A Tree-Based Multiple-Hop Clustering Protocol for Wireless Sensor Networks

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Abstract. This paper introduces a static Tree-based Multiple-Hop Distributed Hierarchical Agglomerative Clustering (TMH-DHAC) approach for wireless sensor networks (WSNs). The proposed TMH-DHAC is derived from the Hierarchical Agglomerative Clustering (HAC) and the distributed HAC (DHAC) methods. TMH-DHAC adopts an energy-aware cluster-head election policy to balance the energy consumption and workload among sensor nodes in the network. The multi-hop tree structure provides the near-optimal routes for intra-cluster data transmissions. The proposed TMH-DHAC method for the time-slot allocation enables simultaneous conflict-free communications between different pairs of sensors and increases the maximum transmission throughput. The simulation results show that TMH-DHAC performs better than previous approaches: LEACH, LEACH-C and the DHAC-RSS (Received Signal Strength) protocols, in terms of the network lifetime, total data amount, energy efficiency, and average transmission distance.

Keywords: wireless sensor networks, clustering, multi-hop, minimum spanning tree, performance evaluation.

1 Introduction

A wireless sensor network (WSN) may consist of a number of sensor nodes which work in a collaborative way. One of the important issues in WSNs is how to manage and organize sensor nodes effectively to perform the data-gathering in the network. In general, sensors consume a considerable amount of energy on wireless communications. Devising an energy-efficient communications scheme is a crucial concern for sensor networks.

Generally, depending on the basic network structures, the routing protocols for WNSs are classified into two categories: flat and hierarchical [9]. Hierarchical protocols have the advantages of scalability, communication efficiency and network lifetime. LEACH [6] is one of the first clustering approaches for WSNs. It has been widely used as a base model for extension and/or performance comparison. Most clustering approaches adopt the same or similar model used in LEACH. One main feature of the LEACH model is the assumption of star or star-like topology within

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clusters. In other words, cluster member (CM) nodes communicate directly with the cluster head (CH). This communication model is not energy efficient as the distances between CM nodes and the CH in a cluster could be large and the energy consumption has a direct relationship with the communication range; see *Transmission Energy Dissipation* in Section 4.

The motivation of this paper is to devise an energy-efficient and distributed hierarchical clustering approach for WSN applications to reduce the transmission distance for sensor nodes and hence the corresponding energy cost. It is well known that the minimum spanning tree (MST) is a mathematical structure connecting all nodes in a network with the minimum sum of weights of its branches/links. Applying the MST concept to a hierarchical clustering protocol can reduce the total transmission distance and achieve saving of energy consumption in communications.

Another direction to improve the energy-efficiency is to exploit the immobility of sensor nodes using static clustering. Sensors can be grouped into an unchanged cluster formation in early phase and avoid the frequent and often less-optimal re-clustering process. The hierarchical agglomerative clustering (HAC) [14] algorithm is a simple but effective centralized clustering approach and has been successfully applied to many disciplines. [11] and [22] adapted HAC and developed a bottom-up method, Distributed HAC (DHAC) algorithm, that forms clusters in a WSN without the global knowledge of the network. This paper proposed a Tree-based Multiple-Hop DHAC (TMH-DHAC) algorithm which is derived from DHAC but further modifies the clustering method by adopting a multi-hop transmission tree structure to avoid most of the long-distance direct transmissions from CMs to the CH to reduce energy consumption.

The rest of the paper is organized as follows: Section 2 describes related work. Section 3 discusses the TMH-DHAC algorithm. Section 4 presents the simulation and results. Finally, Section 5 is the conclusions.

2 Related Work

Hierarchical routing provides a better solution to organize and utilize the resource-constrained sensors to work collaboratively. Hierarchical protocols can be further classified as distributed and centralized approaches. Some representative protocols in these two categories are introduced here.

