s), then it checks the other received *LCREQ* packet(s) to determine whether the *Hop_Count* field equals to its *Hop_Value* + 2, then sends the *LCREQ* to become their candidate parent.

3.5. Data Aggregation

To save energy in the whole entire network, the aggregation is performed in their calculations that all responses received are aggregated before being propagated. The parent node waits for a period of time (T_{Wait}) to collect data packets coming from all its children. When a node receives data packets from its different lower level nodes, it will categorize the packet(s) according to the *Sink_ID* field of the packet. These data packets are then aggregated during a T_{Aggre} time. The parent creates an *Event Range* (*ER*) value that indicates the stable range value of event occurrence, and then sends an *RDACK* packet to the children that transmitted the data packet to it with this *ER* value ($T_{Wait} + T_{Aggre} \leq T_{RDACK}$). The child node records the *Source_ID* and *ER* value into CIT. Finally, only one data packet is transferred to the sink node in a routing path. The sensed nodes later compare the new event value with the parent's *ER* value. If new event value lies in between the *ER* value, then the nodes do not report the event. Otherwise, the nodes send the change value of the event.

In Figure 7, a user wants to inquire about the summary temperature of some area *A*. Sink broadcasts this query to the sensor networks. After received this query, node ㊻ and ㊼ sense the temperature (30° and 35° respectively) and generate data packet forward to their parent node. And then, Node ㉖ uses the received packets to aggregate

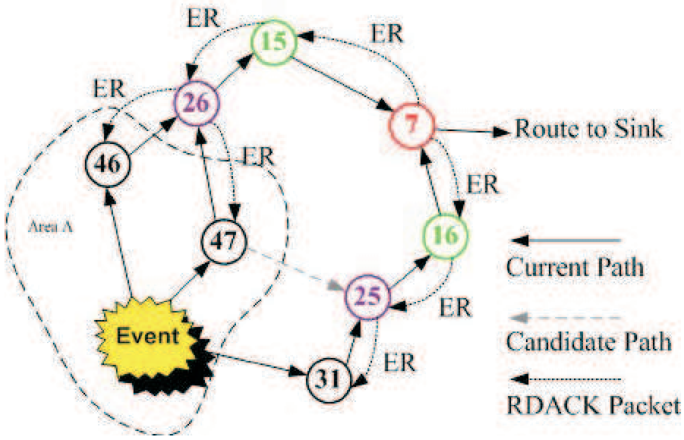

Figure 7. Parent reply a *RDACK* packet with *ER* value.

the temperature packet route to sink and set an *ER* value between 30° to 35° reply to node ㊻ and ㊼. Node ㊻ and ㊼ keep monitoring the area A to check the temperature exceeds the *ER* value or nor. This *ER* value only updates when a new query comes from the sink node.

4. Simulation Results

The energy costs for the various protocols discussed in the previous section were compared with those of the proposed protocol using the first order radio model [7, 10]. The transmitted and received energy costs for the transmission of a k-bit data message between two nodes separated by a distance of r meters are given by Eqs. 1 and 2, respectively.

$$E_T(k,r) = E_{Tx}k + E_{amp}(r)k \tag{1}$$

$$E_R(k) = E_{Rx}k \tag{2}$$

In Eq.1, $E_T(k,r)$ denotes the total energy dissipated in the transmitter of the source node, while $E_R(k)$ in Eq. 2 represents the energy cost incurred in the receiver of the destination node. Parameters E_{Tx} and E_{Rx} are per bit energy dissipation for transmission and reception, respectively, and $E_{amp}(r)$ denotes the energy required by the transmitted amplifier to maintain an acceptable radio for transferring data reliably. The free-space propagation model is applied, and the transmitted amplifier $E_{amp}(r)$ is given by Eq. 3.

$$E_{amp}(r) = \varepsilon_{FS} r^2 \tag{3}$$

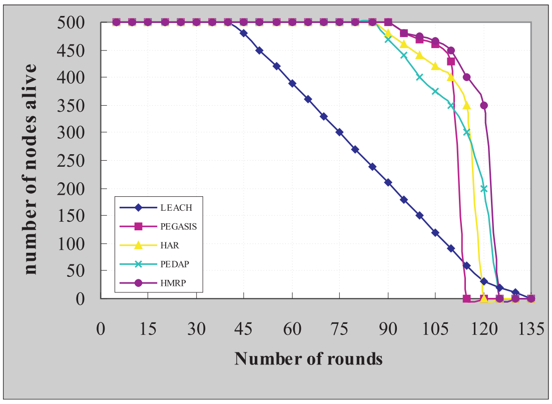

Figure 8. The system lifetime of HMRP and other protocols.

where ε_{FS} is the transmitted amplifier parameter. The set of parameters given in [7, 10] was assumed for all experiments in this work: $E_{Tx} = E_{Rx} = 50$ nJ/bit, $\varepsilon_{FS} = 10$ pJ/b/m^2, and the energy cost for the data aggregation was set to $E_{DA} = 5$ nJ/b/message.