2.1 Distributed Hierarchical Routing Protocols

LEACH [6] is self-adaptive routing protocol. The LEACH protocol randomly chooses some nodes as CHs and organizes the sensor nodes into clusters. CHs collect and aggregate data from regular nodes and send it to the base station (BS). The role of CH is rotated among regular nodes to avoid depleting the batteries of certain sensors. One main drawback of LEACH is the randomness in the clustering procedure. In the unequal clustering mechanism of LEACH [3] and energy efficient CH selection algorithm [15], new CH election methods were proposed, which factor in the energy status of sensors to improve the balance of the energy consumption among sensors and prolong the network lifetime.

HEED [19] improves the cluster selection process in LEACH and also generates well-distributed clusters. In HEED, the energy status of a node is considered to determine the CH and a high-energy node has a better chance to be a CH. HEED also avoids the irregular cluster formation issue in LEACH.

PEGASIS [10] is a chain-based protocol proposed to reduce the transmission distance between nodes. All of the nodes are organized into one logical chain with the greedy algorithm. Every node only communicates with its two direct neighbors in the chain and data are transmitted along the chain.

ERA [2] adopts the same CH election process as LEACH but improves the cluster formation by factoring energy status into the protocol. In LEACH, a non-CH node simply chooses the closest cluster to join. Such design can cause low-energy CHs exhausted early. In ERA, non-CH nodes join the cluster with a path that has the most residual energy to the BS.

DHAC [11, 22] is a novel static clustering protocol inspired by the HAC algorithm. DHAC exploits the immobility attribute in most WSNs and proposes a bottom-up approach in clustering. In DHAC, the clustering structure is formed before the CH selection. The static clustering process is performed when sensor network is initialized and is not required to be repeated later. DHAC groups the similar nodes together by the location or signal strength information exchanged by sensor nodes. DHAC also adopts solutions to reduce the routing overhead and balance the energy consumption of nodes such as the automatic CH rotation and rescheduling.

2.2 Centralized Hierarchical Routing Protocol

LEACH-C [6] utilizes a centralized algorithm for clustering but adopts the same steady-state scheme as LEACH. In the set-up phase of LEACH-C, every node in the network sends its location and residual energy information to BS directly. The BS performs the simulated annealing algorithm with the information to calculate the optimal cluster formation in that round. The BS broadcasts the cluster formation message in the network after it is generated. Every node receives the message and knows its role either as a CH or a CM.

Dynamic/Static Clustering (DSC) [1] is an extension of LEACH-C. Each node gets its location using GPS and sends the location information and energy status to BS. The BS will then determine the number of CHs based on the collected information and broadcast the clustering result to each node.

BSDCP [12] adopts an iterative cluster splitting method to achieve an evenly scattered cluster formation. BSDCP also utilizes a CH-to-CH multi-hop routing scheme to reduce the energy cost. The inter-cluster routing paths are a minimum-spanning-tree structure generated by the BS in a centralized manner.

2.3 Multi-hop Routing

Multi-hop routing is an energy-efficient approach for data aggregation in WSNs. Multi-hop routing for WSNs has been studied by various researchers, e.g., [4], [5], [12] (see BSDCP in Section 2.2), [16], [18], [20], [21]. The objectives of those papers range from studies of energy-aware broadcasting/optimal number of hops, overlapping clusters, cooperative MIMO techniques, to identification of thresholds that are more suitable for different coding, modulation, and fading models.

[5] compares energy efficiency of one-hop vs. multi-hop routing in WSNs using the chain topology in a small network. Both [7] and [16] also uses spanning tree for data aggregation. But clustering is not used in either one and both MST algorithms are centralized for the entire network. [17] discusses how to determine the optimal hop number for energy efficiency. Clustering is not considered in the study and network performance results, such as lifetime, packet delivery ratio, and etc. are beyond its scope. [18] assumes that a network has been hierarchically clustered and then devises a multi-hop scheme. [21] deals with communications of a node to another node in a different cluster.

Our approach, on the other hand, takes into account both clustering and multi-hop at the same time, including the setup, scheduling of data transmissions, rotation of CHs and maintenance of clusters, and the establishment of an MST within a cluster. In addition, interference-avoidance is considered in our multi-hop communications.

3 Tree-Based Multiple-Hop Distributed Hierarchical Agglomerative Clustering Protocol

In this paper, the TMH-DHAC algorithm is proposed to improve the performance of the DHAC algorithm [11, 22]. TMH-DHAC adopts a tree-like intra-cluster structure to shorten data transmission distances within a cluster and simplifies the complexity in the clustering procedure.

TMH-DHAC forms a minimum spanning tree (MST) within a cluster. The CH acts as the root of the tree and every other node has its parent node. In TMH-DHAC, a multi-hop approach is adopted within a cluster to shorten transmission distance and hence energy cost. Data transmissions start from the leaf nodes to their parent nodes which aggregate their own data with those received from their children and send the aggregated data to its upper-level node. The process will be repeated from leaf nodes all the way to the root node in a cluster. By this means, every node merely communicates with its parent node and child node(s). The average transmission distance is much shorter in TMH-DHAC than star-like topology as a result of the MST formation.

3.1 Clustering

This section presents the proposed clustering process. The first two steps are common to well-known HAC methods [14]. The third step is a modification of DHAC to build an MST instead of a star-like topology.

Step 1: Input data set

An input data set for HAC is a component-attribute data matrix. Components are the nodes that we want to group based on the attributes, e.g., their locations, in WSNs. Every node knows its one-hop neighbors by exchanging a topology discovery message. Nodes detect the distance by measuring the signal strength and update their initial matrix. Figure 1 shows an example of an 8-node network.

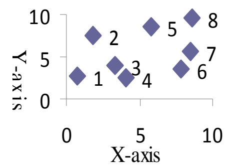

Fig. 1. A Simple 8-node Network

Step 2: Compute the resemblance coefficients

A resemblance coefficient in this context represents the distance between two components or sensor nodes. We can calculate Euclidean distance based on the location information or from the strength of the received signal.

Step 3: Execute the cluster-merging operation

Initially, each node is treated as a singleton cluster and is the CH. Table 1 depicts the matrices for nodes 1 and 4 for illustration. Each cluster finds the smallest coefficient (shown in bold in Table 1) and send a CONNECT message to the corresponding cluster if they have not been merged. The CONNECT message contains the sender and receiver cluster ID and the shortest link to connect the two clusters. Cluster ID is the tie-breaker if both nodes send CONNECT to each other.

Table 1. Initial resemblance matrices for Node 1 and Node 4: an example

Cluster {1}		Cluster {4}	
1-hop Neighbor	Coefficient	1-hop Neighbor	Coefficient
{3}	**2.90**	{1}	3.40
{4}	3.40	{3}	**1.70**
-	-	{6}	3.83

The cluster receiving the CONNECT message performs the merging operation and combines the nodes originally in both of the sender and receiver clusters to form a new larger cluster. Further, the sender and receiver nodes build a link between them. The link will become part of the tree structure used for data transmission in a later phase. The CH in the receiver cluster automatically becomes the CH of the new cluster and updates the resemblance matrix of its cluster. The CH in the sender cluster becomes a regular cluster member. In this step, every node builds a link with its closest neighbor and all of the links together form a minimum spanning tree within the cluster. The number of clusters reduces quickly in the merging process.

The initial 8 singleton clusters in the example are merged into 3 clusters in the first iteration of clustering. Nodes 3, 7, 8 which receive the merging requests, become the cluster heads of the new clusters {1,2,3,4}, {5,8}, and {6,7}, respectively. Table 2 shows the updated matrices for two clusters after all clusters exchange their information. SLINK [14] method is used in TMH-DHAC since it uses the shortest distance to other clusters for resemblance matrix recalculation after merging. The links are necessary to build the MST when clusters are merged.

Table 2. Resemblance matrices of clusters: an illustration

Cluster {1,2,**3**,4}			Cluster {6,**7**}		
Neighbor	Coefficient	Link	Neighbor	Coefficient	Link
{6,7}	3.83	{4}-{6}	{1,2,3,4}	3.83	{6}-{4}
-	-	-	{5,8}	3.80	{7}-{8}

Next, every CH broadcasts an INFORM message containing its cluster members to its neighbor clusters. The clusters receiving the message update their matrices. Then clusters repeat the operation to find the shortest distance in the matrix and send a CONNECT message to the corresponding cluster associated with it. Each cluster repeats the merging step until a certain stop condition or threshold, e.g., maximum cluster size, is met. The merging of two clusters comes with building a shortest link between nodes from the two clusters; thus the MST structure can be maintained in the newly formed cluster. For this example, if the maximum threshold is 4 nodes per cluster, then clusters {6,7} and {5,8} will exchange information due to its shortest distance in the matrix and will merge with each other. The shortest link between them, {7}-{8}, is also captured. Figure 2 demonstrates the MST generated by the TMH-DHAC from the network shown in Figure 1.