To evaluate the performance of HMRP, simulations were run using C++, as described in the section. The performance of the proposed protocol was compared with that of the following other cluster-based routing protocols: LEACH, PEGASIS, HAR and PEDAP. The aim of the experiments was to measure the system lifetime and average energy dissipation. Networks of 100 m × 100 m with 500 nodes and different topologies were simulated. Each node had an initial battery of $2J$, and sent 40 data frames in each round. Additionally, the message size was fixed at 500 bytes in all simulations, and each sensor node was assumed to be able to transmit data directly to the sink.

Figure 8 illustrates the system lifetime of those protocols. HMRP has a good lifetime improvement to others. Additionally, the system lifetime is defined as the number of rounds for which 75% of the nodes are still alive. HMRP produces a better system lifetime than the other protocols: 200% better than LEACH, 8% better than PEGASIS, 5% better than HAR and 14% better than PEDAP. Figure 9 shows the average energy dissipation graph, revealing that HMRP consumes energy consumed more efficiently than the other protocols. HMRP produced an average reduction in energy consumption of 35% over LEACH, because all cluster heads in LEACH send data directly to the sink. However, other protocols alleviate this problem so that only one cluster head node forwards the data to the sink. Nevertheless, HMRP still outperforms PEGASIS by 8%, due to the distance between neighbors, and HMRP outperforms HAR and PEDAP by 4% and 7%, respectively, since HMRP spent less cost of energy than HAR and PEDAP in constructing the hierarchy.

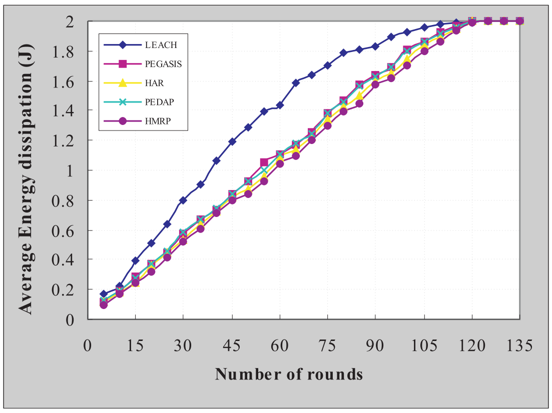

Figure 9. The average energy dissipation of HMRP and other protocols.

5. Conclusions

Energy resource limitations are of priority concern in sensor networks. Distributing the load to the nodes significantly impacts the system lifetime. This investigation proposes a hierarchy-based multi-path routing protocol called HMRP, which minimizes the path loading of the system by distributing the energy consumption among the nodes. In HMRP, sensor nodes do not maintain the whole path information, and so just maintain their CIT. The simulation results indicate that HMRP performs better than LEACH, PEGASIS, HAR and PEDAP. Additionally, HMRP supports multiple-sink-node environments.

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Authors' Information

Ying-Hong Wang is an associate professor in Departmant of Computer Science and Information Engineering of Tamkang University since 1996. And he is the department chair from August First, 2004. He has over 100 technological papers published on International journals and International conference proceedings. He also join many International activities been associate editor of IJCA, program committee members, workshop chair, session chairs and so on. His current research interests are Software Engineering, Distance Learning Technology, Wireless Communication, and Mobile Agent.

Department of Computer Science and Information Engineering, Tamkang University, Tamsui, Taipei City, Taiwan 251, R.O.C.

E-mail: inhon@mail.tku.edu.tw TEL : +886-2-2621-5656 ex 2108

Chih-Hsiao Tsai received his Ph.D from Department of Computer Science and Information Engineering of Tamkang University in 2006. He is currently an assistant professor in Department of Information Technology, Takming University of Science and Technology. His research interest includes mobile computing, wireless communication, embedded system, wireless sensor networks and grid computing.

Department of Information Technology, Takming University of Science and Technology, Huanshan Rd., Neihu District, Taipei City, Taiwan 11451, R.O.C.

E-mail: chtsai@takming.edu.tw TEL : +886-2-2658-5801 ext. 5156

Hui-Min Huang received her Ph.D from Department of Computer Science and Information Engineering of Tamkang University in 2008. She is currently an assistant professor in Department of Appiled Internet Science, Hsing Kuo University of Management.

Department of Appiled Internet Science, Hsing Kuo University of Management, Yuying St., Tainan, Taiwan 709, R.O.C.

E-mail: huanghm@mail.hku.edu.tw TEL : +886-6-2871-894