3.2 Cluster Scheduling

In a tree structure with the CH as the root, the data-gathering should start from the leaf node(s) to their parent nodes and all the way to CH eventually. The procedure of the transmission time-slot allocation takes the reverse order and starts from the CH assigning available slots for its child nodes. Then every child node repeats the action for its own child nodes. The iteration stops at leaf node.

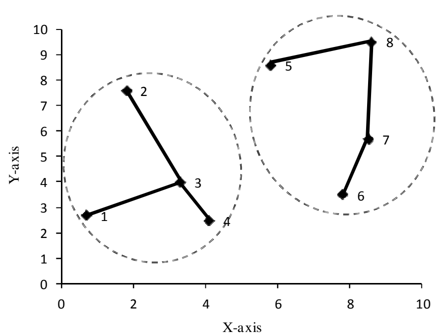

Fig. 2. Cluster formation and intra-cluster MST structure. Dashed circles represents clusters, lines between nodes represent links of MST.

Cluster scheduling is vital to avoid interference in the data transmission phase. Usually in practice, the interference range of a radio signal is considered twice as large as its transmission range [13]. Any other node located in the interference area should not utilize the same time-slot that a pair of nodes use simultaneously. Starting from the CH, when one node chooses the transmission time-slots for its child nodes, it declares the choice with high power level to cover the interference area. The child node receiving the message also responds with a declaration notifying nodes in its interference range with its assigned time-slot. Nodes locating within the interference range must avoid using the same time-slot for their transmissions.

The allocation of time-slot follows the rule of "the one to claim it first is the one to use it". Nodes do not reuse the same time-slots which it knows that they have been chosen by its neighbor(s) from the time-slot declaration. But nodes are not always able to receive the declarations from the neighbors. For example, it is possible that node A is outside of the interference range of node B but node B is within the interference range of A when node A has a longer transmission distance than node B does. If node B declares its time-slot choices first, but node A does not receive it. Then node A may choose a same time-slot and declare it to neighbors including node B. In this case, node B must inform node A to invalidate A's time-slot choice and node A will choose a new slot that has not been used by B. Detailed scheduling and maintenance algorithms can be found in [8].

4 Simulation and Results

The simulation experiments of several WSN protocols were carried out on NS-2 using randomly generated network topologies. Each WSN contains 100 sensor nodes. A number of experiments have been conducted. The simulation results demonstrated in this section are the average based on the simulation tests of 10 random topologies. Table 3 summarizes the simulation parameters and their values used in our experiments, mostly were obtained from LEACH [6]. Note that the initial energy level ($E_{initial}$) is only 0.5 J/node instead of 1 J/node used in LEACH and many other papers due to the longer simulation time needed for TMH-DHAC for each run. With 1J/node, the results for TMH-DHAC will be even better.

Table 3. Simulation parameters

Parameter	Value
Number of sensor nodes	100
Channel bandwidth	1 Mbps
Crossover Distance ($d_{crossover}$)	87 m
Transceiver Electronics Energy Dissipation Rate (E_{elec})	50 nJ/bit
Transceiver Amplifier Energy Dissipation Rate (ϵ_{fs}, ϵ_{mp})	10 pJ/bit/m^2 0.0013 pJ/bit/m^4
Data Fusion Energy Dissipation Rate (E_{fusion})	5 nJ/bit/signal
Data rate	3 TDMA frames per 10s
Data Packet Size	500 Bytes
$E_{initial}$	0.5 J/node
Spreading Factor of CDMA	8

The following energy dissipation models from LEACH are used for the simulation [6]. Though many other clustering approaches have been reported since LEACH in the literature, LEACH can still be used for indirect comparisons with those approaches that have been compared with LEACH.

Receiving energy dissipation. The transceiver energy dissipation rate, E_{elec}, depends on coding and modulation. The energy consumed by receiving an L bit message is given by $E_{Rx} = L \times E_{elec}$.

Transmission energy dissipation. Depending on if the transmission distance (D) is above a certain threshold, ($d_{crossover}$), the multi-path fading model, $E_{Tx} = L \times E_{elec} + L \times \varepsilon_{fs} \times D^2$, or else the free space model, $E_{Tx} = L \times E_{elec} + L \times \varepsilon_{mp} \times D^4$, is used to calculate the signal attenuation compensation.

Computation energy dissipation. Data aggregation and resemblance matrix updating also consumes energy. $E_{com} = E_{fusion} \times Size_{Signal} \times Number_{Signal}$ defines the computational al costs of performing data calculation.

The performance of a sensor network can be measured by several metrics, e.g., network lifetime, energy efficiency. These two metrics are used for evaluating LEACH, LEACH-C, DHAC-RSS (Received Signal Strength) and TMH-DHAC.

4.1 Different Base Station Locations

Figures 3 and 4 illustrate that the network lifetime of the TMH-DHAC algorithm is the longest, while LEACH-C and DHAC-RSS have smaller lifetimes but both are better than LEACH. Let T_n denote the time when *n*th sensor nodes dies. For instance, Figure 3 depicts T_{80} for TMH-DHAC is around 600 sec compared with 400 sec for LEACH. At the time T_{80}, a certain amount of nodes are still functioning in the network. Further, TMH-DHAC prolongs the time T_{20} 27.4% from LEACH, 5.5% from LEACH-C, and 6.0% from DHAC-RSS. TMH-DHAC also prolongs T_{80} 42.8% from LEACH, 23% from LEACH-C, 19.9% from DHAC-RSS.

Figure 4 shows similar results if the BS is farther away at (0, 150), except the offsets become larger. Specifically, TMH-DHAC prolongs the time T_{20} by 26.5% from LEACH, 10.8% from LEACH-C, 10.9% from DHAC-RSS. TMH-DHAC also prolongs T_{80} by 47.0% from LEACH, 29.0% from LEACH-C, 16.8% from DHAC-RSS.

Figure 5 compares the proportion of data amount (in packets)/energy dissipation of four protocols at the time 80% of sensor nodes die, T_{80}. In three cases when the base station's location varies, TMH-DHAC has best energy efficiency and LEACH protocol has the lowest efficiency. When the BS moves from the center (50, 50) to outside of the network (0, 150), energy efficiency reduces in all protocols. Among the four protocols, efficiency in TMH-DHAC reduces the least. The reason is that TMH-DHAC adopts a tree-like structure for each cluster. As a result, the distance is reduced and hence TMH-DHAC becomes more energy efficient.

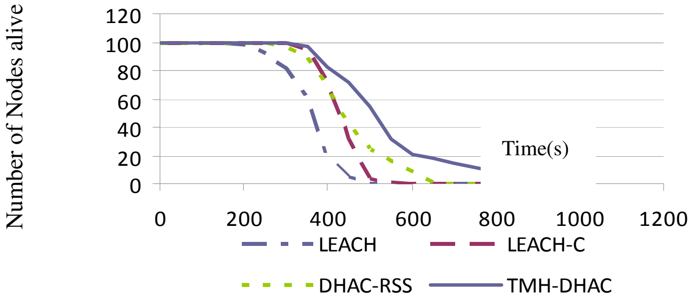

Fig. 3. Network lifetime, base station at (50, 50)

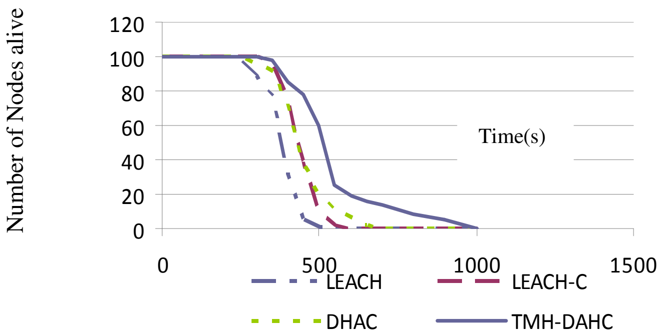

Fig. 4. Network lifetimes with base station at (0, 150)

4.2 Different Node Densities

Table 4 shows the results of three protocols that run in three different sizes of network areas, 100m×100m, 200m×200m, and 300m×300m. Each network still consists of 100 nodes. The BS is at the center of the network for all difference sizes.

With the expansion of network area size, the density of nodes becomes lower and the distance between sensors increases generally. It causes higher energy cost of data transmissions regardless of algorithm adopted. Table 4 reveals that all of the algorithms' total transmission packets drop when the network area enlarges.

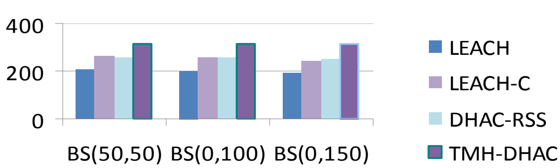

Fig. 5. Total data amount (packets)/energy dissipation when 80% nodes die

Table 4. Total transmitted data amount (packets) with varying network sizes

Sensing Field	Protocol	T_1	T_{25}	T_{50}	T_{75}	T_{100}
(0,0)-(100,100)	LEACH	5792	8836	9767	10043	10219
	LEACH-C	9608	12019	12775	13118	13402
	TMH-DHAC	9640	12278	13746	13889	15660
(0,0)-(200,200)	LEACH	5396	8357	9018	9463	9651
	LEACH-C	8200	11462	12152	12556	12855
	TMH-DHAC	8549	12178	13684	13753	15379
(0,0)-(300,300)	LEACH	3571	6568	7388	7781	7952
	LEACH-C	6996	10211	10876	11276	11525
	TMH-DHAC	7660	11962	13471	13553	14580

When sensor density is 100 nodes in a 100m×100m area, TMH-DHAC is 53.2% more than LEACH and 16.8% higher than LEACH-C. When the sensor density becomes 100 nodes in a 200m×200m area, TMH-DHAC still performs better than the other two protocols in all recorded time. In this setting, the performance of total transmitted data amount for TMH-DHAC is 59.4% better than that of LEACH and 19.6% higher than that of LEACH-C. When the network area is even larger at 300m×300m, TMH-DHAC protocol still has the highest transmitted data amount from time T_1 to T_{100} and the offsets become larger compared with those of smaller areas. It exceeds LEACH and LEACH-C by 83.4% and 26.5%, respectively.

With respect to the network life, it can be observed from Figures 6 to 8 that among 3 protocols, in all area sizes of 100m×100m to 300m×300m, TMH-DHAC performs the best. Its performance advantage becomes more obvious when sensor density is lower in a larger network.

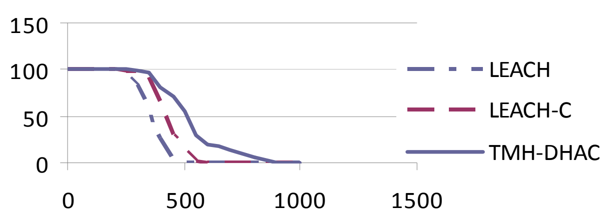

Fig. 6. Network lifetime for 200m×200m, base station (100,100)

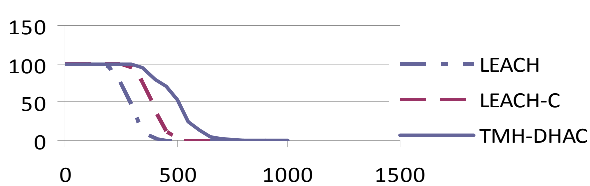

Fig. 7. Network lifetime for 300m×300m. Base Station at (150, 150)

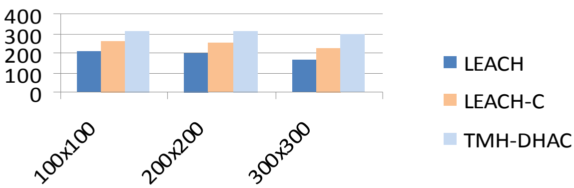

Fig. 8. Total data amount (packets)/energy dissipation at time T_{80}

4.3 Transmission Distance

Generally, tree structure has shorter links between sensor nodes than star structure. As shown in the transmission energy equation in section 3, the energy cost increases when the transmission distance increases. The comparison of the average distance in Figure 9 for different protocols can give us a rough idea as to how these protocols perform.

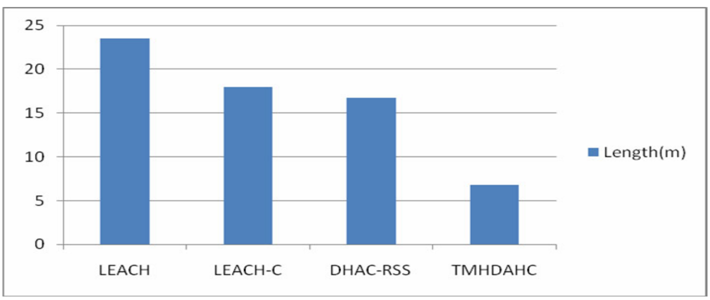

Fig. 9. Average Transmission Distance (100m×100m)

Figure 9 shows the difference in average transmission distance for four WSN protocols. The LEACH protocol has the largest value, about 23.5m, and LEACH-C has a smaller one, 18.0m, which is 23.4% less than LEACH. DHAC-RSS performs slightly better than LEACH-C and has 16.7m, which is 28.9% less than LEACH. The tree-like structure generates the smallest distance, 6.8m, which is 71% less than LEACH.

On the other hand, the quadratic or biquadratic of the distance is used in energy calculation. The comparison of those values can present how the transmission distance affects the transmission cost and the protocols performance. In the simulation, the sensing field is a limited area and most distance between sensor nodes is less than $d_{crossover}$(86.2m), so the comparison of quadratic distance is more typical and shown in Figure 10.

In Figure 10, the order of the average squared distance of four protocols is the same as that of the distance in Figure 9, but the difference between them is much larger. The average squared link length in LEACH is 663m^2, while it is 42.3% smaller in LEACH-C (382.5m^2), 48.6% smaller in DHAC-RSS (340.7m^2), and 91.3% smaller in TMHDHAC (57.7m^2).

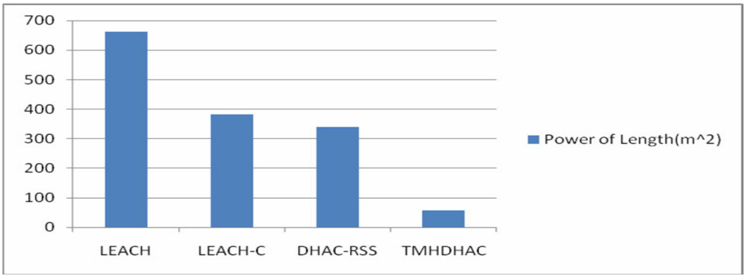

Fig. 10. Average of Squared transmissions Distance (100m×100m)

Both figures show that tree-like structure has an advantage over LEACH-style cluster structure in terms of transmission distance. The shortened transmission distance in sensor network means energy cost for transmission is reduced and network lifetime is prolonged.

5 Conclusions

This paper presented an effective distributed TMH-DHAC clustering algorithm for WSNs. The approach also offers distributed time-slot allocation and scheduling method that enables simultaneous transmissions without interference between different pairs of sensors and reduces the transmission delay of WSNs.

Many clustering approaches use the star-like topology comprised of the CH and member nodes. Its long communication distance could be a major factor that limits the energy efficiency in WSNs. TMH-DHAC adopts the multi-hop relay scheme in the intra-cluster data-gathering process which reduces the transmission distance and hence reduces energy consumption. Based on our simulation experiments, TMH-DHAC shows much improvement in terms of network lifetime, energy efficiency and total data amount due to its effective multiple-hop transmission tree structure.

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